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INTERACTION OF RADIO TRANSMISSIONS ON MINE MONITORING AND CONTROL SYSTEMS

Contract J0123038

A.R.F. PRODUCTS, INC.

BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR

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16. Abstract (Limit: 200 words)

This report deals with the creation of an efficient method to determine if command, control, communication and monitoring (3cm) equipment in coal, metal and non-metal mines is susceptible to Radio Frequency Interference (RFI) from the Medium Frequency (MF) radio communications system. A qualitative and quantitative RFI test plan was developed for in-mine and laboratory evaluation of the equipment. The laboratory testing was accomplished using the TEM Test Chamber. Detailed information on the Test Plan and the TEM Test Chamber is included. During in-mine testing of the MF System some underground equipment malfunctioned when the transmitter's radiating antenna was in close proximity.

Electromagnetic Compatibility (EMC) testing was done on three levels; Component (circuit or box), subsystems and system. Nine tables are included which show the results of testing various equipment for RFI.

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Mines; radio communications; communications; coal mines; metal/non metal mines; radio propagation; tunnel mode, coal seam mode; wave propagation; underground mine; mine rescue radio; trapped miners ; radio vest transceiver; underground mines; medium frequency; existing wireplant; loop antennas, parasitic coupling; line couplers; radio, health and safety enchancement.

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FOREWORD

This report was prepared by A.R.F. Products, Inc., Raton, New Mexico, under USBM contract number J0123038. The contract was initiated under the Mine Health and Safety Program. It was administered under the technical direction of the Pittsburgh Reasearch Center with James R. Means Jr. acting as the Technical Project Officer. Gladys Barrerea was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period 30 September 1982 to 6 June 1985. This report was submitted by the author on 31 May 1986.

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I. EXECUTIVE SUMMARY

OBJECTIVE

The principle objective of this work was to create an efficient method to determine if command, control, communication, and monitoring (3CM) equipment in the nation's coal and metal/non-metal mines were susceptible to radio frequency interference (RFI) from the medium frequency (MF) radio communications system. The project would be used to:

- decrease the possibility of RFI increasing the bit error rate and causing monitoring systems in underground mines to be unreliable,

- speed up mine automation by preventing RFI from causing malfunctions in mining equipment,

- provide the mining industry with information on an electromagnetic compatability (EMC) standard,

- develop a frequency coordination plan for use in underground mining, and

- make the Mine Safety and Health Administration (MSHA) along with the mining equipment manufacturers aware of the need to test and design for RFI suppression.

A central part of the work was to identify classes of mining equipment that could potentially be susceptible to RFI. A list was made of suspect susceptible 3CM products and possible RFI induced failure modes. A qualitative and quantitative RFI test plan was then developed for in-mine and laboratory evaluation of the products. Upon evaluating the various 3CM equipment, the project centered around developing an EMC test standard to test the RFI susceptibility of the 3CM circuits. During the course of the work, the program was expanded to include evaluation of the effects of MF RFI on aircraft aeronavigational devices since non-directional beacons (NDB) use frequencies in the MF band.

BACKGROUND

In recent years, automation in the mining industry has resulted in advanced mine technology which features complex and sophisticated electronic circuits to communicate, command, control, and monitor vital functions in the mining process.

To achieve the degree of automation required in todays competitive mining industry, MF communication links would be required in a wide variety of applications. Although the MF system is a quantum leap forward in underground mine communications, it is possible that the system's radio frequency (RF) waves could interfere with other 3CM circuits and result in the following safety and operational problems:

1. Effect on atmospheric monitoring systems - False readings on methane monitors, CO monitors and heat sensors could trigger false alarms and shut down mining equipment or allow dangerous levels of methane or CO to accumulate undetected.

2. Effect on control systems - Interference with control systems could cause underground and hoist equipment to start and stop at unpredictable times, resulting in decreased safety and production loss.

3. Effect on other communications equipment - Interference with existing communications could affect safety and the orderly operation of the coal mine.

If using the system would increase the susceptibility of other mining equipment to radio interference and thereby cause unexpected changes in the mining process, it could be exceedingly dangerous.

Practical experience gained in the installation and testing of the MF [300-3000 kHz] communications system transmitters in underground mines clearly shows that the transmitters are a potential RFI threat to 3CM circuits. This problem of interference is expected to intensify as the whole mine radio communications systems are made operational in the nation's underground mines.

THE MEDIUM FREQUENCY (MF) COMMUNICATION SYSTEM

Excellent radio coverage by the Medium Frequency (MF) communications system in an underground coal and metal/non-metal mine is due to the multiplicity of efficient (low loss) electromagnetic (EM) wave propagation modes in tunnels, layered formations, and directly through the ore body.

Underground tests proved that electromagnetic signals in the MF band couple into and reradiate from continuous electrical conductors in such a way that these conductors become the transmission lines and antenna system for the signals. The existence of electrical conductors in the entryway provides the means for what is called the "tunnel mode" of radio signal propagation in an underground mine. Testing also showed that MF signals propagating on one conductor would, by magnetic induction, induce signal current flow on other nearby conductors. Thus all of the entryway conductors and the magnetic coupling mechanism between conductors provided a means of minewide signal distribution in an underground mine. Further Bureau testing showed that radio signal propagation was possible in "natural waveguides" (coal, trona, and potash seams that are surrounded by more conductive rock) existing in certain layered formations. Because of signal propagation in the waveguide (seam mode), communication links can be established through coal pillars and can be extended to the "working face" (the focal point of most mining activity). Testing also showed that signal propagation was possible through rock and barricades in the mine. These MF modes result in excellent communication coverage in an underground mine. By way of contrast, very high frequency (VHF) and ultra high frequency (UHF) radio signals exhibit high attenuation rates down tunnels and through natural rock. Unless these signals are guided by a low loss transmission line, unacceptable radio coverage results.

MF EQUIPMENT DESIGN

The MF communications system design was based upon prior fundamental research in MF. The equipment was designed to operate in both the tunnel and seam modes. For the tunnel mode, radio coverage to all vehicle and personnel carried transceivers was provided by magnetic induction (inductively coupling) of radio signals into local electrical conductors. The electrical conductors include AC power cable, telephone cable, metal, water and air pipes, and wire rope. Base station signals are coupled to the conductors to produce local magnetic fields at distant locations. The mobile personnel carried and vehicular transceivers communicate with the base via magnetic coupling to these conductors. The transceivers use tuned loop antennas to receive and generate the magnetic fields. The base station is centrally located in the radio coverage area. Passageway repeaters extend the operating range of the base station, vest and vehicular transceivers. RF line couplers are used to couple the repeaters and base stations to the conductors. The same repeater can be equipped with tuned loop antennas to radiate and receive seam mode signals as illustrated in figure 1.

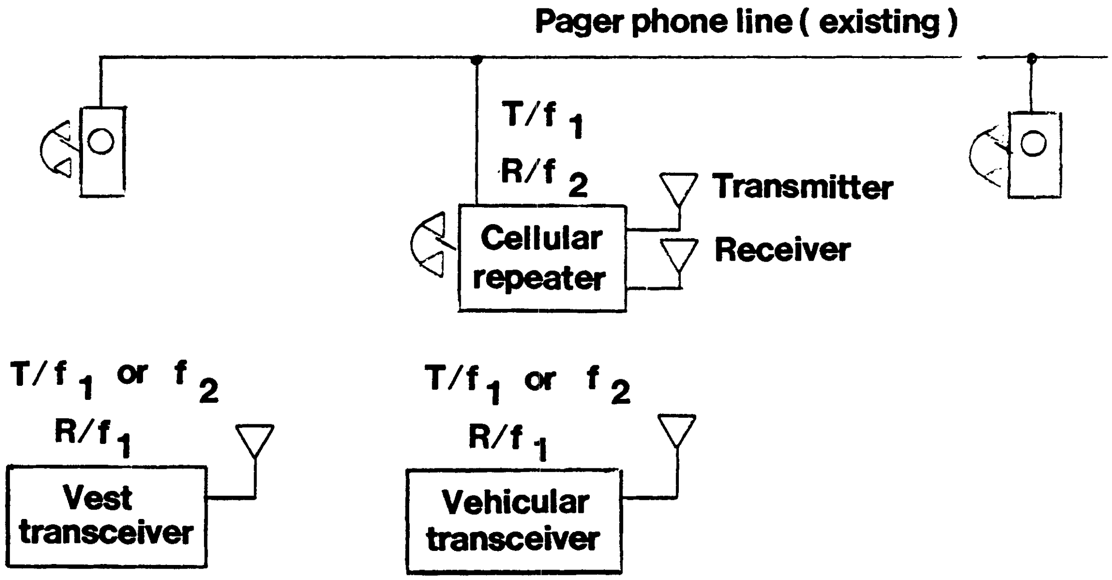

FIGURE 1. - The cellular repeater (seam mode).

Since the repeater services a "cell" (local working area) in the mine, it is called a cellular repeater. This repeater may be connected to the local pager telephone system to enable communications with other distant miners and with the surface communications center. When repeaters are used to extend the operating range, a second operating frequency is assigned to the radio system. A transmission frequency of F2 causes repeater action to occur. The repeater retransmits the message at the frequency of F1 (a high power signal). All receivers are tuned to the F1 frequency; base stations and the mobile transceivers are designed to transmit on F1 or F2 frequencies. A direct communications link between the base and mobile transceivers is created by a transmission frequency of F1; and repeater action extends the operating range by using F2 transmissions from the base or mobile transceivers. The repeaters are essential in large mines since they enable personnel carried transceivers to communicate over ranges which are similar to that achieved by the higher output power vehicular and base transceivers.

The system has been designed to operate on several selectable frequencies in the MF band. Separate communication networks (cells) can be set up by assigning a unique set of frequencies (F1 and F2) to each network which may independently serve the communication needs of maintenance, production, haulage and supervision. Additional networks are created by installing other base stations and repeaters. The base stations, repeaters and mobile transceivers are all tuned to the assigned unique network frequencies. Because digital frequency synthesizers are used in the equipment design, it is possible for mobile transceivers to monitor and communicate with other networks in the mine. Underground evaluation of the radio system showed that it could be used in a wide variety of applications which include command, control, and monitoring of all types of mining equipment. Evaluation of the MF system in four mines determined that an RFI susceptibility problem exists in the automated underground mine.

FINDINGS AND CONCLUSIONS

Results of In-Mine System Tests

The MF communications system was installed and evaluated in four underground mines. The mines ranged in size from small (500 tons/day) to large (67,000 tons/day) capacity and represented several different mining methods. Two of the mines were medium sized coal mines (approximately 1 million tons per year - MTPY). These mines use continuous mining equipment to develop longwall panels and belt haulage systems to transport coal out of the mine. The third mine was a small silver mine which uses the vertical crater retreat mining method. Diesel trucks haul approximately 500 tons of silver ore per day up a 7,000 foot long decline to the adit. The fourth mine was a large copper mine which uses the multiple level block caving method to extract 67,000 tons of ore per day. The mine uses an extensive rail haulage system to transport ore to the ore bins where hoists are used to lift it to the surface.

These mines offered an excellent opportunity to evaluate numerous aspects of the system's features in a wide variety of mining conditions. In-mine tests were conducted to measure:

(1) The MF signal carrier to noise ratio along the entire length of conductors in several entryways; (2) the signal attenuation rate of the MF signal along the conductors; (3) the receive and "talk-back" (transmit) range from mobile transceivers to the base station; (4) electrical and acoustical noise levels in the mine; and (5) receiver quieting. Additional experimental testing involved a simulated rescue and recovery operation and a simulated locating of a trapped miner.

Analysis of the in-mine test results showed that the MF communication system performed equally well in each mine. Because the performance was consistant and predictable in these mines, underground radio system engineering can predict performance in other mines. Furthermore, the in-mine evaluation showed that the system provided high quality radio coverage in most work areas and entryways with electrical conductors; the cellular repeater offers excellent coverage in the face areas of both continuous and longwall mining; "reach time" can be decreased from an average of 35 minutes (with the pager telephone system) to seconds; teamwork improves by allowing first hand information to reach key personnel in the mine; equipment downtime is reduced due to quicker communications between the production and maintenance crews; and safety and productivity are enhanced with the continued use of the system.

MF Communication Quality and Range

MF signals can be received almost everywhere electrical conductors exist in the mine. The talk-back range between a mobile transceiver and the base station or repeater depends upon the distance of the radiating antenna from the conductors and the type of nearby conductors. For radiating antenna-to-cable separation of approximately 7 ft, the vehicular to base communications range exceeded 30,000 ft along unshielded single-pair cables. At 520 kHz the attenuation rate was 2.4 dB/1,000 ft. It was only 1 dB/1,000 ft at 350 kHz. The range along the shielded 3-phase AC power cable exceeded 10,000 ft. At each point where the primary 3 phase power cable connected to a power center, the signal loss increased by 8 to 12 dB. At 400 kHz, the attenuation rate was approximately 4 dB/1,000 ft on 3 phase cable. The personnel carried transceiver talk-back range exceed 16,000 ft. In a layered formation like coal, the personnel carried transceiver talk-back range includes adjacent conductorless entries for a distance of 5,000 ft from the base station. The seam mode radio coverage cell exceeded a radius of 500 ft. This provided an excellent communication link between a roving miner at the face and the cellular repeater at the power center.

The MF carrier to noise (C/N) ratio was measured at each base station in the four mines. The measured C/N ratio often exceeded 50 dB (30 dB above the good intelligibility level) when a mobile transceiver was a mile or more from the base station.

In conductorless entryways, a low cost twin-lead cable was installed to extend radio coverage in one mine. One end of the cable was placed inside an RF line coupler to enable coupling to the entire cable. The cable provided excellent coverage in the entryway for the entire distance of the cable (more than 10,000 ft).

During in-mine testing of the system, underground mining equipment malfunctioned when the transmitters radiating antenna was in close proximity. The first incidents occurred on operating longwall mining systems. Radio communications along the face caused interruption of the longwall mining system's power. The interruption was caused by the susceptibility of the methane monitor to the radio frequency waves. After being made aware of the EMC equipment problems, spot checks of other mining systems were made. These spot checks showed that carbon monoxide monitors were also susceptible to the radio frequency waves. These findings gave rise to the formal EMC investigation decribed in this work.

II. SUSCEPTIBILITY MEASUREMENT METHODOLOGIES

A test plan was developed for in-mine, open field, and laboratory RFI surveys of susceptible equipment. The test plan was designed to 1) develop qualitative procedures for identifying the RF susceptibility of an operating coal or metal/non-metal mine and 2) develop qualitative procedures to measure the RF levels that cause malfunctions in underground mining equipment.

CHARACTERISTICS OF ELECTROMAGNETIC WAVES

The characteristics of the electromagnetic (EM) waves radiated by the MF communication system's transmitting loop antennas must be known in order to accurately simulate EM fields in the underground mine environment. Equations describing the EM waves produced by a tuned loop antenna in free space, within a coal seam, and through natural media have been previously developed in literature as well as in prior U.S. Bureau of Mines research. These equations were used to determine the radiated field strength in the vicinity of the transmitter's antenna.

Free Space Wave Equation

The electromagnetic fields produced by a transmitting loop antenna in free space will be analytically presented in this section. Figure 2 illustrates the geometry of the antenna in full space (spherical coordinate system).

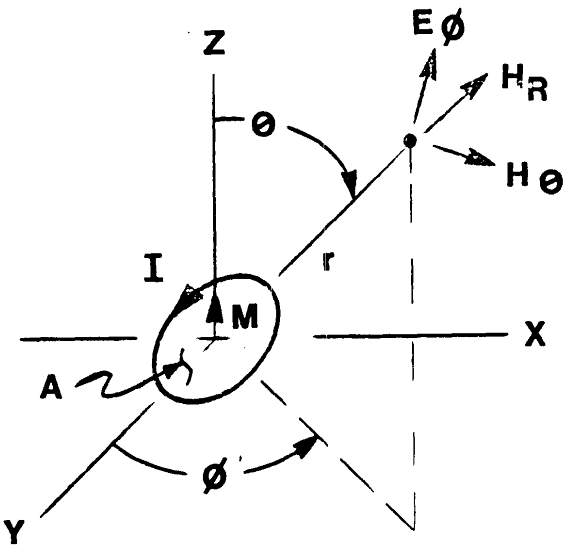

FIGURE 2. - Geometry of the transmitting loop antenna in free space (loop in Y-X plane).

The loop of small area A is enclosed by a conductor with an excitation current amplitude (I) of 1 ampere. The fields produced at the observation point P are given by:

$$H_\theta = \frac{\beta^3 M}{4\pi}\left[\frac{1}{(\beta r)^3} - \frac{1}{(\beta r)} - \frac{1}{J(\beta r)^2}\right] \text{SIN } \theta \qquad (1)$$

$$H_r = \frac{\beta^3 M}{2\pi}\left[\frac{1}{(\beta r)^3} - \frac{1}{J(\beta r)^2}\right] \text{COS } \theta \qquad (2)$$

$$E_\phi = \frac{\beta^4 M}{4\pi W E_o}\left[\frac{-1}{(\beta r)} - \frac{1}{J(\beta r)^2}\right] \text{SIN } \theta \qquad (3)$$

where β = the phase constant, and

M = the magnetic moment of the antenna.

The above set of equations are noteworthy in several respects. When the radial distance (r) from the excited loop antenna exceeds $\lambda/2$, the terms involving 1/r dominate the field equations. When θ = 90 the H_θ field strength is maximum. A companion receiver with a tuned loop antenna would receive a maximum signal level when the transmit and receiving loops lie in the same plane (coplanar). Terms with $1/r^2$ identify the "induction" field components in the EM waves. The "static" field terms are identified by $1/r^3$ in equation 1. While power transfer to the distant point is associated with 1/r components, a large amount of power can be transferred through the near field "induction" and "static" fields. Terms are in equations 1, 2, and 3.

Equation (1) has been evaluated for a unit magnetic moment. Table A shows the free space wave length (λ) and phase constant (β) at selected frequencies used in LF and MF communications. Table B gives the amplitude of the azimuthal component of the EM wave at different radial distances from the antenna. The tabular data in table B shows that the azimuthal field component is independent of the frequency near the loop antenna.

TABLE A. - Free space wave length and phase constants.

Frequency (kHz)	Wave Length (Meters)	Phase Constant (Radians/Meters)
60	5000	1.2566 x 10-3
100	3000	2.094 x 10-3
200	1500	4.19 x 10-3
300	1000	6.28 x 10-3
350	857.143	7.330 x 10-3
400	750	8.38 x 10-3
520	576.9	10.89 x 10-3
600	500	12.6 x 10-3

TABLE B. - Free space magnetic field strength versus distance of a magnetic dipole (M=1).

Radial Distance Meters	Azimuthal Component Field Strength (μA/m) ReH$_\theta$	ImH$_\theta$	H$_\theta$
Frequency 60,000 Hz			
3.8099	1439	6.889	1439
7.6198	179.85	1.7223	179.86
15.24	22.474	0.43056	22.478
30.479	2.8064	0.0765	2.8085
60.959	0.34924	0.026911	0.35027
91.4399	0.10272	0.011961	0.10342
121.919	0.042881	0.0067276	0.043405
159.399	0.01886	0.0039358	0.019267
Frequency 100,000 Hz			
3.8099	1439	11.482	1439
7.6198	179.826	2.870	179.847
15.24	22.459	0.717	22.47
30.479	2.799	0.179	2.8048
60.959	0.3455	0.04485	0.3484
94.4399	0.100266	0.019933	0.1022
121.919	0.041048	0.01121	0.04255
159.399	0.017458	0.0065598	0.0186504

TABLE B. - Free space magnetic field strength versus distance of a magnetic dipole (M=1) - Con.

Frequency 350,000 Hz

3.8099	1437.8	40.187	1438.4
7.6198	179.308	10.048	179.59
15.24	22.2	2.511	22.343
30.479	2.6	0.627	2.743
60.959	0.281	0.157	0.322
91.4399	0.057	0.069	0.090
121.919	-8.838	0.039	0.040
159.399	-0.000717	0.023	0.024

Frequency 400,000 Hz

3.8099	1437.4	45.928	1438.0
7.6198	179.1373	11.482	179.5049
15.24	22.115	2.87	22.30
30.479	2.627	0.717	2.773
60.959	0.259	0.179	0.316
91.4399	0.043	0.079	0.090
121.919	-.001898	0.045	0.0448
159.399	-.015389	0.0262	0.0304

Frequency 520,000 Hz

3.8099	1436	59.7	1437
7.6198	178.6315	14.926	179.254
15.24	21.862	3.7314	22.178
30.479	2.501	0.932	2.669
69.959	0.196	0.233	0.304
91.4399	0.0860	0.0104	0.103
121.919	-0.033.5	0.058.3	0.067
159.399	-0.039.5	0.034.1	0.052

UNDERGROUND WAVE EQUATIONS

Coal seam and tunnel signal propagation modes were evaluated in a series of underground tests conducted by the Bureau (1,2). The test results indicated that the coal seam mode enabled maximum communications range in the frequency band extending from 400 to 700 kHz. This band is a subset of the medium frequency, (300 kHz to 3000 kHz) portion of the electromagnetic spectrum. Further, as predicted by theory (3), low loss signal propagation modes existed in entryways with electrical conductors. In-mine testing confirmed the existence of low loss signal propagation in the entries of both coal and M/NM mines.

Coal Seam Propagation Mode

The theory of electromagnetic wave propagation in layered formations has been rigorously developed by Wait (4). Figure 3 illustrates the model used to analytically determine the wave propagation characteristics in a coal seam.

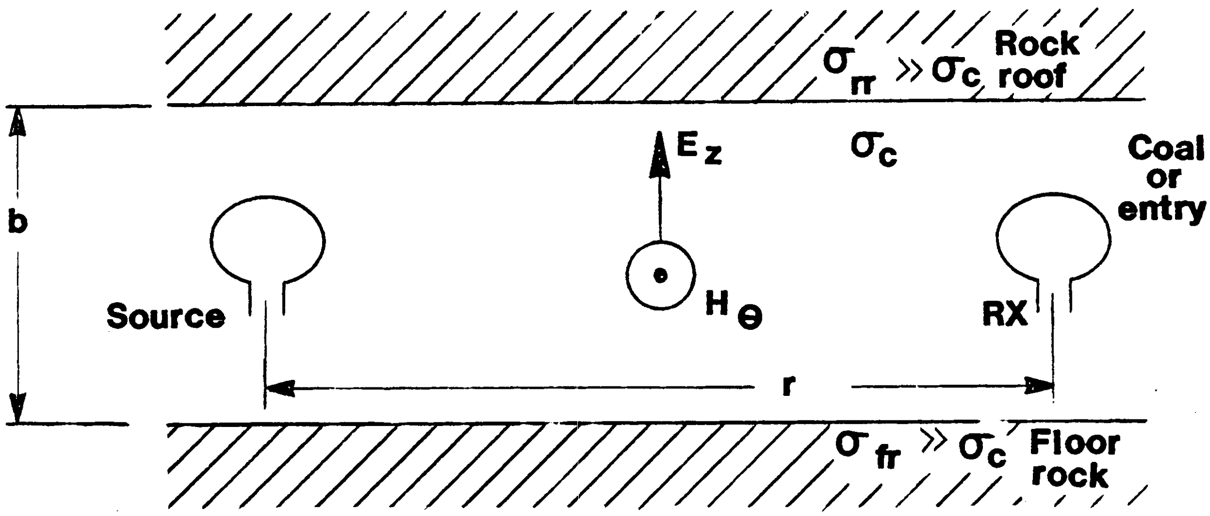

FIGURE 3. - Seam mode field components.

The coal seam is bound by two conducting half spaces with the conductivity of the roof rock (σ_{rr}) being several orders of magnitude more than the conductivity of coal (σ_c). Along the transmission path (r), the vertical orientation of the transmitting loop antenna (source) produces a horizontal magnetic field H_θ and a vertical electrical field E_z. These fields are relatively constant over the height of the coal seam. It has been shown (5) that the fields die off exponentially in the rock[1]. At large radial distances (r) from the antenna, the fields decay exponentially. The rate of this exponential decay is determined by an effective attenuation constant (α) which depends on the conductivity of the coal and rock, and on the

[1]Skin depth in rock is 0.69 meter; (σ_{rr} = 1 mho/m, 520 kHz).

coal's dielectric constant. There is also a $r^{-1/2}$ factor at large radial distances because of the wave's cylindrical spreading. The zero-order TEM magnetic field H_θ in the transmitting loop plane is given by:

$$H_\theta = (iMk / 8\, b_e)\, H_1^{(2)\prime}(kr) \tag{4}$$

where M = the magnetic moment of the transmitting loop antenna,

b_e = $b + 1/2\delta_r$ is the effective half-height of the coal seam[3],

δ_r = the z direction skin depth in the rock,

$k=\beta-i\alpha$ = the complex propagation constant in the radial direction, and

$H_1^{(2)\prime}(kr)$ = the derivation of the first-order Hankel Function for an outgoing wave.

On taking the asymptotic form of the Hankel Function, the azimuthal component of the magnetic field[4] is:

$$|H_\theta| \approx \frac{M(\alpha^2 + \beta^2)^{3/4}}{(8\pi)^{1/2}\left[(h+\delta_r)^2 + \delta_r^2\right]^{1/2}} \cdot \frac{e^{-\alpha r}}{\sqrt{r}} \cdot \tag{5}$$

The attenuation is mathematically represented by:

$$\alpha = \{ (\tfrac{1}{2}) \left[(p^2 + q^2)^{1/2} + p\right] \}^{1/2} \tag{6}$$

the phase constant by

$$\beta = \{ (\tfrac{1}{2}) \left[(p^2 + q^2)^{1/2} - p\right] \}^{1/2} \tag{7}$$

and

$$p = \frac{2(\sigma_c - 2\pi f \varepsilon_c)}{h} \left(\frac{\pi \mu_o f}{\sigma_r}\right)^{1/2} - 4\pi^2 f^2 \mu_o \varepsilon_c \tag{8}$$

where

$$q = \frac{2(\sigma_c + 2\pi f \varepsilon_c)}{h} \left(\frac{\pi \mu_o f}{\sigma_r}\right)^{1/2} + 2\pi f^2 \mu_o \sigma_c \tag{9}$$

f = the operating frequency

h = the coal seam height

[3]b_e may be complex.

[4]Valid at ranges $kr >> 1$.

σ_c = skin depth in coal

$\varepsilon_c = \varepsilon_o \, \varepsilon_r$ = dielectric constant of coal

The zero-order TEM wave described by equation (4) has been compared with experimental measurements (6). These measurements were found to be in close agreement with equation 4. Equations 6, 8, and 9 are useful in determining the dependence of the wave propagation constant on seam parameters.

The attenuation rate in coal is approximately 4 dB/100 ft (σ_c = 1.4 x 10^{-4} mho/m, ε_r = 7, $\sigma_{rr} = \sigma_{fr}$ = 1 s/m, h=1m, 350 kHz). The attenuation rate is expected to increase with decreased coal seam thickness and increased conductivity. The rate decreases with increased rock conductivity. The rate also depends upon frequency.

Tunnel Propagation Modes

Bifilar and monofilar signal propagation modes exist on a pair of wires in the wireplant. The current flow of each mode is shown in figure 4.

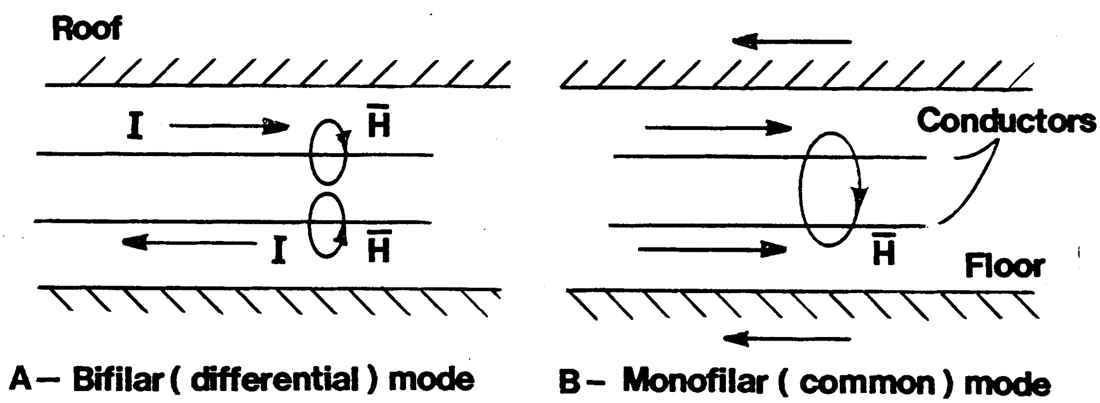

FIGURE 4. - Signal current (I) flow on conductors.[5]

The excitation of monofilar and bifilar modes on a tunnel's transmission line have been examined (3). In the monofilar mode (also called the balanced, differential,

[5]The number of possible modes is n-1 where n is the number of electrical conductors in the entryway. One of the conductors may be the conducting wall of the tunnel.

coaxial, or symmetrical mode) the current flows in the same direction in each conductor and returns as a surface current in the mine tunnel. In fact, only one conductor is actually needed. This mode is easily excited by a magnetic coupling from a loop antenna anywhere in the mine tunnel, but it suffers high attenuation because the return current flows in the lossy tunnel wall.

In the bifilar mode which requires two conductors (also called the unbalanced, asymmetrical or differential mode), the forward current in one conductor returns through the other conductor. This transmission line mode has low attenuation because the return current flows on the second wire rather than through the surrounding rock. Excitation of this mode depends upon magnetic flux threading the area between the transmission line conductors.

Random imperfections in the wireplant and mine tunnels cause mode conversion to occur on a two-wire transmission line. Non-uniformities in the tunnel cross section, cable sagging with respect to the roof, and incidental changes in conductor spacing cause the characteristic impedance (z_0) of the cable to change along the line. Changes in this line characteristic impedance cause radiation and reflection of the signal energy thereby causing monofilar and bifilar mode interchange conversions to occur all along a line.

Radio coverage in conductorless entries can be provided by installing a dedicated cable such as two-wire telephone cable. It is easy to install and supports both the monofilar and bifilar modes of signal propagation. The MF antenna-to-cable coupling efficiency is high due to monofilar coupling and the operating range is great due to the bifilar mode propagation.

COMPARISON OF MAGNETIC FIELD LEVELS MEASURED ON THE SURFACE AND IN UNDERGROUND MINES

The magnetic field data measured on the surface of the earth and in the drifts of a coal mine are illustrated in figure 5. The magnetic field strength is plotted versus radial distance (r) from the radiating antenna. For comparison purposes, the free space theoretical data is also plotted in figure 5. The data taken from table A was adjusted to account for an increase in magnetic moment from 1 to 4.6 Ampere Turn Meter^2 (ATm^2).

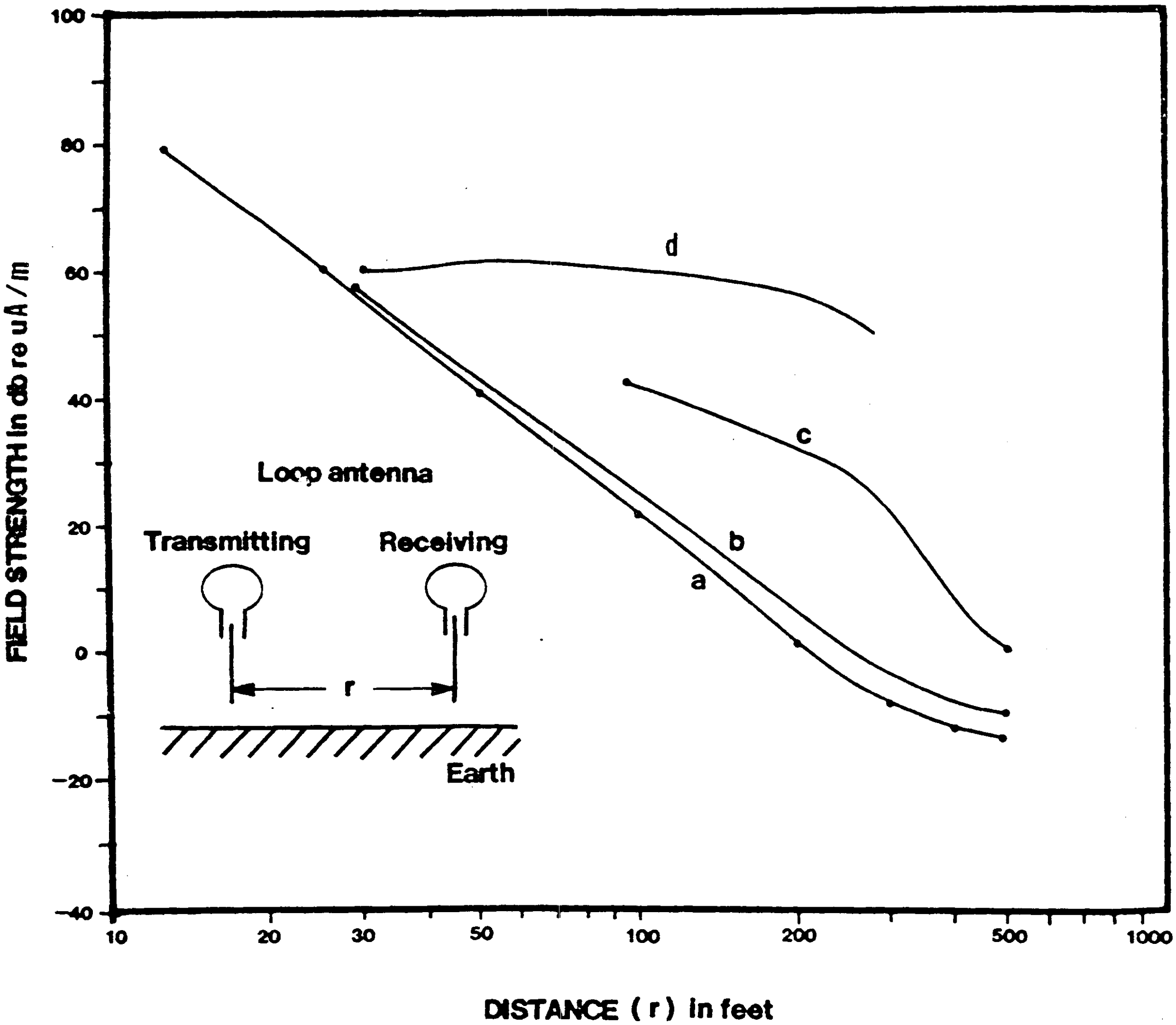

FIGURE 5. - Measured magnetic field strength versus distance (r) from between excited transmitting antenna

The plotted curves illustrate several characteristics. Curve a illustrates the free space values; curve b illustrates the values measured over a conductive free earth; curve c illustrates the effect of a nearby conductor (tunnel mode); and curve d illustrates the magnetic field strength versus range in an underground coal mine. As can be seen in the figure, the free space values (curve a) are in close agreement with the values measured over a conductor free earth (curve b). The agreement improves as the radial separation distance decreases. In the case of curve c a single conductor pair (500 ft long) was placed along the propagation path. As expected the conductor aided in the propagation of the EM wave. Near the end of the conductor (last 200 ft), the induced signal current decreases resulting in smaller fields. The measurements for curve d were made in a uniform coal seam. The field strength values are greater than the free space values owing to the cylindrical spreading of the wave in the rock-coal waveguide. In the near vicinity (less than 20 ft) of a radiating loop antenna, the field strength approaches the free space values. In conclusion, a radiating loop antenna can be used in qualitative evaluation of mine equipment.

MEASURED MAGNETIC FIELDS

Magnetic field produced by excited loop antennas have been measured on the surface of the earth and in drifts in an underground coal mine. The test setup is illustrated in figure 6.

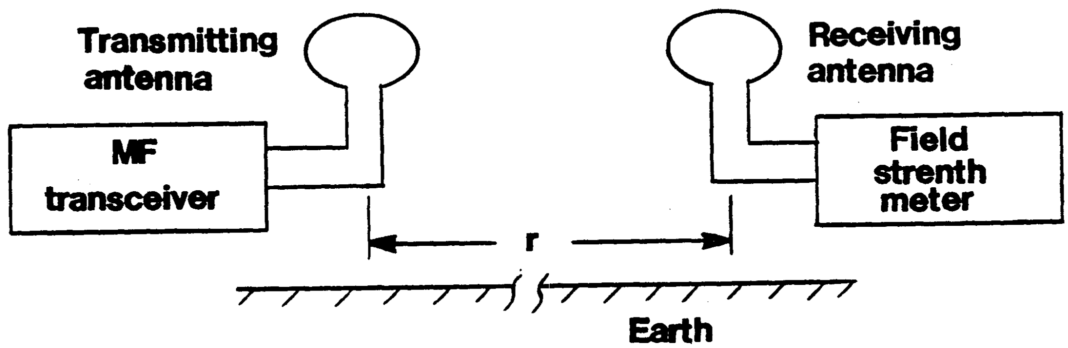

FIGURE 6. - Planar alignment of antennas.

The MF transceiver efficiently drives the antenna. The magnetic moment (M) produced by the antenna is given by:

$$M = NIA \quad \text{(Ampere Turn Meter}^2\text{)} \qquad (10)$$

where N = the number of turns in the loop,

I = the peak current in amperes, and

A = the area of the loop.

The magnetic moments produced by the MF equipment antennas are:

$$M = \begin{cases} 2.1 \text{ ATm}^2 & \text{personnel carried antenna} \\ 4.6 \text{ ATm}^2 & \text{vehicular antenna} \end{cases} \qquad (11)$$

The transmitting and receiving antennas are positioned in a vertical plane (Horizontal Magnetic Dipole - HMD) Measurements are made with the coplanar orientation of the antennas. The field strength produced by the radiating antenna along the propagation path is mathematically represented by:

Field Strength = Meter Reading + Antenna Correction Factor -51.5 dB*

*dB = $10 \log_{10} 377$

The field strength reading is in dB above 1 $\mu A/M$ (dB re 1 $\mu A/M$). The Field Strength Meter (FSM) reading is calibrated in dB above one microvolt (dB re $1\mu V$). The antenna correction factors are given in table C.

TABLE C. - Antenna correction factors.

Frequency (kHz)	Factor (dB)
350	43.5
440	39.75
520	38.7
820	38.9

III. RFI SUSCEPTIBILITY TESTING OF MINE EQUIPMENT

TEST PROCEDURE

The main objectives of the test procedure were to determine possible effects in mining equipment and to set forth the appropriate test method. Manufacturers were for the most part unwilling to provide detailed drawings of the equipment; however, drawings of some of the equipment under test were obtained from the mine maintenance office. Prior to the test, schematic drawings were reviewed to determine circuitry that would be susceptible to either conducted or radiated RFI. The effects of the RFI and possible failure scenarios were studied before testing began.

The procedures used in the examinations depended upon the prior RFI assessment of the schematic drawings and possible failure scenarios. In some notable cases, RFI testing could possibly cause severe damage to the mining equipment. For example, RFI examination of hoist controls could cause inner or outer control loop failure. This could lead to a possible runaway condition in the hoist system.

RFI examination requires that the EM wave source be used in near proximity to the mining equipment. The data presented in Table B and Figure 6 shows that in the neighborhood of a radiating antenna, the surface of the earth and the coal seam electrical parameters have negligible effects on the magnitude of the radiated EM wave field strength. Since the EM wave field strength can be accurately determined (analytically and by measurement), consistent RFI results can be obtained in the underground mine and on surface test ranges.

TEST PLAN

Electromagnetic compatibility (EMC) testing was done on three levels: component (circuit or "box"), subsystem and system. Component level testing includes the testing of black boxes such as methane spotters, toxic gas detectors, etc. A subsystem, on the other hand, is any electronic or electrical entity that performs a specified function within an overall system and is usually characterized by having terminal leads - included in this category are SCR switching packages, vehicular speed controllers, etc. The system, by contrast, is the overall complex of equipment used to perform a specific function. Component testing can be carried out at surface facilities of the mine or an antenna test range.

The testing was setup as illustrated in figure 7.

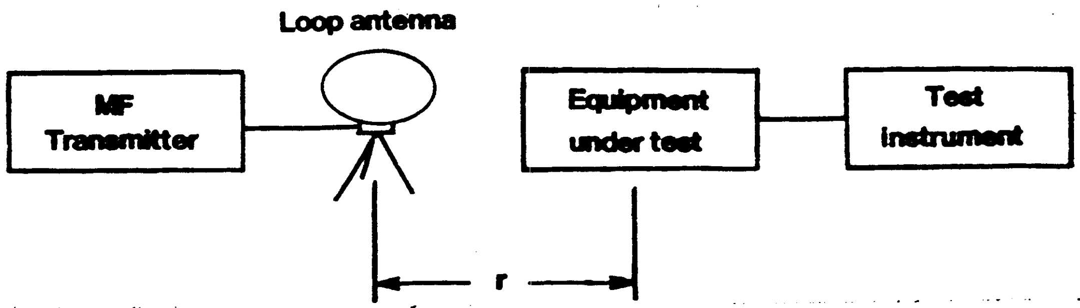

FIGURE 7. - RFI test setup.

The radiating loop antenna is located on a tripod. The antenna is then connected to a battery powered MF transmitter. The antenna and transmitter have the capability of being tuned in the field to 300, 400, 500, and 600 kHz. The equipment under test is located a distance r from the antenna. Test instruments may be connected to the equipment under test to measure the effects of the radiated signals.

Tables D through L list the mining equipment tested for RFI susceptibility and give the results of that testing.

TABLE D. - Atmospheric monitors.

Manufacturer	Description	Results	Notes
National Mine Service	Methane remote sensor module	No effect	
	Oxygen remote sensor module	No effect	

TABLE D. - Atmospheric monitors -- Con.

Mine Safety Appliance Co. (MSA)	Methane monitor model VI	No effect	
	Minico Company monitor	Fluctu- ations	See note A
	Spotter,methane detector	Slight effect	See note A
	Spotter QII-LEL combustible gas detector	Fluctu- ations	See note A
	Model 245 oxygen indicator	output decreased 1%	See note A
	Model 245 R oxygen indicator	output increased by 1-2%	See note A
Echolizer	Model 3000 CO detector	Failed	See note B
Bacharach	Models 23-7285 and 23-7288 methane monitors	Failed	See note C

NOTE A: In-house tests were conducted at MSA's Ryan Lab, located in Pittsburgh, Pennsylvania, on five hand-held monitor devices. All units were exposed to an excited 520 kHz loop antenna. The results were as follows:

1) The MiniCO CO monitor has an LCD readout in parts-per-million. When irradiated, this output fluctuated randomly between 0-400.

2) The Spotter permissible methane detector has a meter movement output. When irradiated, the output decreased in level readings by a slight amount. The environment was methane free.

3) The Spotter Model QII LEL combustible gas detector has an LED readout. The level fluctuated randomly between 0-60% when irradiated.

4) The MSA Model 245 oxygen indicator has a meter movement output. When irradiated, the output level decreased by 1%.

5) The MSA Model 245R oxygen indicator is similar to Model 245, but has the sensor located on a remote wire assembly. This indicator showed a 1-2% increase in readings when the sensor was laid on the loop. No change was detected when the unit itself was brought into proximity of the loop antenna.

6) MSA Hand-held methane spotters (Models 23-7285 and 23-7288) were highly sensitive to RFI. The instruments not only read high but they remained high for a long period.

NOTE B: The Echolizer Model 3000 carbon monoxide monitor was installed in the MAGMA Copper mine San Manuel, Arizona, and was found to be extremely susceptible to RFI. The monitor went into alarm when radiated by an MF signal. The monitor was connected to an Outokompu telemetry system. The system, however, did not report an alarm. It may be that only the local alarm circuits were activated by the MF signal.

NOTE C: The Bacharach methane monitor Models 23-7285 and 23-7288 were tested at the York Canyon Mine and were found to be highly susceptible to MF signals. These signals caused the power system to trip.

TABLE E. - Remote radio controls.

Manufacturer	Description	Results	Notes
Moog Inc.	NDL radio control system	No effect	
GLI Corp.	Radio remote controls	Failed	

NOTE D: Testing at Island Creek Coal Company's V.P. mine #6 showed that the Giangarlo 2002 telemetry system is susceptible to MF signals. The system is used to monitor methane levels in fresh air entries. The central station and three outstations communicate via a two-conductor shielded cable using FSK. The FSK signal level decreased substantially anytime the mine's carrier phone system, which operates at 100 kHz, was being used. At the same time, there was a definite increase in the noise level on the line. It was evident that the SCR controls for the shaft hoist also induced noise spikes on the telemetry lines. Mine personnel said they had witnessed communication failures in the telemetry system on past occassions. The failures were attributed to the carrier phone interference. The MF interference equipment was setup to directly irradiate the telemetry lines. A junction box located across the building from the central station was opened and transmitted into. The Giangarlo system immediately lost communications ability. A Kidd telemetry system was also tested in the V.P. Mine #6. The system is used to monitor methane levels in the return air entries. This system communicates from outstations to a central processing station using FSK on a coaxial line. Mine personnel indicated that this system was immune to failures of the type experienced in the Giangarlo system. The system was irradiated at an outstation point near the central processor location. No apparent effect to the system was detected.

TABLE F. - Electrical power system monitors.

Manufacturer	Description	Results	Notes
National Mine Service	Ground sentinel II ground fault detector	No effect	
	GM-2001 ground fault detector	No effect	
Pemco Corp.	Modd CM-110 ground fault detector	No effect	
Ohio Brass Co.	O-B ground monitor ground fault detector	No effect	
American Mine Research Inc.	Model GM-200 ground fault detector	No effect	

TABLE F. - Electrical power system monitors -- Con.

Line Power Manufacturing	Ground monitor ground fault detector	No effect	
Westinghouse	Type DS ground fault detector	No effect	
	Type DSL ground fault monitor	No effect	
Plains Electric Co-op	Power line carrier current signal	No effect	See note E

NOTE E: Measurements were made in the vicinity of the transmission lines near Kaiser Coal's York Canyon mine portal. The measurements showed that the underground MF communication system induces signals that are 17 dB below power line carrier current signals. It is unlikely that the MF signals will interfere with power lines since the power line carrier current receiver has a low sensitivity (-10 dBm).

TABLE G. - Communications equipment.

Manufacturer	Description	Results	Notes
National Mine Service Co.	SBM-5000 trollyphone	No effect	
	Loudspeaking mine telephone	No effect	
	Central amplifier audio system	No effect	
CSE Mine Services	Model 170 carrier communications system	No effect	
American Mine Research Inc.	TC-650 loop trolly communications unit	No effect	

TABLE G. - Communications equipment -- Con.

Control Corp.	Loudmouth telephone	No effect	
	Motormouth trolly radio	No effect	
Gai-Tronics Corp.	Model 490 mine pager phone	No effect	
	Mine dial/ page phone II	No effect	
Mine Safety Appliance Co.	Pager III mine communications system	No effect	
	Pager IV mine communications system	No effect	
	Multiphone mine communi- cations system	No effect	

TABLE H. - Fire detection systems.

Manufacturer	Description	Results	Notes
National Mine Service Co.	Belt head fire suppression system	No effect	
Mine Safety Appliance Co.	Belt fire de- tection system	No effect	

TABLE I. - Electronic longwall controls.

Manufacturer	Description	Results	Notes
Dowty Corp.	Electronic longwall ad- vance controls	No effect	
Heinscheidt	Entire longwall system		See note F

NOTE F: Longwall controls are known to be susceptible to RFI signals in the Medium Frequency (MF) range. In previous MF testing in Kaiser Coal Corp's York Canyon mine, the methane monitor was found to read high when MF signals were present. The monitoring system was observed to turn off the longwall power; therefore, the longwall mining system was investigated for RFI susceptibility. After a gas level check, the entire longwall system was investigated using the equipment described for the test plan. The test included the shearer controls, chair conveyor belt controls and the methane monitor. The shearer was an Eickhoff Model 300L and the methane monitor was manufacturer by Bacharach. The methane monitor sensor was located at the tailgate and the indicator/control enclosure was located at the headgate. MF signals did cause the methane monitor to read high and interrupt the longwall.

TABLE J. - Telemetry.

Manufacturer	Description	Results	Notes
National Mine Service Co.	R5000 central control system	No effect	
Outokumpu	Mine monitoring system	No effect	See note G
Motorola	Mine monitoring control system	No effect	
Slo-Electronics	Procol 240 telecontrol system	No effect	
Davis Derby	Telecontrol system	No effect	
Mine Safety Appliance Co.	Scada system	No effect	
Walter Kidde	Automated system	No effect	
Grancarlo Scientific Corp.		Fluctu- ations	See note D

TABLE J. -- Telemetry - Con.

Conspec Controls Inc.		No effect	
Aqua Trol		No effect	
Hawker Siddely DOE/Bituminous Coal Research		No effect	
Kidde	Telemetry system	No effect	
Mundix	Telemetry system	No effect	See note H
RFL Industries	Telemetry system	No effect	
San Gauro-Weston	Telemetry system	No effect	

NOTE G: The Outokompu telemetry system was extensively investigated for RFI susceptibility at the MAGMA Copper mine. The system includes a surface reporting and control center, subsurface outstations, and low current loops (1mA). The system was not susceptible to RFI.

NOTE H: The RFI susceptibility of the Mundix telemetry system was evaluated at Occidental Oil Company's oil shale Logan Washsite. The Mundix telemetry system in the mine uses a daisy chain loop to monitor multiple outstations. The surface control room is located in the head frame. It includes the controls for a Canadian General Electric hoist system as well as the video terminal for the Mundix telemetry system. The Mundix system uses "off the shelf" hardware manufactured by Cutler-Hammer. This equipment features the use of an Intel computer and software program. The Mundix system features the use of polling at a baud rate of approximately 500 kHz. The interrogation signal includes the address of the outstation. The outstation replies as a result of being addressed. Fast polling allows the system to provide surveillance without a needed vector interrupting the operating system. The outstations are located in fresh air. Intrinsically safe barriers are used on leadout wires to sensors located beyond seals in the retort area. The barrier strips are manufactured by Stahl, Inc. and TransAmeric Deleval. RFI susceptibility tests were conducted at the collar in accordance with the RFI test procedure. The Mundix system did not respond to the test signals at 150 kHz and 520 kHz. An RFI test was also conducted on the hoist control telemetry system cables located in the same raceway. No malfunctions were found in the hoist control cable.

TABLE K. - Hoist Controls.

Manufacturer	Description	Results	Notes
General Electric	Drives and controls		See note I
Westinghouse	Drives and controls		See note I
Rexnord	Controls		See note J

NOTE I: The RFI susceptibility of five hoist systems at the MAGMA Copper mine were investigated. The hoist network speed regulator, acceleration/deceleration rate controls, etc. were found not to be susceptible to signals in the MF band. This was true even when the radiating antenna was placed inside the control cabinets. By way of contrast, Very High Frequency (VHF) signals from handheld transmitters (Motorola brand) did cause the hoist system to trip-off. General Electric and Westinghouse static power supplies were used in the hoist system. Falkner gear boxes were used to drive the drum; and in the event of an unexpected trip, hydraulic breaking systems were used to bring the cage to a safe stop. Nuisance tripping may require that the maintenance man enter and inspect the shaft.

NOTE J: The RFI susceptibility of three hoist control systems were evaluated in a series of field tests. The hoist systems are located at Union Oil/Molycorp, Inc.'s mine near Questa, New Mexico. The main mine hoist motor is a 500 HP 500 volt DC shunt wound motor. A 6-pulse thyrister power converter is used to supply power to the hoist system. The entire control system includes more than 40 networks. The networks include speed regulators, acceleration/ deceleration rate control, etc. The control circuits were mounted in equipment cabinets. Sensors such as slack rope detectors, RPM monitoring, ground fault monitors, etc., were located at critical locations on the hoist system. A radiating loop antenna was used in near proximity to the control networks and the remote sensing points. The system was not susceptible to RFI.

In addition to the above tests, an RFI susceptibility test of hand held methane gas detectors was made in a TEM mode test chamber (Crawford Cell) driven by a sweep generator. The results are given in table L.

TABLE L. - RFI susceptibility test of hand held methane gas detectors.

Manufacturer	Description	Results	Notes
Mine Safety Appliance Co.	Analog	No effect	
	Digital	No effect	
Bacharach	Digital	No effect	

* A description of this test and the test data is given in Appendix A.

Testing for the effect of RFI susceptibility to aeronavigational devices was also performed. These tests showed that MF signals from mine communications do not interfere with aeronavigational devices. A description of the test along with the test results are given in Appendix B.

IV. REFERENCES

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2. Cory, T.S. Propagation of EM Signals in Underground Mines. (Contract H0366028, Collins Radio Group). BuMines OFR 136078, 1977, 158 pp. PB289757/AS.

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7. Crawford, M.L., "Generation of Standard EM Fields Using TEM Transmission Cells", IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-16, No. 4, November 1974.

8. Crawford, M.L., Improving the Repeatability of EM Susceptibility Measurements of Electronic Components When Using TEM Cells, SAE Technical Paper Series, 830607.

9. Crawford, M.L., and Workman, J.L., "Using a TEM cell for EMC measurements of electronic equipment, NBS Technical Note 1013", Revised July 1981, 65 pp. National Bureau of Standards, Boulder, CO 80303.

APPENDIX A
TEST PLAN
RF SUSCEPTIBILITY TEST OF MINING EQUIPMENT
USING TEM CELL

1. PURPOSE

The purpose of the TEM Cell is to determine, using a repeatable quantitative method, failure condition in susceptible equipment, due to MF electromagnetic interference.

The failure modes will be determined qualitatively

- RF frequency range of failures,
- approximate field strength (if possible),
- failure characteristics,
- modulation of the RF frequency (if critical),
- any other observations.

2. THEORY

Two suitable methods of evaluating susceptible electronic equipment to electromagnetic (EM) interference are:

- Open field test range, where a known EM field is established in the vicinity of equipment under evaluation.

- a TEM cell, where a known constant field is established within an enclosure.

The first method is widely used in equipment RFI susceptibility evaluations. Its main advantage is that it is relatively easy to setup the open field test range. Larger equipment can be evaluated with this method. Its disadvantage is that it is difficult to maintain calibration between different test sites. The TEM cell, on the other hand, is basically self-contained and can be set up at any convenient location, since it is self shielding. The desired fields are easily established within the cell and are comparatively uniform. The technical papers by Crawford describe the theory of operation in more detail (7,8). Additional information is also contained in NBS Technical Note 1013 (9).

3. EQUIPMENT AND TEST SETUP

The following test equipment is necessary to perform the tests:

- Signal Generator (covering the desired RF frequency range).
- TEM Cell (Model CC103)
- 50 ohm Load

The test equipment setup is shown in Figure A-1.

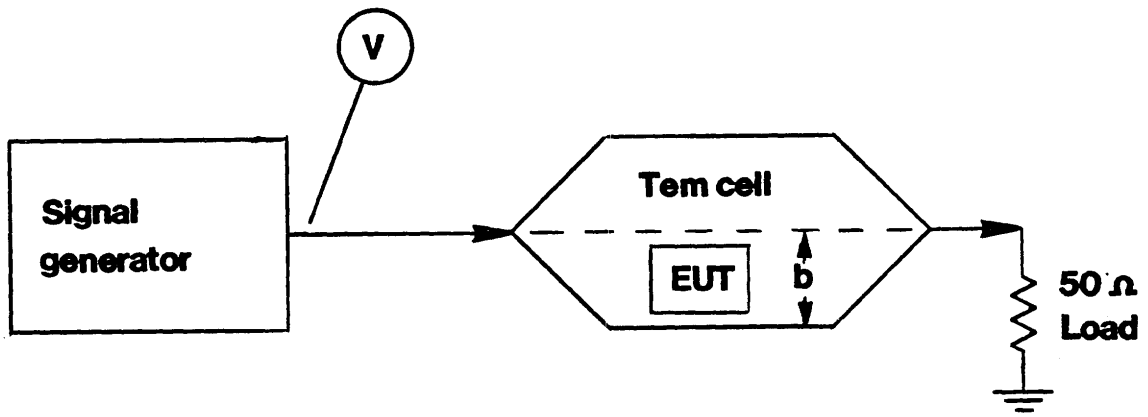

FIGURE A-1. -- Test Setup

Place the equipment under test (EUT) in the chamber. The height of the equipment should not exceed 9 inches using the specified cell.

4. CALIBRATION

The TEM Cell relationship between the electric and magnetic fields is:

$$H = \frac{E}{377} \tag{1}$$

In a TEM Cell the established electric field within its operating limits is mathematically given by:

$$E = \frac{V}{b} \tag{2}$$

where V = input voltage

b = the distance between the center conductor and the bottom of the cell.

Using b = 0.22 meters for the specified cell:

$$H = \frac{V}{(377)\ (0.22)} = 0.012V \tag{3}$$

or

$$V(\text{volts}) = 83H\ (\text{amperes/meter}) \tag{4}$$

For instance to establish a magnetic field of 2000 micro-amperes per meter a signal input of:

$$V = 83 \times 2000 \times 10^{-6} = 0.166 \text{ volts}$$

or -2.6 d"Bm is required.

5. PROCEDURE

5.1 Record information on EMI susceptibility in paragraph 2 of the test data sheet. A blank and examples follow Appendix B.

5.2 Also record value of used multiplier (Equation 4) on data sheet.

5.3 Set signal generator output to establish a field strength, H, of 2000 μA/m. (Use equation 4)

5.4 Slowly sweep the RF range of 80 kHz to 1.0 MHz and record all frequency ranges over which malfunction occurs.

5.5 Over each frequency range recorded in 5.4, reduce field strength to a minimum value at which a malfunction still occurs. Record frequency (or frequency range) and field stength level.

5.6 If failure modes are different at different frequencies and field strength levels, indicate this in the failure mode column. Note any other pertinent data in the otes column.

5.7 In Paragraph 3 of the test data, note any pertinent information received with the test unit (comments, references, etc.) and any special observations and comments from the laboratory testing.

APPENDIX B

RFI SUSCEPTIBILITY TESTING OF METHANE INSTRUMENTS

SUSCEPTIBILITY OF HAND-HELD METHANE GAS DETECTORS TO MEDIUM FREQUENCY SIGNALS

The RFI susceptibility tests were performed using a TEM Mode Test chamber (Crawford Cell) driven by a sweep generator.

Subjecting the equipment under test to an E and H field of from 80 kHz to 1000 kHz at a predetermined level of H field level of 2000 µA/m (microamperes per Meter) and higher levels as specified.

METHANE METER TESTS

Three hand-held Methane Gas Detector Meters were evaluated, two by MSA and one by Bacharach as follows:

MSA "Spotter" Model N, LED readout, SN 02325
MSA Permissible Methane Spotter, Analog Meter, SN 20089
Bacharach Methane Indicating Detector, Model 23-7600, SN JJ0586

Test equipment used:

Voltmeter, AC	Hewlett Packard	410C
Timer, Counter, DVM	Hewlett Packard	5326B
Generator, Sweep	Hewlett Packard	675A
"T" Probe	Hewlett Packard	11042A
RF Power Amplifier	A.R.F. Products	301D177
Power Supply	A.R.F. Products	AAP-12
Load, 50 ohm	Sierra	160-20FM
TEM Cell	Instruments for Industry, Inc.	Model CC103 SN 227

Calibration Gas, Methane 2.5% as supplied by Bacharach with Calibration Kit.

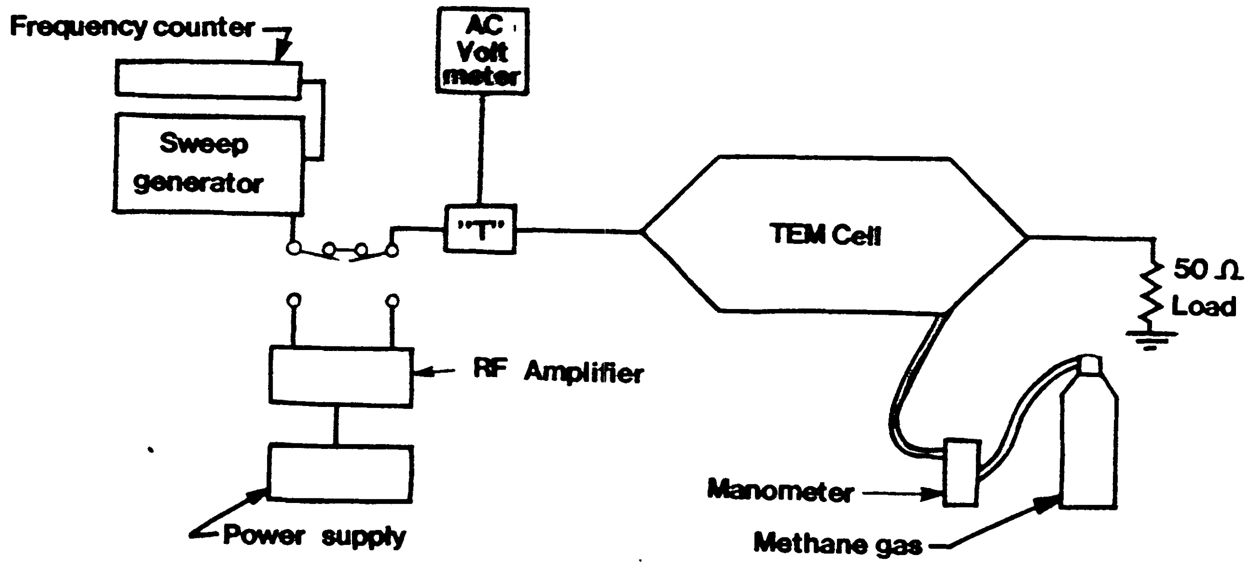

FIGURE B-1. - Test setup

The signal generator was driven direct to the TEM Cell for output levels of .153 V and 1.0 V. The RF amplifier was placed in the setup only for the 30V tests.

The sweep generator was set to the slowest sweep rate available for complete range coverage (80-1000 kHz) in 100 seconds.

The high impedance AC voltmeter monitored the actual input voltage to the cell.

The frequency counter was monitored during the sweep tests to determine the exact frequency a failure might occur.

The units-under-test were each tested in three orientations: Vertical, horizontal longitudal, and horizontal transverse. The test unit was placed on a styrofoam block center inside the TEM Cell. Each test unit "push on" switch was fixed "ON" during tests by the use of small block and tape. The readout of each test unit was oriented for observation during each sweep test and position.

CALIBRATION

The TEM Cell relationship between the electric and magnetic fields is:

$$H = \frac{E}{377} \tag{1}$$

In a TEM Cell the established electric field within its operating limits is:

$$E = \frac{V}{b} \quad (2)$$

where V = Input voltage

and b = distance between center conductor and bottom of the cell.

Using b = 0.203 meters for the specified cell:

$$H = \frac{V}{(377)(0.203)} \quad (3)$$

or V (volts) = 76.5 H (Amperes/Meter)

Example to establish a magnetic field of 2000 μV/m

$V = 76.5 \times 2000 \times 10^{-6} = 0.153$ volts

TEST PERFORMANCE

Each methane meter was tested at three different power levels and three orientations for each power level with methane gas and without methane gas. Initial tests performed at the level of 2000 μA/m (.153V) revealed absolutely no interference in any test condition. Therefore, two higher levels were selected and cell tests re-run. The 1.0 volt level was the maximum output of the sweep generator directly and the 30 volt level was derived using a MF transceiver with transmitter operating at approximately 20 watts.

The frequency was slowly swept from 80 through 1000 kHz in each power level and in each of the three orientations. Tests were performed with a continuous wave (CW) signal and with 30% AM modulation.

The methane meters were closely and carefully monitored during every sweep test to observe for any possible momentary malfunction.

TEST RESULTS

All three methane meters tested performed without malfunction during all tests with and without methane gas.

CONCLUSION

The test performed using the TEM Cell method revealed no failure conditions due to electromagnetic interference in all of the following conditions:

- RF frequency range of 80 to 1000 kHz.
- Up to the maximum field strength (392156 µV/m).
- Modulation of the RF carrier to 30% AM.
- With and without methane calibration gas into the instruments under test.

These laboratory tests show no need to devise method to avoid EMI as applies to these particular instruments.

TEST DATA

EMI SUSCEPTIBILITY

1. REFERENCE

Test Plan, EMI Testing Using TEM Cell

2. TEST INFORMATION

Date ____________________ Taken by ____________________

Multiplier (See equation 4) V (volts) = 76.5 H(A/m)

See data sheet attached.

3. TEST SAMPLE

Name ____

Type ____

Ser. No. ______________________________________

Manufacturer __________________________________

Notes _______________________________________

TEST DATA EMI SUSCEPTIBILITY

Frequency	Level V, volts	Level H, $\mu A/m$	Failure Mode	Notes
80 - 1000 kHz	.153	2000	None	Vertical Position
80 - 1000 kHz	1.0	13070	None	Vertical Position
80 - 1000 kHz	30	392157	None	Vertical Position
80 - 1000 kHz	.153	2000	None	Horizontal-Longitudal
80 - 1000 kHz	1.0	13070	None	Horizontal-Longitudal
80 - 1000 kHz	30	392157	None	Horizontal-Longitudal
80 - 1000 kHz	.153	2000	None	Horizontal-Transverse
80 - 1000 kHz	1.0	13070	None	Horizontal-Transverse
80 - 1000 kHz	30	392157	None	Horizontal-Transverse

TEST DATA

EMI SUSCEPTIBILITY

1. REFERENCE

Test Plan, EMI Testing Using TEM Cell

2. TEST INFORMATION

Date 7 March 1985

Multiplier (See equation 4) V (volts) = 76.5 H(A/m)

See data sheet attached.

3. TEST SAMPLE

Name Permissible Methane Indicating Detector

Type Model 23-7660

Ser. No. JJ0586

Manufacturer Bacharach

Notes Tested with NO Methane at zero level, zero modulation (CW) and 30% AM modulation.

TEST DATA EMI SUSCEPTIBILITY

Frequency	Level V,volts	Level H,μA/m	Failure Mode	Notes
80 - 1000 kHz	.153	2000	None	Vertical Position
80 - 1000 kHz	1.0	13070	None	Vertical Position
80 - 1000 kHz	30	392157	None	Vertical Position
80 - 1000 kHz	.153	2000	None	Horizontal-Longitudal
80 - 1000 kHz	1.0	13070	None	Horizontal-Longitudal
80 - 1000 kHz	30	392157	None	Horizontal-Longitudal
80 - 1000 kHz	.153	2000	None	Horizontal-Transverse
80 - 1000 kHz	1.0	13070	None	Horizontal-Transverse
80 - 1000 kHz	30	392157	None	Horizontal-Transverse

TEST DATA

EMI SUSCEPTIBILITY

1. REFERENCE

Test Plan, EMI Testing Using TEM Cell

2. TEST INFORMATION

Date 7 March 1985

Multiplier (See equation 4) V (volts) = 76.5 H(A/m)

See data sheet attached.

3. TEST SAMPLE

Name Permissible Methane Indicating Detector

Type Model 23-7660

Ser. No. JJ 0586

Manufacturer Bacharach

Notes Tested with 2.5% Methane gas, zero modulation (CW) and 30% AM modulation.

TEST DATA EMI SUSCEPTIBILITY

Frequency	Level V,volts	Level H,μA/m	Failure Mode	Notes
80 - 1000 kHz	.153	2000	None	Vertical Position
80 - 1000 kHz	1.0	13070	None	Vertical Position
80 - 1000 kHz	30	392157	None	Vertical Position
80 - 1000 kHz	.153	2000	None	Horizontal-Longitudal
80 - 1000 kHz	1.0	13070	None	Horizontal-Longitudal
80 - 1000 kHz	30	392157	None	Horizontal-Longitudal
80 - 1000 kHz	.153	2000	None	Horizontal-Transverse
80 - 1000 kHz	1.0	13070	None	Horizontal-Transverse
80 - 1000 kHz	30	392157	None	Horizontal-Transverse

TEST DATA

EMI SUSCEPTIBILITY

1. REFERENCE

Test Plan, EMI Testing Using TEM Cell

2. TEST INFORMATION

Date 7 March 1985

Multiplier (See equation 4) V (volts) = 76.5 H(A/m)

See data sheet 2

3. TEST SAMPLE

Name Permissible Methane Spotter

Type P/N 457167 Analog Meter Readout

Ser. No. 20089

Manufacturer Mine Safety Appliances

Notes Tested with NO Methane at zero level, zero modulation (CW) and 30% AM modulation.

TEST DATA EMI SUSCEPTIBILITY

Frequency	Level V,volts	Level H,μA/m	Failure Mode	Notes
80 - 1000 kHz	.153	2000	None	Vertical Position
80 - 1000 kHz	1.0	13070	None	Vertical Position
80 - 1000 kHz	30	392157	None	Vertical Position
80 - 1000 kHz	.153	2000	None	Horizontal-Longitudal
80 - 1000 kHz	1.0	13070	None	Horizontal-Longitudal
80 - 1000 kHz	30	392157	None	Horizontal-Longitudal
80 - 1000 kHz	.153	2000	None	Horizontal-Transverse
80 - 1000 kHz	1.0	13070	None	Horizontal-Transverse
80 - 1000 kHz	30	392157	None	Horizontal-Transverse

TEST DATA

EMI SUSCEPTIBILITY

1. REFERENCE

Test Plan, EMI Testing Using TEM Cell

2. TEST INFORMATION

Date 7 March 1985

Multiplier (See equation 4) V (volts) = 76.5 H(A/m)

See data sheet attached.

3. TEST SAMPLE

Name "SPOTTER" Model N Methane Detector

Type P/N 465005 Digital LED Readout

Ser. No. 02325

Manufacturer Mine Safety Appliances

Notes Tested with 2.5% Methane calibration gas, zero modulation (CW) and 30% AM modulation.

TEST DATA EMI SUSCEPTIBILITY

Frequency	Level V,volts	Level H,μA/m	Failure Mode	Notes
80 - 1000 kHz	.153	2000	None	Vertical Position
80 - 1000 kHz	1.0	13070	None	Vertical Position
80 - 1000 kHz	30	392157	None	Vertical Position
80 - 1000 kHz	.153	2000	None	Horizontal-Longitudal
80 - 1000 kHz	1.0	13070	None	Horizontal-Longitudal
80 - 1000 kHz	30	392157	None	Horizontal-Longitudal
80 - 1000 kHz	.153	2000	None	Horizontal-Transverse
80 - 1000 kHz	1.0	13070	None	Horizontal-Transverse
80 - 1000 kHz	30	392157	None	Horizontal-Transverse

TEST DATA

EMI SUSCEPTIBILITY

1. REFERENCE

Test Plan, EMI Testing Using TEM Cell

2. TEST INFORMATION

Date 7 March 1985

Multiplier (See equation 4) V (volts) = 76.5 H(A/m)

See data sheet attached.

3. TEST SAMPLE

Name "SPOTTER" Model N Methane Detector

Type P/N 465005 Digital LED Readout

Ser. No. 02325

Manufacturer Mine Safety Appliance

Notes Tested with NO Methane at zero level, zero modulation (CW) and 30% AM modulation.

TEST DATA EMI SUSCEPTIBILITY

Frequency	Level		Failure	Notes
	V,volts	H,µA/m	Mode	
80 - 1000 kHz	.153	2000	None	Vertical Position
80 - 1000 kHz	1.0	13070	None	Vertical Position
80 - 1000 kHz	30	392157	None	Vertical Position
80 - 1000 kHz	.153	2000	None	Horizontal-Longitudal
80 - 1000 kHz	1.0	13070	None	Horizontal-Longitudal
80 - 1000 kHz	30	392157	None	Horizontal-Longitudal
80 - 1000 kHz	.153	2000	None	Horizontal-Transverse
80 - 1000 kHz	1.0	13070	None	Horizontal-Transverse
80 - 1000 kHz	30	392157	None	Horizontal-Transverse

TEST DATA

EMI SUSCEPTIBILITY

1. REFERENCE

Test Plan, EMI Testing Using TEM Cell

2. TEST INFORMATION

Date 7 March 1985

Multiplier (See equation 4) V (volts) = 76.5 H(A/m)

See data sheet attached.

3. TEST SAMPLE

Name Permissible Methane Spotter

Type P/N 457167 Analog Meter Readout

Ser. No. 20089

Manufacturer Mine Safety Appliance

Notes Tested with 2.5% Methane calibration gas, zero modulation (CW) and 30% AM modulation.

TEST DATA EMI SUSCEPTIBILITY

Frequency	Level V, volts	Level H, μA/m	Failure Mode	Notes
80 - 1000 kHz	.153	2000	None	Vertical Position
80 - 1000 kHz	1.0	13070	None	Vertical Position
80 - 1000 kHz	30	392157	None	Vertical Position
80 - 1000 kHz	.153	2000	None	Horizontal-Longitudal
80 - 1000 kHz	1.0	13070	None	Horizontal-Longitudal
80 - 1000 kHz	30	392157	None	Horizontal-Longitudal
80 - 1000 kHz	.153	2000	None	Horizontal-Transverse
80 - 1000 kHz	1.0	13070	None	Horizontal-Transverse
80 - 1000 kHz	30	392157	None	Horizontal-Transverse

APPENDIX C

RFI SUSCEPTIBILITY TESTS OF AERONAVIGATIONAL BEACONS

RFI SUSCEPTIBILITY OF AERONAUTICAL NAVIGATION

Aeronautical navigation, remote AC power transmission system switchings and MF communication systems employ carrier frequency signals in the LF and MF bands. Since these sytems use the same frequency bands, it is important that the radio signals in one service not interfere with normal operations of the other.

To test if the MF system has an effect on aeronautical navigation, measurements were made in the vicinity of the transmission lines near Kaiser Coal Co.'s York Canyon mine portal and the Municipal Airport near Raton, New Mexico. The measurements at York Canyon mine show that the underground MF communications system induces signals that are 17 dB below power line carrier current signals. This would indicate that the MF system shouldn't have an effect on the aeronautical navigation system. The Federal Aviation Administration (FAA) has determined that no incidence of aeronautical navigation interface from powerline carries has been reported in the New Mexico regions. It is also unlikely that the MF signals would interfere with remote power line switching since the power line carrier current receiver has a low sensitivity (-10 dBm). Testing at the Raton Municipal airport also showed no interference between MF signals and navigational beacons.

FREQUENCY BANDS AND SURFACE TRANSMISSIONS OF AERONAUTICAL NAVIGATION BEACONS

Non-directional Beacon (NDB) transmitters are used as a crosscountry aeronautical navigation aid. The signals are amplitude modulated (90-100%) with audio tones. The audio tone modulation provides a Morris Code identification of the NDB location. Table C-A shows the frequency bands allocated for surface navigation.

TABLE C-A. - Allocated radio spectrum in the LF and MF band.

Frequency, MHz	Service
0.010 - 0.014	Radionavigation
0.014 - 0.200	Fixed, Maritime Mobile

TABLE C-A. - Allocated radio spectrum in the LF and MF band. Con.

Frequency, MHz	Service
0.200 - 0.285	Aeronautical Radionavigation
0.285 - 0.325	Maritime Radionavigation
0.325 - 0.405	Aeronautical Radionavigation
0.405 - 0.415	Maritime Radionavigation
0.415 - 0.490	Maritime Mobile
0.490 - 0.535	Mobile
0.535 - 1.605	Broadcasting
1.605 - 1.800	Aeronautical Radionavigation Fixed, Mobile, Radiolocation
1.800 - 2.000	Radionavigation
2.000 - 2.850	Maritime Mobile
2.850 - 3.155	Aeronautical Mobile

Surface AC power transmission systems use single sideband (SSB) carrier current signals on power lines to monitor and remotely control substation switching. Table C-B illustrates the transmission characteristics of the radio control system.

TABLE C-B. - Power line characteristics.

Modulation	SSB
Receiver Sensitivity	-10 dBm
Receiver Bandwidth (BW)	16 kHz
Transmitter Power	40 Watts
Frequency Range	60 to 300 kHz
Leading Manufacturers	General Electric and Lynch

Substation voltage and current levels are monitored and then analogue values are modulated on the SSB carrier. The SSB signal is coupled to a single conductor of the transmission system. The signals are received at dispatching centers and used to control and monitor the transmission system. A typical use of the carrier current communication system occurs when the dispatching center remotely switches the substation breakers. Up to four digitally encoded signals can be encoded on a single suppressed carrier channel.

RFI SUSCEPTIBILITY OF AERONAVIGATIONAL BEACONS

Raton Municipal Airport Testing

The susceptibility of aeronavigational beacons to MF signals was evaluated during tests at Raton Crews Municipal Airport near Raton, New Mexico.

The airport's non-directional beacon is located two miles south of Runway 20 and operates on an assigned frequency of 284 kHz. The planview of the airport is given in figure C-1.

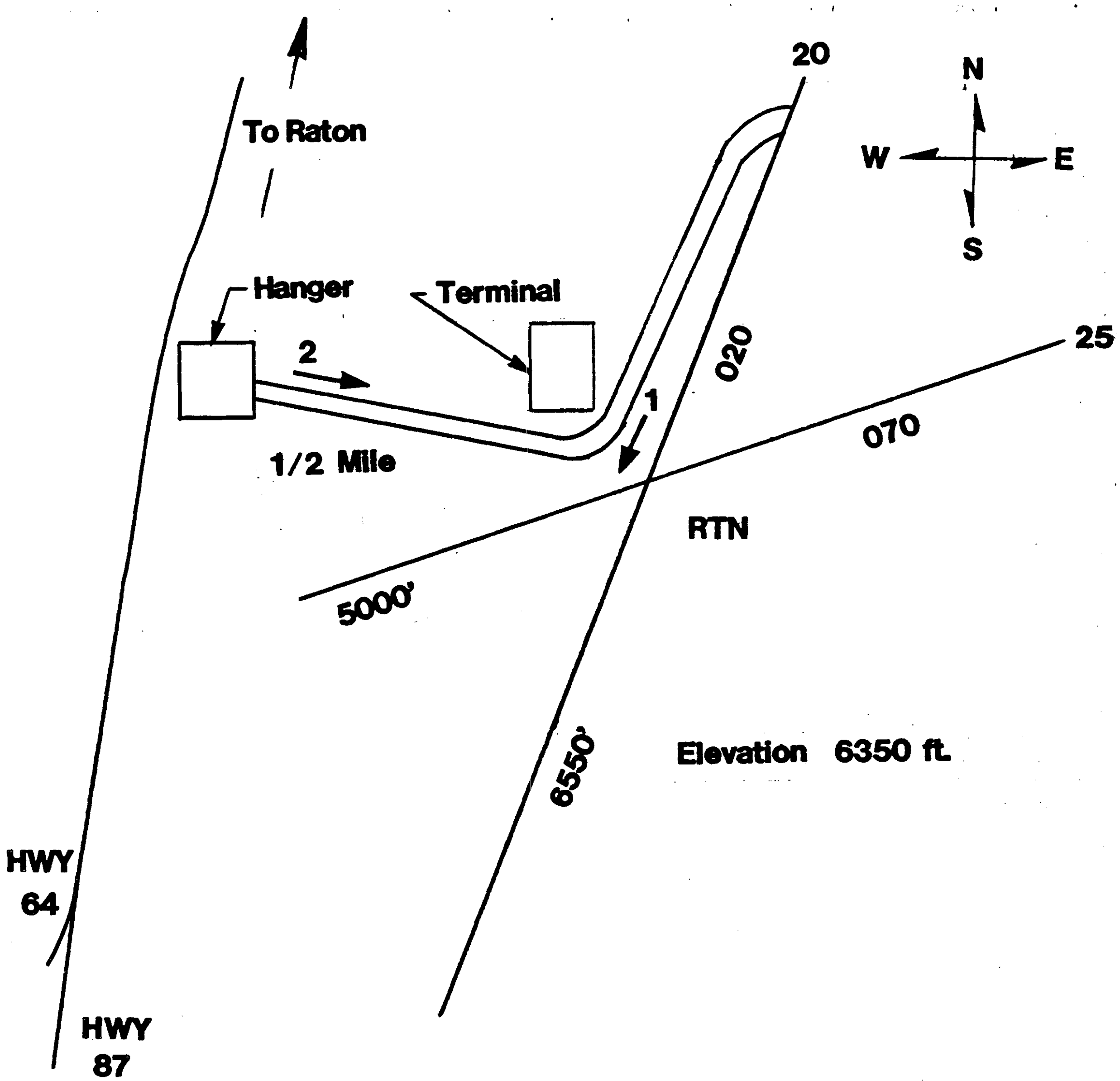

FIGURE C-1. - Planview of Raton Municipal Airport.

The evaluation was made by placing the MF transmitter at locations 1 and 2 (arrow symbols) as shown in figure C-1.

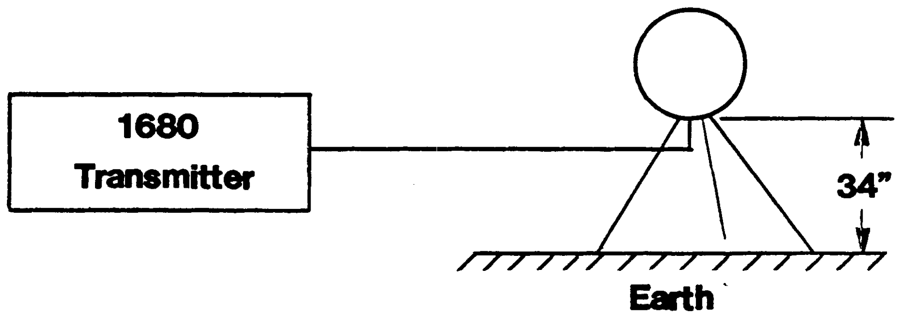

FIGURE C-2. - Transmitter setup.

The radiating antenna produces a magnetic moment of 6.0 ampere turn meters. Its vertical plane heading is indicated by the arrow symbol. The automatic direction finding (ADF) receiver, which included a heading indicator, was located in a turbo charged Lance aircraft.

The test was started with the aircraft flying at an altitude of 11,500 ft on a north heading 60 miles south of the airport. The pilot tuned the ADF between 300 kHz and 284 kHz during the test. The flight path included a 1000 ft (7350 ft) flyover as well as a ground check at the terminal location. During the test, the ADF, when tuned to 284 kHz was not affected by the 300 kHz test signal.

In a second test, the aircraft was on a flight path set to intercept the 7350 ft flyover altitude. Approximately 5 miles south of the airport, the flyover segment was heading in the direction of runway 20. During this test, the transmitter was located at the airport terminal. When the air craft was on a northerly flyover heading, the MF signal was detected at a radial range of approximately 1500 ft from the transmitter location. After landing, the aircraft was parked at the terminal and the transmitter was moved to the hanger location for a third test.

In the third test, the ADF receiver monitored the MF transmitter as it moved toward the hanger location. Beyond the 1/4 mile mark, the ADF receiver did not respond to the MF signal transmission but it did respond to the NDB beacon signal. The ADF receiver was also not affected by the MF transmission when the frequency separation was 16 kHz and the interference range was 1500 ft.

York Canyon Mine Testing

The MF communications system was tested at the York Canyon mine to determine if transmission of the MF signals over an AC power line would cause interference with aeronavigational beacons.

An MF communications system was installed in the York Canyon mine. The system used a multiple pair telephone cable for distribution of radio signals within the mine. These signals couple to the underground AC power system and induce carrier current flow in the electrical conductors. On the surface, the telephone cable and three phase conductors (and ground) are supported on the same wooden poles. Figure C-3 illustrates the surface AC power and telephone cable transmission system and figure C-4 illustrates the measurement setup.

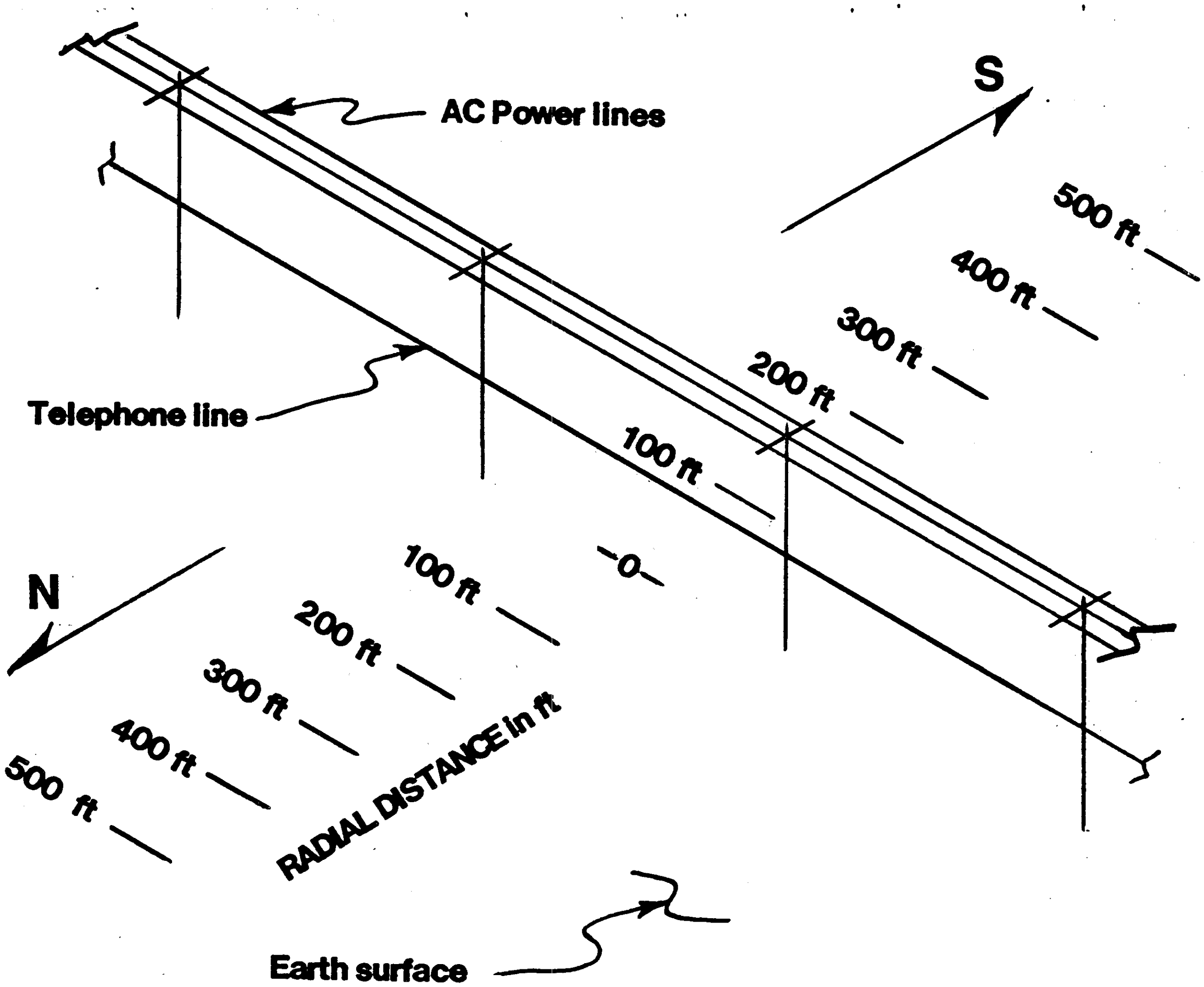

FIGURE C-3. - Surface AC power and telephone cable transmission system.

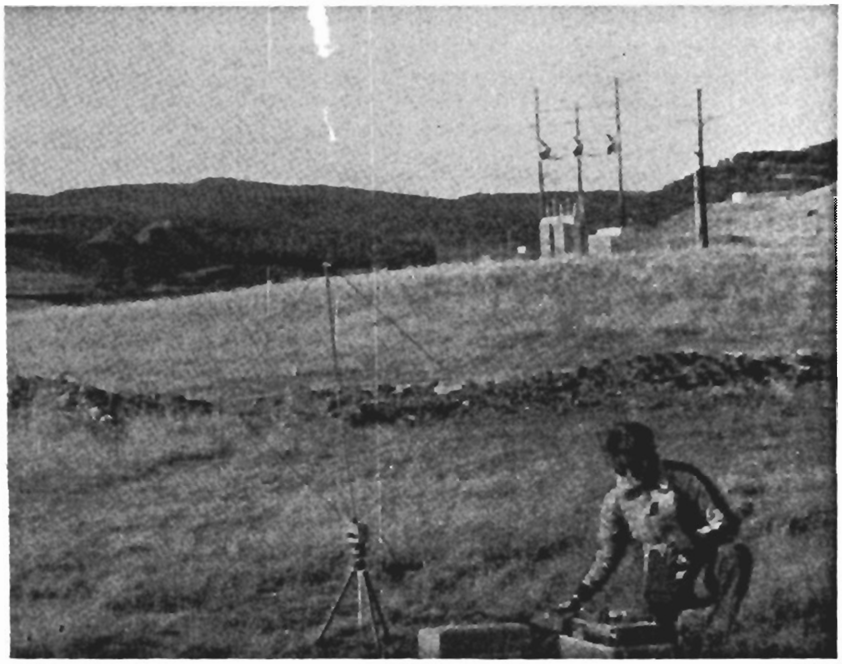

FIGURE C-4. - Measurement setup.

The loop antenna was mounted on a tripod with its plane perpendicular to the AC power wires. Measurements were made at the radial distances shown in table C-C.

TABLE C-C. - MF communication system signal levels radiated from a surface AC power transmission line (520 kHz).

Distance Along Surface	Field Strength (dB re 1 µA/m)	Location
130	-17.8	South
260	-20.8	South
390*	-22.8	South
518*	-26.8	South
130	-19.2	North
260	-22.1	North
390*	-23.2	North
518*	-28.1	North

Table C-D gives the power line carrier signal strength measured in the vicinity of the power transmission structure. The carrier current second harmonic level was 4 dB below the fundamental carrier current level.

TABLE C-D. - Power company power line with remote switching signal levels radiated from a surface AC power transmission line (167 kHz).

Radial Distance Along Surface	Field Strength (dB re µA/m)	Location
130	-0.7	South
260*	-1.0	South

TABLE C-D. - Power company power line with remote switching signal levels radiated from a surface AC power transmission line (167 kHz) -- Con.

390	-2.0	South
560	-3.7	South
130	-0.8	North
270*	-1.3	North
390	-2.3	North
560	-3.8	North

The level of carrier current signals arriving at the Kaiser substation was approximately 21 dB below the Kaiser substation output. This indicates that the signal propagating loss over 34 miles of power line is only 0.6 dB per mile.

SUMMARY OF TESTING

Testing showed that MF signals induced on AC power transmission lines will not interfere with aeronautical navigation and AC power line signals.

The data indicated by the * indicates that the measurement signal level at 300 ft exceeds the FCC part 15.7 limit by approximately 6 dB. The FCC limit at 400 kHz is -28 dB re 1 A/m.