WIRELESS COMMUNICATIONS FOR TRACKLESS HAULAGE VEHICLES

PREPARED FOR

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

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6. Abstract

This report describes a complete system design methodology for medium frequency (MF) wireless radio systems for use in coal mines. The emphasis is on AC mines where no trolley wire exists and, for which, conventional trolley phone communications can not be used.

The report constitutes an MF system design handbook and includes a compendium of all previous MF technology elements as well as a reference index with abstracts of all pertinent literature.

A particular strawman system design analysis is included for the Helvetia Coal Co. Lucerne #8 mine in the Upper Freeport seam.

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FOREWARD

This reportwas prepared by Terry S. Cory, P.E. for the U.B. Bureau of Mines under Contract J0395072. The contract was initiated under the Coal Mine Health and Safety Program. It was administered under the technical direction of PMSRC, Bruceton Research Center, with Mr. Robert Chufo acting as the Technical Project Officer. Mr. Mike Nowicki was the Contracting Officer for the U.S. Bureau of Mines.

This report builds on work completed during calendar 1977 under the original Wireless Communications for Trackless Haulage Vehicles contract, Phase I, (H0377013) with Rockwell/Collins and bears the same title. This report is intended to replace the Phase I draft report, same title, originally submitted by Rockwell/Collins in August, 1977. The current work was performed beginning May 11, 1979 and completed with the submittal of this report on July 17, 1979.

Any reference to specific brands, equipments, or trade names either specifically written or implied does not imply endorsement by the U.S. Bureau of Mines.

Work performed under this contract has not resulted in any patentable items of equipment, designs, or techniques.

Table of Contents (cont.)

List of Illustrations

List of Illustrations (cont.)

List of Tables

1.0 INTRODUCTION

This report presents the first complete treatment of medium frequency wireless radio communication system design methodology published as a result of U.S. Bureau of Mines funded research and development.

The report contents consist of a compendium of all medium frequency foundation technology elements to-date in a form directly usable for system design; a detailed description of medium frequency system architecture and of the equipment elements comprising the system; and of a particular system design example in an AC mine with trackless haulage leading toward a prototype system demonstration plan.

The work reported herein includes technological developments from several sources within the USBM PMSRC research community being brought together for the first time as a composite methodology. Some of the analysis techniques reported herein are newly developed by the author or are being applied to medium frequency (MF) systems by the author for the first time.

The starting effort to develop an MF system design concept was performed for the Bureau by Rockwell/Collins under contract #H0377013 entitled, Wireless Communications for Trackless Haulage Vehicles, Phase I. This contract "vehicle" for motivating MF system design thinking was predicated on the most obvious and needed requirement for wireless communications in underground coal mines; namely, to provide vehicular communications in AC mines equivalent (or superior) to trolley phone communications in DC mines. Previous medium frequency electromagnetic mine measurements has shown the feasibility of serving this need through carrier current coupling into existing mine wiring.

Using the original Rockwell/Collins results and their review by PMSRC as a starting point, this report extends these results and provides the basis for complete system design. This report has been prepared by Terry S. Cory, P.E. under separate contract J0395072. The work has been accomplised over a 90 day period from April through July, 1979.

1.1 STATEMENT OF THE PROBLEM

This report serves a dual purpose; namely to focus all previous wireless MF R & D in underground coal mines toward a general mine-wide system design concept, and then to apply the concept to a particular practical communications problem - providing communication in AC mines for which there is no direct track and trolley connection to vehicles. Once established, an MF communication system offers increased versatility over the use of trolley phones because it is not constrained to locations where there is track and trolley, but includes an operational area for vehicular communications potentially covering all locations where vehicles may be found. Also, the system is usable with man-carried portable radios which may talk to the vehicles or, by themselves, directly back to the base station.

As a "parallel" to conventional trolley phone communications, the wireless system also depends upon carrier current flowing in mine wiring conductors for long range communications in mines. Previous R & D has established medium frequencies in the 300-1000 kHz range as being optimum for wireless coupling into these conductors with the normal trolley phone frequency band of nominally 88-108 kHz as being too low for efficient coupling. An added feature of the use of medium frequencies is that they have also been found to be optimum for wireless transmission directly through the coal seam in absence of conductors. While MF is optimum for wireless coupling, the coupling losses plus increased attenuation of carrier current in long runs (with respect to trolley phone frequencies, due to the higher frequencies involved) will most often require the use of repeaters. This is in contrast to trolley phone operation, where repeaters are not used.

A general purpose MF system may have wide applicability to many types of underground mines, including improved DC coal mine mine communications and metal/non-metal mine communications. The trackless haulage application, for which the trolley phone parallel is drawn , serves haulageway communications only. Additional requirements in underground coal mines which may be served via an MF wireless system include:

- Section Communications

  voice communication coverage possibilities forward of the section power center into the area where coal is being mined

  voice communications control by a face boss of all shift crew and maintainance or inspection personnel over an entire panel

  to serve automatic remote monitoring of airflow, methane, and carbon monoxide levels in an area being mined

- Paging

  the location of particular personnel in the mine rather than just a vehicle

- Emergency

  wireless communications within the seam may not be hampered by rock-falls or broken phone lines, etc.

  inspector discovering potentially hazardous conditions can quickly inform all personnel affected

- Hoist/shaft Communication

  possible simplified communications surface-to-underground in portal area via carrier current induced in hoist/cage conductors

In common with trolley phone operation, the use of MF wireless radio communications uses existing mine wiring conductors; thereby eliminating the need to "string" additional wires.

1.2 HISTORY OF MF WIRELESS RADIO R & D

The possibility of extended through-the-seam wireless communications (with respect to that through homogeneous earth) was first observed in August 1974 by PMSRC personnel testing a pair of South African ECAM radios in the Ireland mine.

As part of a USBM sponsored mine wireless prototype hardware development program in early 1975 (H034067), magnetic field strength measurements were performed by the author toward selecting the best operating frequency for the radios. MF was determined to be optimum in areas without conductors in the Pittsburgh seam. Under USBM contract (H0346045), Arthur D. Little, Inc. (ADL) identified theoretically the quasi-TEM parallel plate waveguide mode as being predominant in conductor-free areas. Concurrently with this, the author noted substantial coupling of carrier current into existing mine wiring conductors, and the first coupling models were developed.

In 1976-1977 under PMSRC sponsorship (H0366028), the author performed magnetic field strength measurements in 6 mines in 3 seams in high coal in both quasi-conductor-free and conductor-proximity areas. The results were analyzed by ADL, producing estimates of the constituitive parameters in the coal seam environment (H0346045). Concurrently, the author developed the scatter gain theory, using ADL's 3-layer field strength model as a basis, for coupling into conductors from a remote transmitter.This theory was used to show, for the first time, that near-optimum frequencies for direct through-the-seam transmission and for remote couplin into conductors were compatible.

In 1977-1978 under PMSRC sponsorship (H0377053), the author performed magnetic field strength measurements in 5 mines in 4 seams in low coal in both quasi-conductor-free and conductor-proximity areas. These results were again analyzed by ADL (H0346045) in the same fashion. Care was taken to obtain experimental measures of scatter gain and, using the ADL derived constituitive parameters, the remote coupling scatter gain theory was validated via close comparison of theoretical and empirical results.

In 1978, under PMSRC sponsorship (P0382223), the author developed prototype vehicular antenna hardware for evaluation (trackless haulage vehicles) and conducted "close" conductor coupling studies including graphical field mappings of magnetic field in typical entry crossections. This work, in conjunction with the remote coupling scatter gain technique has provided the basis for the predictive coupling model presented in this report.

In 1978 and 1979, as part of a program to measure noise on twisted pair phone lines (P0382497), the author extrapolated common mode noise data into field strength near conductors and combined the results with previous NBS derived noise data. This has provided the basis for selection of noise levels near conductors in AC mines and has provided the first estimate of the impulsive nature of noise near conductors in DC mines.

It has also provided the basis for estimating bifilar mode control link performance at MF over phone lines including the first estimates of phone line attenuation in the MF region.

Principal contributors to medium frequency technology at PMSRC have been H. Dobroski and R. Chufo. Principal contributors to medium frequency technology at ADL have been Robert Lagace and Fred Emslie.

The above is a rather short summary of selected MF R & D activities which have lead directly to system design. A more complete understanding of all the medium frequency work and its chronology, including the fine ADL work in the area of dedicated wire and multi-conductor mode analysis can be obtained from Section 7 of this report.

1.3 REPORT CONTENTS

Two particular sections, Section 3 and Section 5 , have been prepared on a stand-alone basis. These are, respectively, MF System Design Primer, and Compendium of Foundation Technology Elements.

Section 2 comprises the Executive Summary of the work.

Section 4, MF System Element Specifications, draws heavily on Sections 3 & 5 and summarizes pertinent equipment parameters in a single location in the report.

Section 6, System Capability Demonstration Plan, is written in the form of a proposal based on the implementation of a "test-bed" system in the Helvetia Coal Co. Lucerne #8 mine - the mine for which the strawman calculations given in this report were made.

Section 7, Reference Index of MF Technology Resources, includes a rather complete bibliography of the topic together with brief abstracts of the work performed.

2.0 EXECUTIVE SUMMARY

The potential performance characteristics of medium frequency (MF) wireless communications systems in underground coal mines are well understood. The state of developed hardware to implement MF systems in U.S. coal mines is embryonic, but growing.

This technology was initiated through testing of a 15-20 watt SSB portable radio developed in South Africa by ECAM. The possibilities for wireless communications in underground mines stimulated the development of the first U.S. prototype radios by PMSRC during 1975-1976 via Rockwell/Collins. These radios, consisting of portables and a base station, were tested along with the ECAM radios in conjunction with the magnetic field strength measurement program. The Collins portable, packaged nearly identically to the ECAM radio, was a 20-watt norrowband FM unit. Unfortunately, both of the above radios embodies cumbersome designs and rigid antennas which were unappealing and could not be conveniently "worn" without hampering the normal work duties of a miner. Both of these radios (ECAM @ 335 kHz and the Collins @ 520 kHz) exhibited similar maximum range performance in conductor-free areas, giving up to 1600 feet of range in the Pittsburgh seam and up to 400 feet of range in the Herrin #6 seam. During this early 1975-1976 period, these radios were viewed primarily as curiosities by the industry with little active interest in the technology being expressed.

The first industry-stimulated "look" at MF occurred during the 1976-1977 timeframe when Consolidation Coal (via Lee Engineering and Ferry Telemetry of Hiawatha, Iowa) developed a low power (7-watt) "second generation" SSB portable for testing based on CONSOL requirements in the environmental safety area. Somewhat concurrently with this, a new smaller South African radio (1-watts) of improved packaging design was devloped by RACAL and is now available in limited quantities in the U.S. market. Unfortunately, both of the above radios have been found to be unsatisfactory for extended system use in coal mines because:

- The power level is too low (in the case of the RACAL radio)
- SSB radio inherently suffers severely from impulse noise near conductors (in particular, the automatic squelch on the RACAL radio and its long AGC recovery time constant renders it nearly unusable in impulse noise

During the 1975-1976 USBM evaluation of the "first generation" prototype radios, comparative tests near conductors were neglected in favor of tests to support characterization of performance in quiet areas; the case of most scientific interest, but least operational significance. Currently, the narrowband FM radio is clearly viewed by the author as being the type most desired for use in large-scale MF systems in both AC and DC mines. During this same time period, and into 1978, PMSRC was instrumental in the development of improved "second generation" FM radio hardware for a different reason; namely, the development of a multiplex wireless MF methane monitoring system for continuous miners.

A new industry-stimulated interest in wireless communications in coal mines has evolved naturally because of the trackless haulage communication problem in AC mines. Trolley phone manufacturers are now working towards wireless-coupled vehicular radios to solve this problem. Additionally, interest is growing in the potential of wireless communications in sections.

It is now safe to say that MF wireless radio development will occur via natural industry stimulation over the next several years for coal mines, even without additional R & D sponsored by USBM. The idea was spawned by the early :feasibility" technology transfer efforts by PMSRC.

The only problem with this natural growth is that it is likely to occur to meet specific isolated requirements without ever recognizing the full large-scale communication system potential that is possible by fitting the radio designs into an overall architecture. Recognizing this, PMSRC has provided for the controlled development of a "third generation" of radios (H0395120) which will, hopefully, be compatible with a concept for large-scale system implementation.

PMSRC has recognized the need for this "system design leadership" since 1976 when the (H0366056) Wireless Communications for Trackless Haulage Vehicles contract was initiated. Circumstances beyond the control of USBM and the R & D community have prevented a earlier treatment of systems and the dissemination of MF system design guidance to the industry.

Hopefully, it is not too late to guide the course of developments in this exciting technology area to its full potential.

2.1 MF SYSTEM POTENTIAL

2.1.1 POTENTIAL FEATURES

As will be shown in this report, the use of a suitably designed MF wireless radio communication system provides the capability for mine-wide communications,not limited by very close proximity to conductors, between Portable, Vehicular, and Base Station radios in underground coal mines.

Amajor feature of an MF system is that it is not inherently constrained by special wiringand, in fact, requires no special wiring save, perhaps, for a separate phone line cpntrol link to Remote Base repeaters.

Because there is no"cable plant" directly interfacing the system and powering any of the system elements, the intrinsic safety of the system resides soley in the intrinsic safety of the individual radio units. To drive home this point, the reader is reminded of the MCM-101 system in which the intrinsic safety of any element of the system is tied into the intrinsic safety of the entire system. The system, thus, provides an interface between the haulageway "long-haul" links and the conductor-free local links in the area being mined that is no more complicated than the design of the individual element radios.

2.1.2 SYSTEM PERFORMANCE OVERVIEW

While the maximum communication range near the optimum frequency in conductor-free areas employing direct through-the-seam transmission varies considerably with seam characteristics, the maximum range in close proximity to conductors varies only slightly for different seams. Thus, for remote coupling into conductors, only the coupling lateral range is significantly affected by the seam.

Detailed dependancies of communication range on frequency and on seam characteristics are illustrated in Section 5.1 of this report.

As a typical case, the communication ranges expected via close coupling in the Upper Freeport seam are illustrative of performance achievable in many mines.

For a continuous conductor string without standing waves or taps/branches and for Radio Terminal Elements with the above cited close coupled spacings for both transmitter and receiver (antenna centers to conductor ensemble center), the maximum communication ranges along the conductor string are:

(1) In an AC mine

Radio type	Range Along Conductors
P-P	4019m (2.50 miles)
V-V	3428m (2.13 miles)
B-B	6096m (3.79 miles)

(2) In a DC mine w/belt haulage

Radio type	Range Along Conductors
P-P	2727m (1.69 miles)
V-V	2136m (1.33 miles)
B-B	4805m (2.99 miles)

(3) In a DC mine with tracked haulage & no trolleyphone interferance

Radio type	Range Along Conductors
P-P	1013m (0.63 miles)
V-V	422m (0.26 miles)
B-B	3091m (1.88 miles)

the mine type differences being the noise levels experienced; these operationally significant types to be shown in Section 5.2.

Close examination of a great deal of magnetic field strength data has resulted in the following expectations for monofilar mode standing wave levels and tap losses:

For standing waves

± 3 dB in long haulageways with tap spacing of at least 1000 feet

± 4 dB in submains with approximate 400 foot tap spacings, single tap

± 6 dB in submains with approximate 400 foot tap spacings, double tap

± 6 dB in conductor-dense areas in sections near center of sections

± 10dB in conductor-dense tracked, belted sections with service tracks

Note: ± 10 db was also measured in Lucerne #8

For taps/junctions

-3 dB/single tap

-5 dB/double tap

For a large scale overview, the following average conditions may be assumed:

1 each NS or EW mains split	-3 dB
1 each submain split	-3 dB

(A) For haulage areas

2 each double taps	-10 dB	plus ± 6 dB VSWR
or		
4 each single taps	-12 dB	

giving an aggragate approximate loss to consider of -22 to -24 dB with respect to a flat untapped line

(B) For section areas

2 each single taps	-6 dB	plus ± 10 dB VSWR

giving an aggragate approximate loss of -22 dB

Note that the assumption for both haulageway and section areas produce about the same loss estimate of -22 dB in signal margin due to the combination of standing wave and junction effects under average conditions. Under this assumption, the closely coupled maximum communication range estimates along conductor strings without repeaters becomes:

(1) In an AC mine

Radio type	Range Along Conductors
V-B	3138m (1.95 miles)
P-P	2859m (1.78 miles)
V-V	2268m (1.41 miles)
B-B	4937m (3.06 miles)
P-B	3729m (2.32 miles)

(2) In a DC mine w/belt haulage

P-P	1566m (0.97 miles)
V-V	976m (0.61 miles)
B-B	3644m (2.26 miles)
P-B	2437m (1.51 miles)
V-B	1846m (1.15 miles)

While these ranges are achievable when the transmit and receive radios are in the same entry as the conductors, an important feature of the MF system is the areas coverage in terms of lateral (or transverse) range away fromconductors. For vehicular operation, providing continous coverage from a 5-watt radio with an assumed ± 10 dB SWR on the conductor(s), the lateral ranges vs range along along conductors are illustrated for Vehicular-to-Base Station and Vehicular-to-Vehicular operation both for a long continuous conductor without branches and for an average condition of 4 branches in Figure ! . These are ranges without repeaters. In the Pittsburgh seam (the best seam for conductor-free transmission) the lateral range will be about 20-25% greater except that the direct through-the-earth range itself will be 1200-1600 feet. In the Herrin #6 seam (the worst seam for conductor-free transmission) the lateral ranges will be about 20-25% less.

With repeaters in an AC mine for transmission back to a Base Station from a radio located one-entry removed from the nearest conductor, repeater spacings will be ½ - 3/4 mile (Line Amplifiers) in areas with multiple branches and nearly a mile along major haulageways where theone-entry-away coverage is desired. For transmission area coverage constrained to the major haulageway entry crossections, the allowable repeater spacing will approach 2 miles. Using Remote Base Repeaters, where extended mobile unit-to-mobile unit performance is not required via repeaters, therepeater spacings above may be nearly doubled.

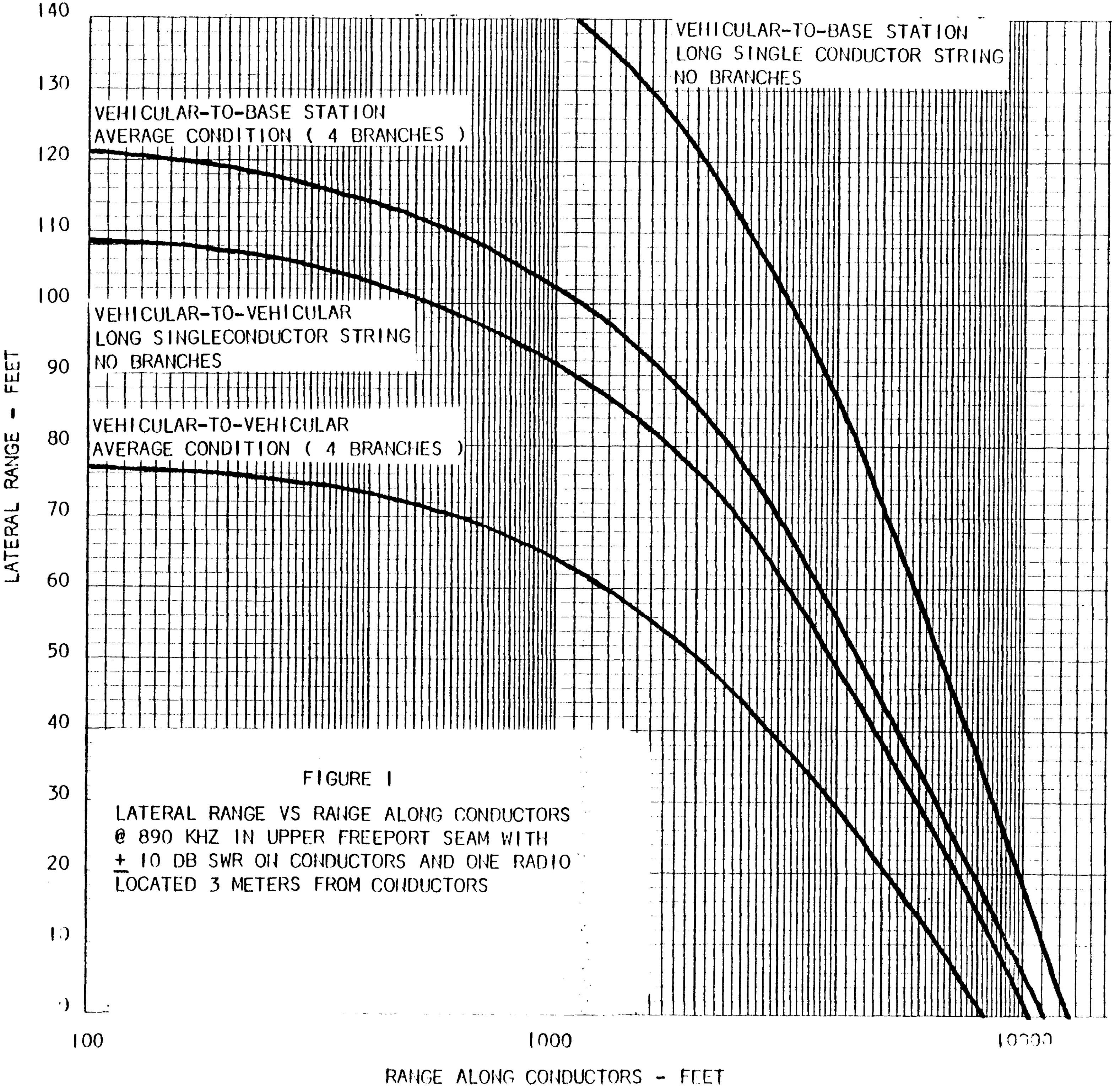


FIGURE 1

LATERAL RANGE VS RANGE ALONG CONDUCTORS
@ 890 KHZ IN UPPER FREEPORT SEAM WITH
$\pm$ 10 DB SWR ON CONDUCTORS AND ONE RADIO
LOCATED 3 METERS FROM CONDUCTORS

2.2 SUMMARY OF PREFERRED SYSTEM CONCEPT

The communication link possibilities on an overall mine-wide basis employing all the System Elements are illustrated in Figure 2 . The reader is referred to Section 3 for precise definition and features of the particular System Elements.

The design is based on the use of nominally 5-watt radios employing narrowband FM transmission for all Radio Terminal Elements and for all Repeater Elements. In actual equipment design, the maximum common usage of transmit and receive "modules" between all active system elements is assumed.

The design uses some Continuous Tone Coded Squelch (CTCS) decoding and encoding to provide operator simplecity on the part of the Portables and Vehiculars, and to help"decouple" the transmission modes. Use of additional CTCS control is discussed as providing embellishments beyond the basic design; but are not included as part of the basic design because of the recognized size of commercially available encoder and decoder components and because their use may not prove operationally feasible (except of supervisory radios, if two "tiers" of radios are practical) until experience has been gained with an actual operating system.

The frequency plan is a two-frequency plan providing for both simplex and half-duplex types of operation. The frequency plan is the same for all Radio Terminal Elements, with a variation in the Base Station. The frequencies, designated f_1 and f_2, are expected to occur in the 500-1000 kHz range with a minimum of 10% separation and with f_1 being the higher frequency of the two.

The frequency plan options for the Portables and Vehiculars are envisioned as being selectable via a three-position switch on the enclosure as follows:

"Local"	Transmit	f_1	no CTCS
	Receive	f_1	no CTCS
"Base"	Transmit	f_1	CTCS
	Receive	f_1	no CTCS
"Remote"	Transmit	f_2	CTCS
	Receive	f_1	no CTCS

A single tone encoderis used with both transmit frequencies (and a single tone is used throughout the system). Use of the single receive frequency, of course, poses the ambiguity of which "mode" is being received. This is acceptable in this type of service where the operator generally knows to whom he is talking and whether it is "Local" or "Base"; otherwise, it will most often be remote.

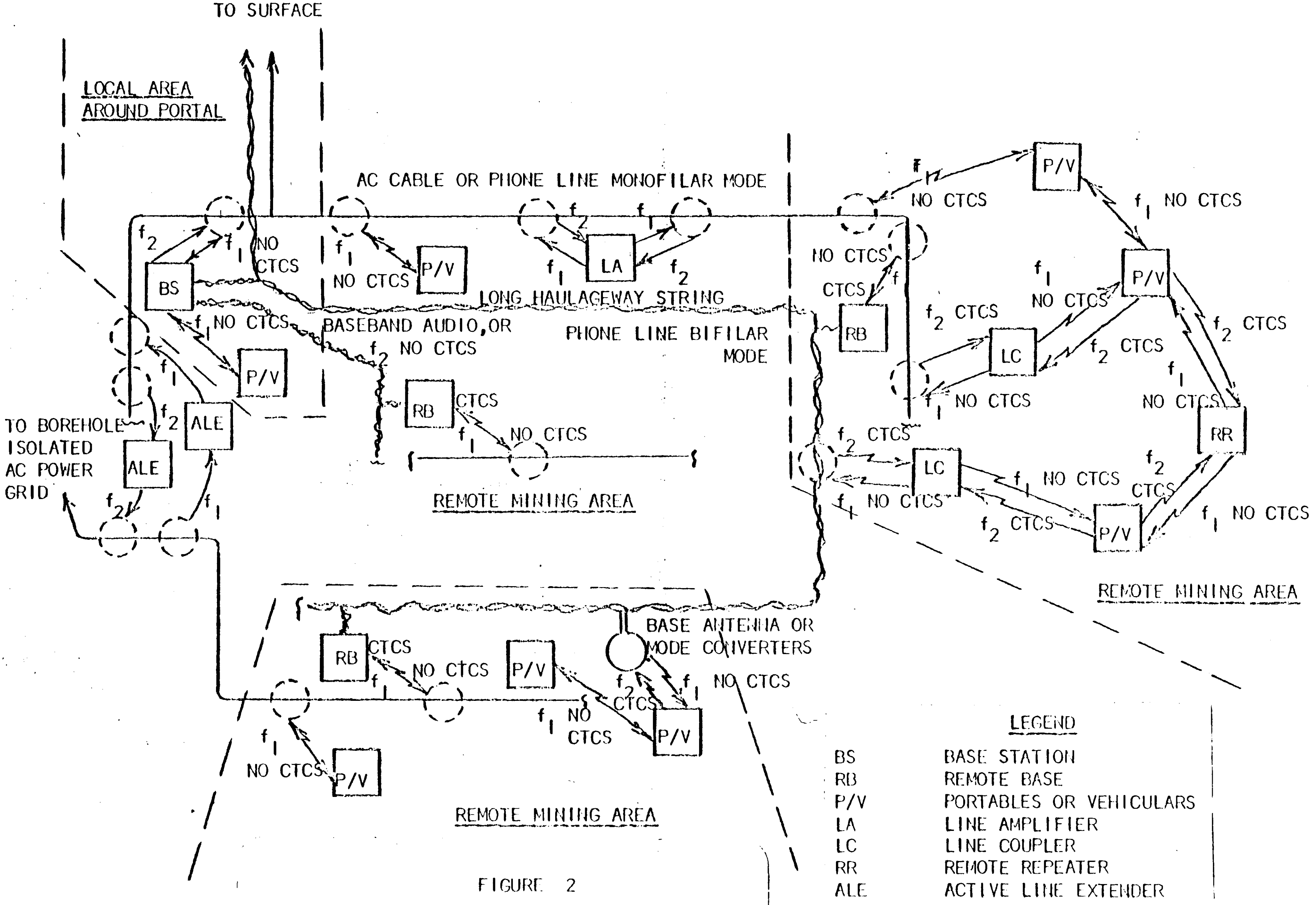


FIGURE 2

OVERVIEW OF COMMUNICATION LINK POSSIBILITIES FOR MEDIUM FREQUENCY SYSTEM

The dispatcher has additional visibility with regard to the type of communications being serviced and can differentiate between Remote Base and "Local" or "mobile unit" links. The frequency plan for the Base Station is:

"Local"	Transmit	f_1	no CTCS
	Receive	f_1	no CTCS

Note: on base station antenna or on a coupled monofilar conductor

"Remote Base"	Transmit	f_2	no CTCS, or baseband audio
	Receive	f_2	no CTCS, or baseband audio

Note: on phone line only, bifilar mode

"Remote/Mobile Unit"	Transmit	f_2	CTCS
	Receive	f_1	no CTCS

Note: on coupled monofilar conductor

If provisions are made in the Base Station design for simulcasting and, if Line Coupler elements are linked to the phone line (bifilar mode); then, in the simulcast mode, CTCS should be transmitted on f_2 on the phone line (assuming f_2 is used rather than baseband audio).

The frequency plan for the Remote Base is:

Receive	f_2	no CTCS, or baseband audio on wireline link
	f_1	CTCS on MF link
Transmit	f_2	no CTCS, or baseband audio on wireline link
	f_1	no CTCS on MF link

The frequency plans for the Line Amplifier, Line Coupler, and Remote Repeater are identica, and are:

Receive	f_2	CTCS
Transmit	f_1	no CTCS

As an overlay on this basic frequency plan, additional CTCS tones could be added to provide:

- Paging/Call Alert from the Base Station

  Each or certain Portables and Vehiculars would have a "home" address tone decoder such that if this tone was received, it would audibly or visually signal the operator of the radio of a call

- Private Line (blocking) from selected radios

  Selected supervisory radios would have a tone encoder and each non-supervisory radio would have a tone decoder such that if the tone were sent, it would block the receiver of each radio having the decoder

The system provides for four quasi-decoupled types or modes of communications. These are:

- Base Station-to-local area(Portable/Vehicular) communications via the Remote Base repeater.

  The link is provided using the bifilar phone line transmission mode which isolates it from types using monofilar mode coupling and transmission. This link is isolated from long distance local area-to-local area transmission via frequency separation for transmissions originating from a Line Coupler Repeater and by CTCS for transmissions originating from the Base Station

- Long distance Base Station or Portable/Vehicular-to-mobile unit communications via a Line Amplifier repeater

  The link is provided using the monofilar mode transmission on the AC power cable and/or phone line which isolates it from types using the bifilar mode for transmission. This link is isolated from links employing a Line Coupler and the monofilar mode because of frequency separation (two repeaters with like frequency plans cannot be chained)

- Extended range local-area-only type of communications via a Line Coupler repeater, coupled to a monofilar conductor

  Same rationale applies as for the above mobile unit monofilar link.

- Extended range local area-to-local area communications via a Line Coupler Repeater, coupled to the bifilar phone line mode

  Same rationale applies for isolation as for the above Base Station-to-local area link.

Additionally, local area simplex communications are somewhat isolated from communications from the local area to the Base Station via the Remote Base through the use of CTCS.

Of course, CTCS does not provide much isolation under dense traffic conditions; and,due to the common receive frequency, there will be interferance between "Local" and "Remote" transmissions and between "local-area-only" transmissions.

2.3 FURTHER R & D RECOMMENDATIONS

For futhering the combined USBM R & D community interest plus industry interest in MF system potential, the following items would be profitable to pursue:

- Using Collins prototype FM radios, conduct maximum range testing in several coal mines, including a link to the surface - thus demonstrating, with hard data, the maximum range capability

- Using a Collins prototype FM radio working into a vehicular prototype antenna, demonstrate the ability to couple into complex mine wiring geometries

- Using a pair of Collins prototype FM radios, demonstrate the communication range through a roof-fall (containing one or more broken or unbroken conductors); thus illustrating the potential of MF for rescue communications

- Using a pair of Collins prototype FM radios, conduct communication range experiemnts near conductors in a DC mine, thus providing hard data on the performance in a highly impulsive noise environment; the range should be correlated with measurement of the signal carrier current level

2.4 STRAWMAN SYSTEM DESIGN FOR LUCERNE #8

Caluculations of communication area coverage for Vehicular-to-Vehicular (V-V) and Vehicular-to-Base Station operation including the location of repeaters has been made for the Helvetia Coal Co. Lucerne #8 mine in the Upper Freeport seam. This mine is familiar to PMSRC and is one for which the Bureau has an ongoing communications system test-bed program under cooperative agreement with the mine. The author visited this mine during August, 1977, and performed a an electromagnetic field mapping at medium frequency in this mine at that time. A summary mine map was prepared illustrating the status of mining operations, topologically, together with assumed area coverage regions for a trackless haulage MF system as of late 1977. Also shown are areas to be mined in the near future. This summary mine map is given as Figure 3 . The assumed desirable communication coverage area is given by crosshatching on the figure. The lateral haulageway coverage area assumed was governed by communications in all fresh air entries, with the result

145 feet lateral range in South Mains
80 feet lateral range in North Mains
80 feet lateral range in sections.

The required area in sections included the size of the room-and-pillar areas extending about 400 feet on either side of a center line. The acceptable lateral range coverage in haulageways has been taken to be

80 feet in all haulageways, nominal
65 feet minimum
Note: the 65 feet minimum reflects the range required 1 entry removed from the conductor entry as the pillars are nominally on 65-foot centers.

Also shown on the map are rectangular areas showing rooms to be mined (as of that date) and dashed lines representing expected future extensions of the AC power cable and beltways.

The exact operational status of Lucerne #8 as of the time of this writing and that expected at a future time when demonstration hardware will be available for testing are not known. The following analysis, therefore, assumes all dashed AC power cable and beltway extensions to be active.

The analysis of V-B and V-V transmission in this mine are illustrated respectively in Figures 4 and 5 . The lateral range predicted at selected locations adjacent to the coverage contours and especially near the ends of particular power cable/beltway runs.

The V-B coverage illustrates the placement of Line Amplifier or Remote Base repeaters to give mine-wide coverage.

Specific conclusions afforded by this analysis include:

(1) The maximum through-the-seam (quasi-conductor-free) range expected is 108 meters (354 feet).

(2) If both Radio Terminal Elements of a pair are closely coupled to conductors, approximate mine-wide coverage is expected V-B, and Vehiculars will be able to communicate with other Vehiculars (V-V) over either the North Mains or the South Mains areas without repeaters.

(3) V-V coverage without repeaters with one radio located one entry removed from conductors is limited to about 2500 feet or less.

(4) V-V coverage without repeaters with both radios removed one entry from conductors is limited to about 1000 feet or less.

(5) With a Base Station assumed to be located in the portal area, and to maintain nominal one-entry-away coverage with vehicles, a Line Amplifier or a Remote Base Repeater is required 2500 feet away in the North Mains and 3750 feet away in the South Mains.

(6) With therepeater spacing of (5), a lateral range in excess of 80 feet is assured over all haulageway Mains, in excess of 60 feet at the end of all Butt Sections (Submains) panels, and in excess of 50 feet at the extreme ends of room-and-pillar area assuming the AC cable runs this far (this should assure at least 60-65 feet of lateral range at all section power center locations).

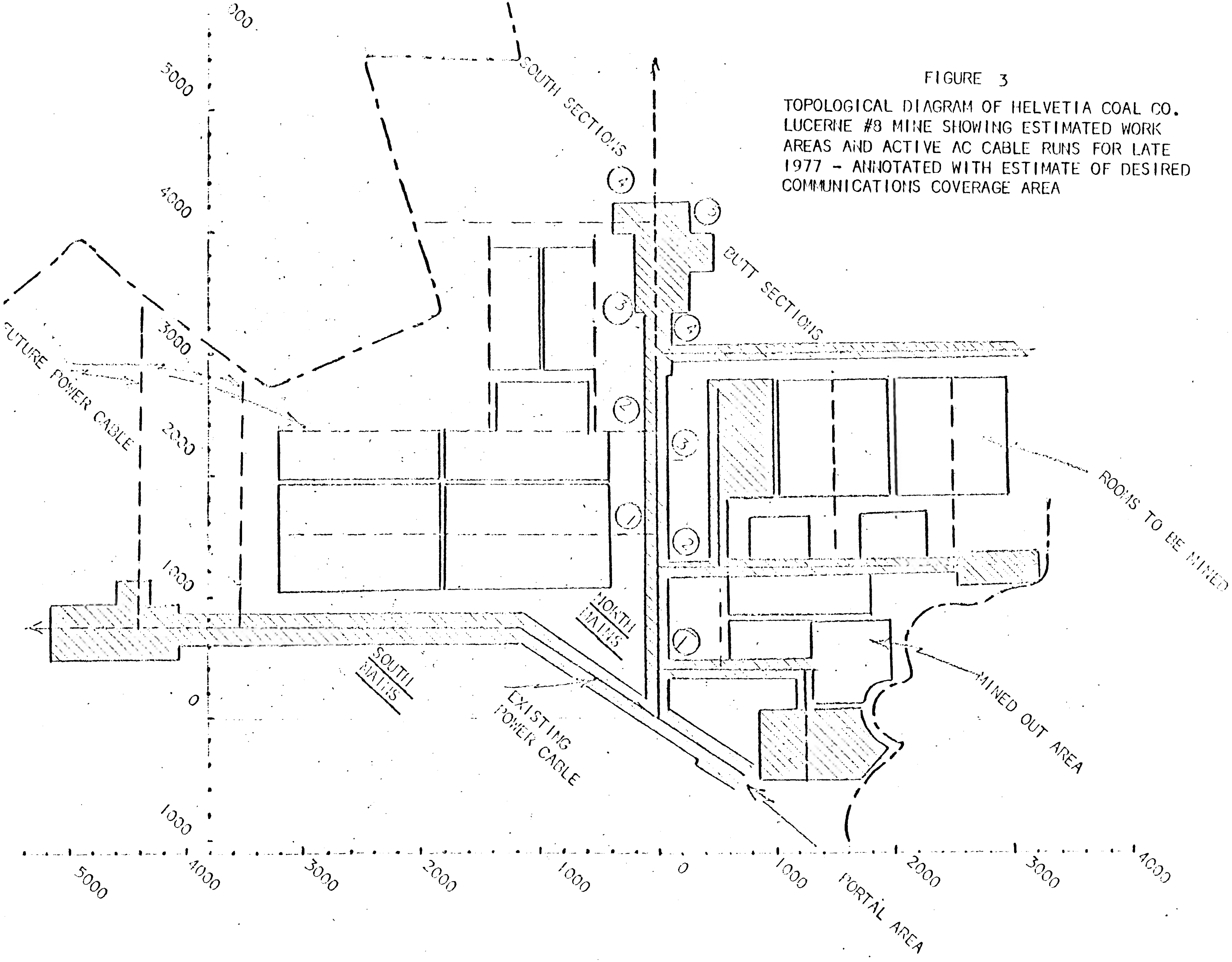


FIGURE 3

TOPOLOGICAL DIAGRAM OF HELVETIA COAL CO. LUCERNE #8 MINE SHOWING ESTIMATED WORK AREAS AND ACTIVE AC CABLE RUNS FOR LATE 1977 - ANNOTATED WITH ESTIMATE OF DESIRED COMMUNICATIONS COVERAGE AREA

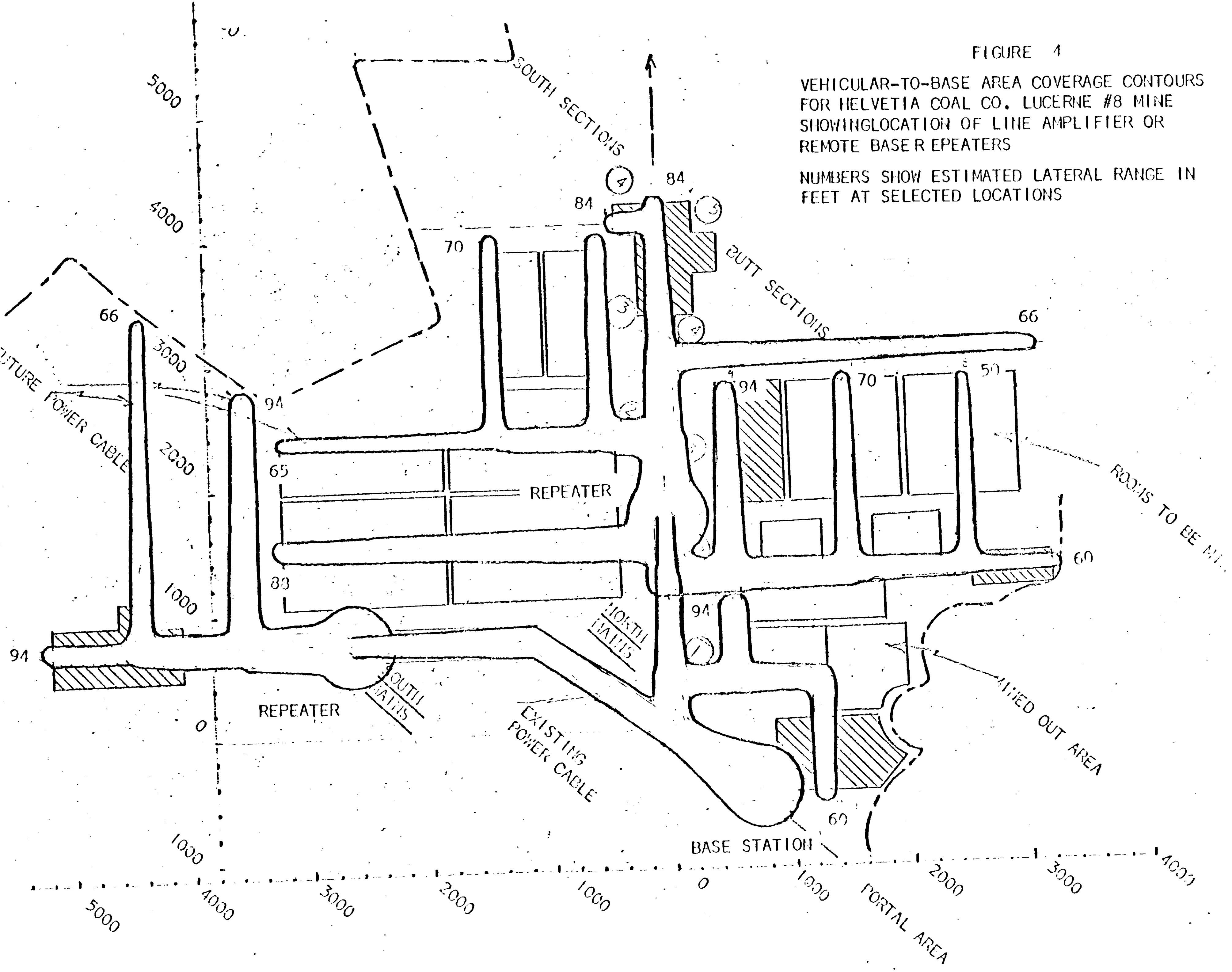


FIGURE 4

VEHICULAR-TO-BASE AREA COVERAGE CONTOURS FOR HELVETIA COAL CO. LUCERNE #8 MINE SHOWINGLOCATION OF LINE AMPLIFIER OR REMOTE BASE R EPEATERS

NUMBERS SHOW ESTIMATED LATERAL RANGE IN FEET AT SELECTED LOCATIONS

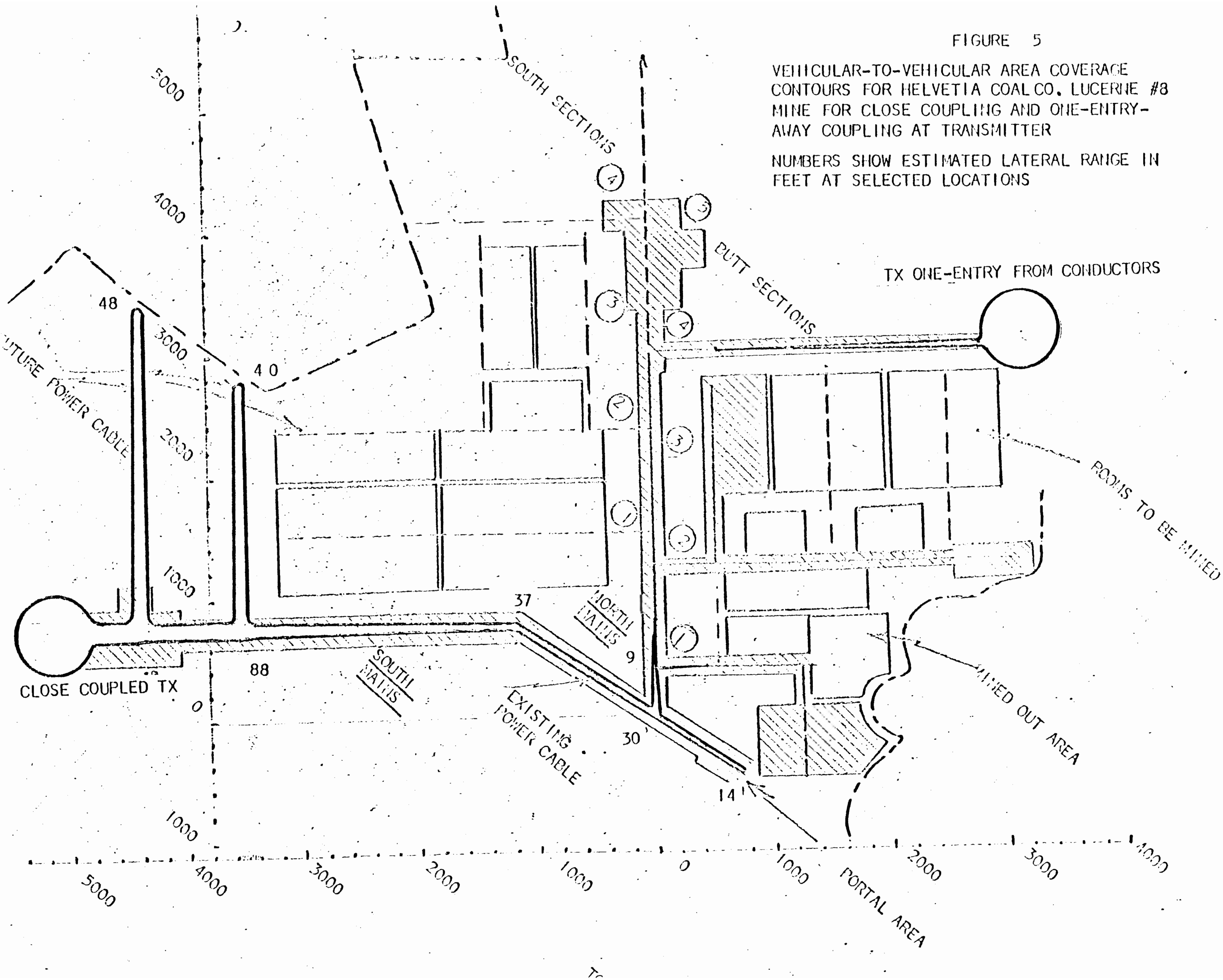


FIGURE 5

VEHICULAR-TO-VEHICULAR AREA COVERAGE CONTOURS FOR HELVETIA COAL CO. LUCERNE #8 MINE FOR CLOSE COUPLING AND ONE-ENTRY-AWAY COUPLING AT TRANSMITTER

NUMBERS SHOW ESTIMATED LATERAL RANGE IN FEET AT SELECTED LOCATIONS

3.0 MF SYSTEM DESIGN PRIMER

The purpose of this section is to provide the MF system design methodology in sufficient detail so that systems can be configured once particular elements of radio equipment are available. The methodology is placed in the context of coal mines; however, except for details of system performance analysis involving radio propagation effects, the methodology is applicable to any type of mine.

Because particular radio elements for MF systems are not yet available, the functional characteristics of MF systems are described generically rather than specifically. This does not dilute the methodology but, rather, places the important features and limitations of MF systems in perspective. A great deal is now known about the expected performance of MF systems in coal mines. This section should, indeed, prove invaluable to potential developers and manufacturers of MF equipment in the assessment of the relative importance of particular features and design parameters.

3.1 SYSTEM OPERATIONAL REQUIREMENTS

3.1.1 REQUIREMENTS FOR COMMUNICATIONS

All underground coal mines require large scale communications to facilitate efficient mining operations. To date, these communications consist mostly of analog voice plus fire control monitoring of belt haulageways. At a minimum, all underground coal mines employ baseband pager phones for section-to-place communications; the communications being generally centralized at the "dispatcher's" center (usually located underground near the entry portal). Most DC mines currently employ trolley phones for "enroute" haulage and service vehicle traffic control and logistics. The trolley phone is a low frequency radio (generally operating in the 88-108 kHz frequency range) by direct coupling of carrier current into the DC trolley wire/DC bus via the vehicular powering arm. Newer AC mines, while not experiencing the direct haulage traffic of older DC mines without belt haulage, have no means of mobile communications with personnel carriers(man-trips), service vehicles, and mobile supervisory personnel underground. Often, the dilute pager phone system provides for phones near section power centers, section belt headpieces, and at major main/submain junction points only.

Additionally, newer AC mines often employ extended working section panel topologies of up to 3500 feet (room and pillar mining) in length when the headings are fully driven. Section mining operations in these long panels often includes the coordination of activities of maintainance/ support crews and inspectors by the face boss in addition to the face work crew. In high-production room-and-pillar mining and/or long wall mining using modern mining machines, even the face crews are separated by distances well beyong the normal voice or convenient walking range of the boss. There is, thus, a need for improved section communications in these modern mines.

Use of medium frequency permits wireless communications to be implemented in mines. The direct radio-to-radio range obtainable is greater than that in any other frequency range (except, perhaps, for UHF along a large smooth entry in high coal without any bends/corners) and does not vary significantly whether along headings or crosscuts ordiagonally through coal blocks/pillars. This frequency range usage also enables the most efficient wireless coupling into existing mine wiring.

The particular requirements for communications vary from mine-to-mine, but generally include the following whether the mines are AC or DC:

- Haulageway Coverage

  along (within one or more entries of) the major vehicular traffic routes through the mine back to a central communications center and/or back to major producing or maintaining areas of the mine.

  In AC mines, vehicular coverage is required along the haulageway an into branches where vehicles are parked while men perform maintainance; and is also required along the belt haulage entry both back to the communications (dispatcher) center and to the sections.

  Generally, vehiclesr or men carrying portable radios can be expected to be within 1-2 entries of meadings containing mine wiring.

- Section Area Coverage

  over all section panel headings (including return air),plus recently mined-out room-and-pillar areas, plus current face areas. Often, there will be no conductors forward of the present section power center location. Usually, the face is within about 800 feet of the power center and the room-and-pillar areas in which men may be expected to be found are within about 1300 feet of the power center. Toward the submain from the power center, there will be at least an AC power cable, a phone line, beltway support and control/alarm cabling; and sometimes metal water and/or rock dust lines. Section headings seldom exceed a five-entry pattern, so that all locations are usually within 1-2 entries of mine wiring conductors.

  Local communications over the section area are generally required plus distant communications from the section along haulageways and/or directly back to the dispatcher or to the surface.

- Maintainance Area Coverage

  for single-portal (or large mines with several widely separated portals), the maintainance areas are located undergorund near the portal. These areas include an electrical shop, a mechnical shop, and one or more rooms for personnel and vehicles. In punch mines or drift mines, there may be no maintainance (or limited maintainance) underground; with these functions being located on the surface near each drift portal. It is important to provide communications from the dispatcher location (at least) to these maintainanace areas and, if possible, from the major workings directly to these maintainance areas.

- Remote Inspection Area Coverage

  Nearly every older and/or larger underground coal mine has fixed areas, removed from active working areas and hence from existing mine wiring, requiring periodic inspection and/or maintainace and from which communications to the dispatcher or to the surface would be highly desirable. These include:

  - Previously mined-out areas, generally being "bled-out" into return air
  - Fresh air escapeways not along major traffic routes
  - Isolated fresh air ventilation boreholes or exhaust return air vent holes
  - Areas toward the end of previously driven main or submain headings to eventually be extended in future mining operations.

  Communication links are highly desirable between these isolated areas or specific locations and the dispatcher or to the surface.

These situations requiring communications are illustrated in Figures

3.1.2 AVAILABLE MF COMMUNICATION LINKS

From the requirements outlined in Section 3.1.1, there are three major identifiable types of wireless communications needed in underground coal mines. These types consist of:

- Local area communications only

  Between crews or functional operations within crews in a given operating area such as a working section panel (or perhaps more than one working section panel, if adjacent), a long wall section, or a maintainance area typically near a portal. Typical functional operations in a conventional room-and-pillar section include roof bolting, rock dusting, timbering, masonry constructing of air flow barriers, miner and shuttle car operating, and tipple operating controlling the loading of coal from a section beltway either onto a submain belt or onto coal cars (including the snapper).

  An extension of this type of communications includes transmission between distantly separated local areas.

- Communications between a local area and a central underground dispatcher or an operations center on the surface

  In addition to working areas described above are remote inspection areas. In case of a major logistics/repair problem or of a health/safety problem, a direct link to the centralized location is required.

- Communications from local areas or from the central dispatcher to mobile units enroute or working along major arterial haulageways in the mine.

  Included here as mobile units are haulage trains, supply trains, service/maintainace vehicles and crews, inspectors, and at-large supervisory personnel.

The local area communications are accomplished either directly using through-the-coal-seam radio transmission or else via carrier current coupling into the existing metallic conductors which are usually rather densly distributed over these working areas. Most often, the communications can be accomplished via transmission between portable radios and/or between vehicular radios only with aiding electronics such as repeaters or line extenders not being required. Occasionally, such as in larger-than-usual room-and-pillar mining areas or between nearby mined areas requiring inspection and current face areas, the use ofrepeaters or line extenders to aid communicationsarea coverage will be required.

The medium affecting longer distance transmission required for communicating from local areas to a central dispatcher or from either or these to mobile units is via purposeful coupling into existing mine wiring. Considering the dilutely distributed conductor ensembles normally encountered in AC mines, the transmission medium is via either the monofilar mode along the AC power cable or along the phone line (co-directional currents excited in each of the conductors) or bifilar mode transmission along the phone line. Other modes are possible between these conductors, but these are the predominant ones in AC mines. In DC mines, the complex conductor ensembles include the track, the DC trolley wire, the DC feeder bus, and the ground return bus. Often, the excitation of extraneous multi-conductor modes will cause null areas in field strength radiation along these ensembles and junction effects will cause unequal current split (signal "suck-out" if the current goes the wrong direction) at these junctions. Primary consideration for the remainder of this section will be given to the simple AC power cable/phone line geometries of AC mines as these are the most previalent in trackless haulage applications.

To assure the longest distance transmission underground, the local area-to-dispatcher communications is accomplised by coupling to the bifilar phone line mode. This may be accomplished in several ways, as will be discussed later in this section. Once coupled to the phone line in the normal bifilar mode (bidirectional currents in each conductor), the signal currents can travel long distances without being strongly influenced by the proximity of other nearby conductors. If the existing pager phone line line is used, the signals will be influenced by the loads and junctions; however, these are more predictable than the monofilar mode effects by far.By the same token, only a little radiation will occur from a phone line carrying this mode so that only minimal wireless coupling can occur to nearby radios not directly terminating the line. Direct radiation from the bifilar mode may be usable within the entry(heading) containing the phone line with the operation being analogous to low-frequency leaky feeder operation. This radiation occurs only due to line unbalance; it is possible to enhance this radiation at certain preferred locations with mode converters or with balanced loop antenna radiators.

For the local area/central dispatcher-to-mobile unit transmission, portable and/or vehicular radios must be able to couple into the mine wiring ideally up to 1-2 entries away. This type of communication depends on the monofolar mode(s) transmission. In AC mines, the effect of branching and/or standing waves on AC power cable/phone line conductor ensembles is predictable. In large mines, the principal monofilar conductor which is the AC power cable may be partitioned into more than one power grid. This either localizes the extent of this type of communications or else requires a bridging between these grids to be accomplished.

The operational communications requirements in underground mines and the available communication links to satisfy these requirements at medium frequency define the nature of the system elements and generic groupings of elements comprising the configuration architecture and operating methodology of MF systems.

3.2 SYSTEM ELEMENT OPERATING DESCRIPTION

3.2.1 SYSTEM ELEMENT DESCRITION

This section defines the system elements, key generic groupings of elements, and identifies the element/element groupings with particular communication requirements and with available link characteristics. The system elements consist of

- Radio Terminal Elements
- Repeater Elements
- Line Extender Elements

The basic Radio Terminal Elements consist of personal man-carried portable radios (hereafter called "Portables"), vehicular mounted radios (hereafter called "Vehiculars"), and base station radios (hereafter called "Base Stations"). Both Portables and Vehiculars have their own special antennas whose designs form an integral part of the element design. The Portables are presumed to be powered from their own integral intrinsically safe battery supplies. The Vehiculars are presumed to be powered from the vehicle battery or, optionally, from a separate intrinsically safe battery supply. All Radio Terminal Elements provide for simplex and half-duplex operation.

Considerable effort has been expended toward indentifying practical portable radio packages in recent years and two candidate packages have emerged. Both of these have evolved from the cumbersome South African (ECAM) and Collins FM prototype packages which were very similar and generally unsatisfactory for use in coal mines. These three package types are illustrated pictorally in Figure 6 . Vehicular radio packages are presumed to be very similar to the trolley phone packages currently available in the marketplace, with the exception of the antenna. Previous prototype vehicular MF radios have not been built. The typical vehicular radio package concept and antenna are illustrated in Figure 7 . Prototype vehicular antennas have been built.

The Base Station package is presumed to be table mountable and of size and configuration very similar to VHF or UHF land mobile units currently available. Terminations for the base station package are varied;but, at a minimum will likely include the following:

- A large single-turn base station antenna tuned to a single frequency
- A multi-turn loop designed for permanent close-proximity mounting to conductors as a current transformer for exciting monofilar carrier current in these conductors; this loop being tunable to more than one frequency. Or, alternatively, a ferromagnetic (Magnetic dipole) generically similar to the hoist radio couplers which may be permissible for use (by MSHA) in certain installation situations; also tunable to more than one frequency.
- One or more balanced phone line terminations

  Note: additionally, a combined current transformer and antenna termination will probably be required in most installations, employing a power splitter to divide the two. Also, a Base Station should provide for both separate and combined transmit and receive terminations on the package.

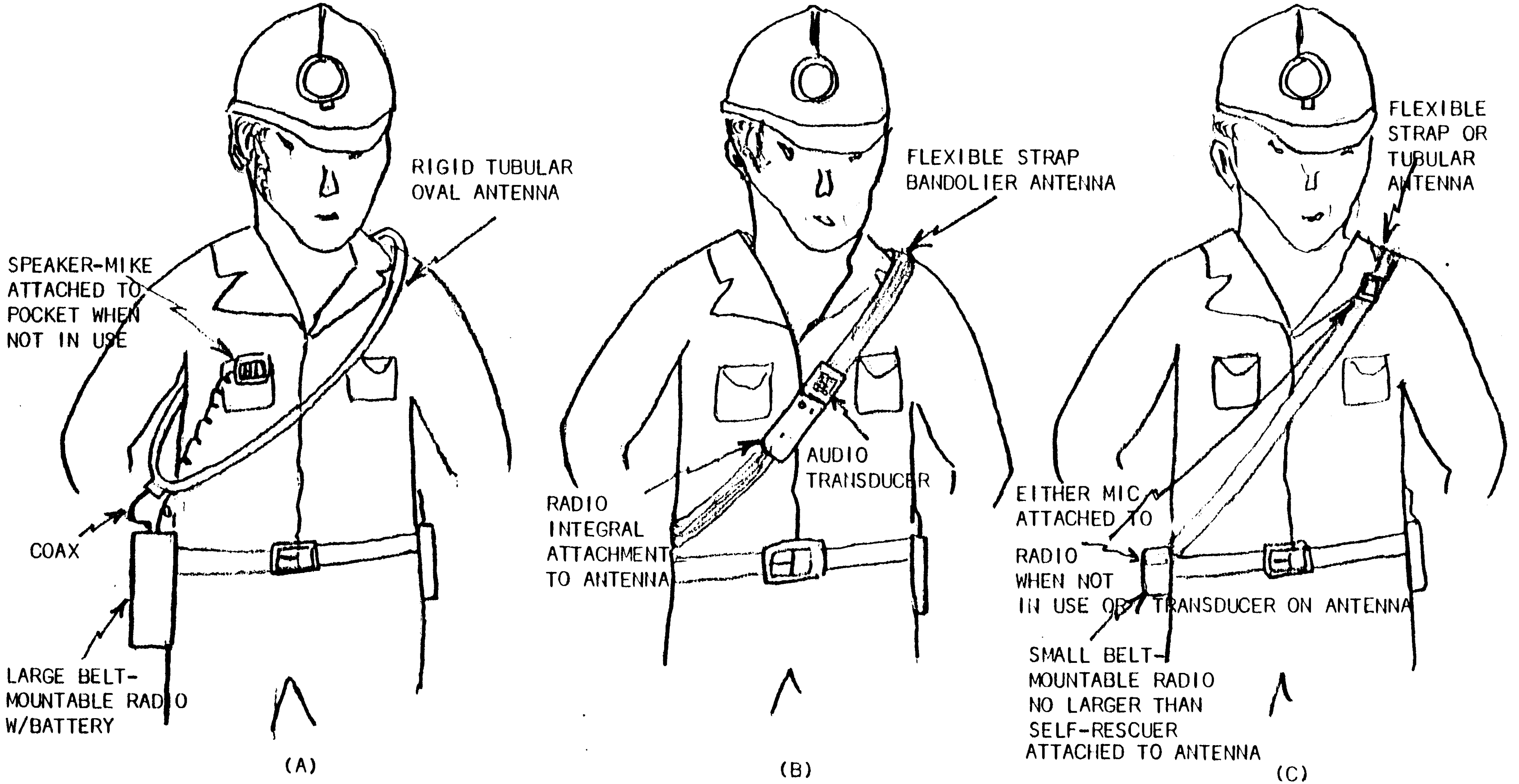
The Base Station is presumed to be powered from a 110 VAC line; or, alternatively, directly from a battery power supply. The Base Station and its termination options is illustrated in Figure 8 .

The basic Repeater Elements are of the conversion/remodulation type (to be differentiated from Active Line Extenders), each consisting of a receiver and transmitter operating at different frequencies plus control circuitry. These elements constitute several generic groupings according to the type of communication link being used and the particular communication requirements being served. The individual element groupings to be discussed in the paragraphs to follow consist of:

- Remote Base Station
- Line Amplifier
- Line Coupler
- Remote Repeater

FIGURE 6

ILLUSTRATIONS OF PROTABLE MF RADIO
PACKAGE DESIGNS



(A)

ORIGINAL COLLINS & ECAM RADIO
CONFIGURATION

(B)

NEW SLIMLINE RADIO CONFIGURATION
SIMILAR TO RAGAL BUT WITH SMALLER
RADIO PACKAGE

(C)

ALTERNATE RADIO CONFIGURATION
IMPROVED PACKAGE DESIGN

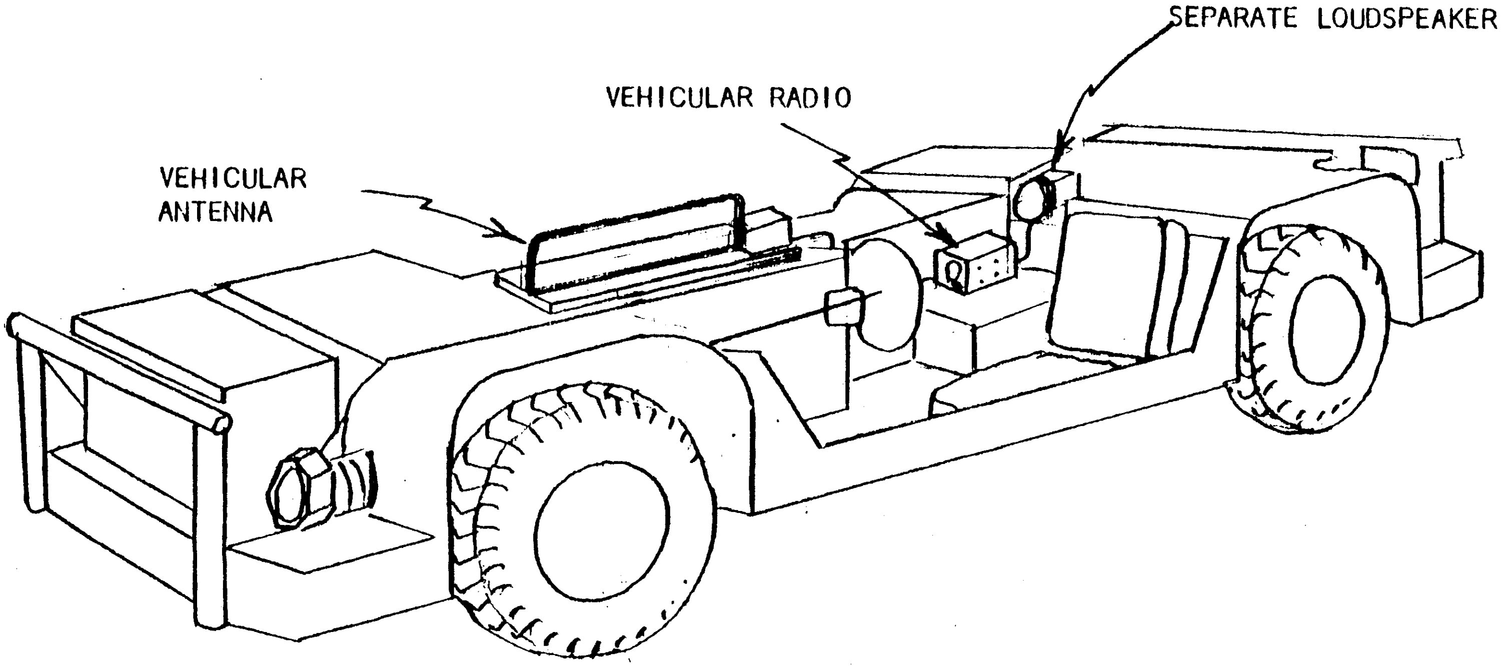
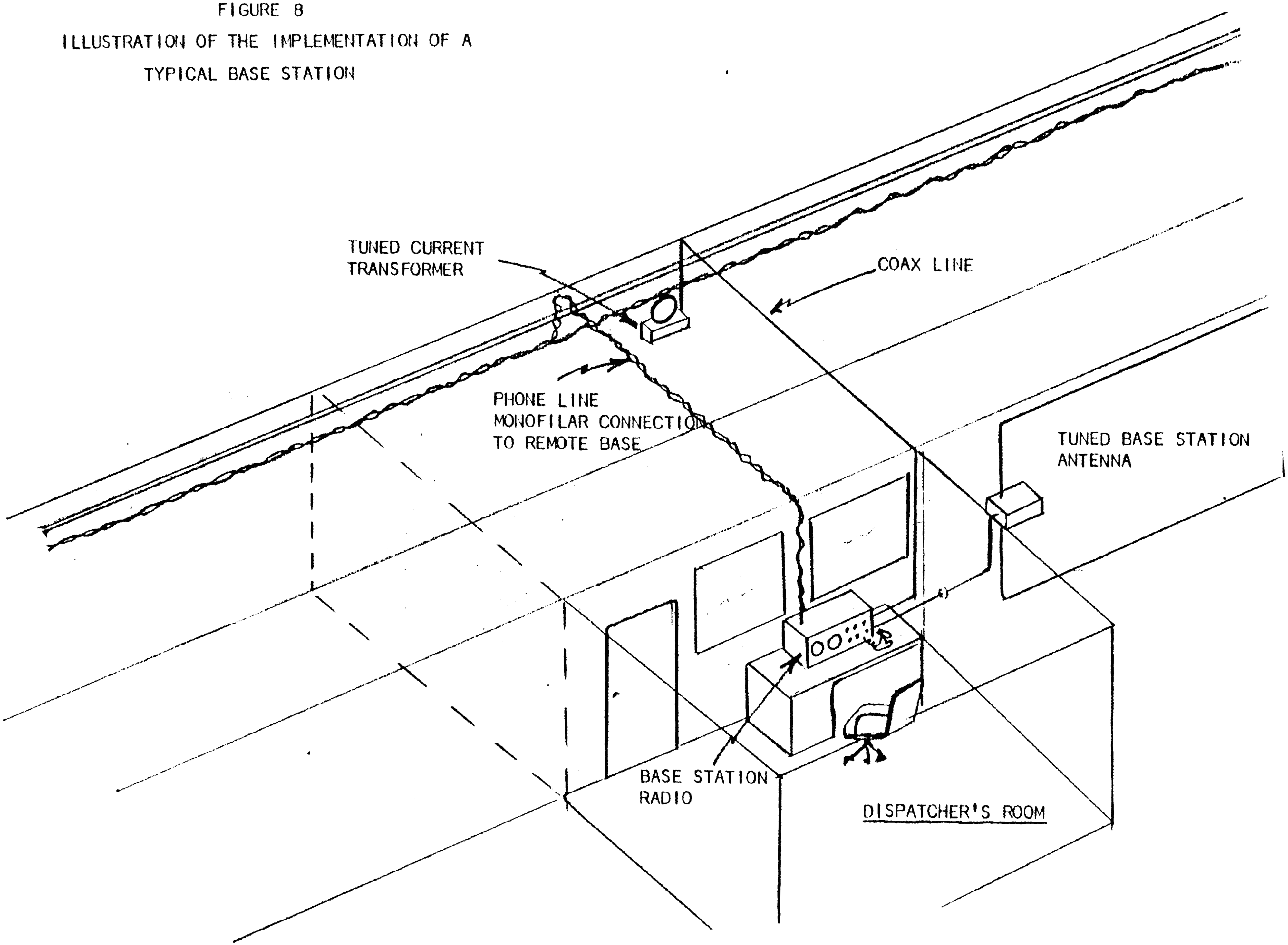


FIGURE 7
ILLUSTRATION OF THE IMPLEMENTATION OF A
TYPICAL VEHICULAR RADIO SYSTEM

FIGURE 8

ILLUSTRATION OF THE IMPLEMENTATION OF A
TYPICAL BASE STATION



All Repeater Elements provide for the half-duplex mode of operation (as opposed to full-duplex) which, in certain of the above configurations, complicates the termination interfaces but which provides for the more cost effective design through requiring only about half the hardware.

The Remote Base provides phone line termination of one link end with control emanating directly from the centrally located Base Station. This type of repeater services the local area-to-central dispatcher type of communications. Generically, it simply provides the means of interfacing the bifilar mode phone line and wireless transmission/monofilar carrier current media with amplification. In some applications, the Remote Base function could be served passively using mode converters at a given desired locale to convert the phone line bifilar mode to the monofilar mode. In its most sophisticated form, the Remote Base converts a Radio Terminal Element MF frequency to a lower frequency for transmission over the phone line (and visa versa) ; and, also, providesthe transmitter and audio slope control to enable simulcast transmission from the central Base Station.

A Remote Base is envisioned for use as follows:

- To be located at or near a section panel belt head piece coupling into the belt drive AC power cable segment; or, at the AC power cable junction switch or beltway fire alarm cable junction joining more than one working section panel so as to define a single large and contiguous operating area
- To be located so as to couple into anAC power grid presumed to be isolated from the grid in the immediate vicinity of the central Base Station location; thus, providing the bridge between isolated power grids with the connection being at the Base Station
- To serve as the Base Station for one of two or more separate mining operations served from the same central dispatch or operations center

In its simplest active form, the repeater couldtranslate MF to baseband audio thus interfacing with (but also competing with) an existing pager phone system.

In instances where "leaky Feeder" operation of the phone line at a higher translation frequency (presumed to be compatible with Portable and Vehicular MF frequencies) is not desired, the use of a separate above-base-band translation frequency could provide essentially private line communications to the surface.

In its simplest passive form, simple passive circuits are clipped onto the existing phone line to affect mode conversion in a given locale; or else, a balanced antenna is connected to the phone line at the desired location.

Terminations to the active Remote Base package include the phone line and a current transformer jointly bridged to both the transmitter and Receiver (or current transformer plus an antenna) for coupling into the local area mine wiring. The active Remote Base is presumed to be powered from the belt drive power source with floating battery backup.

Possible implementation of the Remote Base is illustrated in Figure 9 .

The Line Amplifier provides a "boost" in the monofilar carrier current serving the local area/central dispatcher-to-mobile unit type of communications. Both link ends are current transformer coupled into the monofilar conductor via separate transformers for the receive and transmit inputs; alternate transformer coupling into the bifilar phone line to amplify long transmissions between local areas is also possible. The Line Amplifier is used in long monofilar runs which would normally experience high mode attenuation; or else, following junction points experiencing unusually high splitting loss. In long bifilar runs, the Line Amplifier provides frequency compatibility with Line Couplers at the link ends. If there is a reason to enhance the wireless coupling range to the monofilar conductor in the immediate vicinity of the Line Amplifier, loop antennas may be bridged with the current transformers. If used, these antennas should be oriented so as to minimize direct coupling back into the monofilar conductor and between each other.

The Line Amplifier is presumed to be located near a local permanent power source; this source to be used with floating battery backup.

Implementation of the Line Amplifier is illustrated in Figure 10 .

The Line Coupler provides an aid in wireless radio coupling at a particular location to the monofilar mode, reducing the coupling loss from remotely located Portable or Vehicular radios. This will result in achieving the full quasi-conductor-free communication range away from the conductor rather than the shorter range to accomodate the field coupling loss mechanism. Alternatively, the Line Coupler couples to the phone line bifilar mode to enable transmission between distant local area The termination for one link end is a current transformer which provides maximum coupling to the conductor. The termination for the other link end is a larger base station type antenna. Of course, to make this a half-duplex bidirectional repeater, both the transmitter and receiver must be bridged across each link end termination. The Line Coupler operates essentially identically to a Line Amplifier in which the local communication range has been extended through the use of antennas.

Optionally, the antenna link end of the Line Coupler can be remoted through a long length of coaxial cable to, say, the center of an operating area somewhat removed from the nearest conductor grid. This option forms a variation of the Active Line Extender to be discussed later in this section.

Again, the Line Coupler is presumed to be powered from a local permanent power source with floating battery backup.

Operationally, the Line Coupler is expected to be used in developing mine areas of large extent beyond the nearest AC power center or section phone; or in certain areas along haulageways in which operations (such as a logistical staging area) are removed from the nearest conductor; or to provide communications from beltways in wide multiple-entry mains or submains (say, 12-14 entries wide) requiring periodic maintainance and/or inspection where the beltway is several entries removed from the AC power cable.

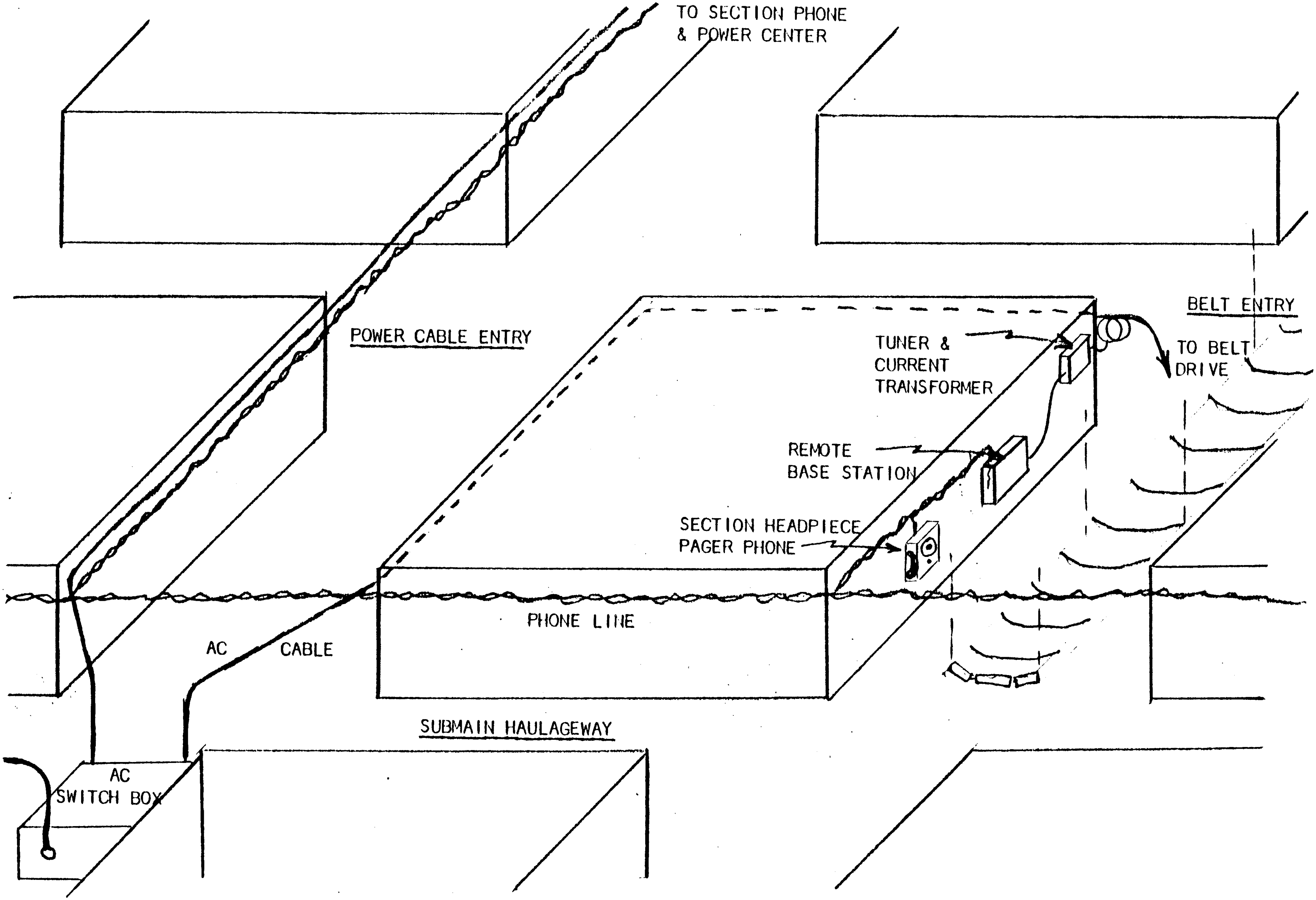


FIGURE 9

ILLUSTRATION OF THE IMPLEMENTATION OF A
REMOTE BASE STATION

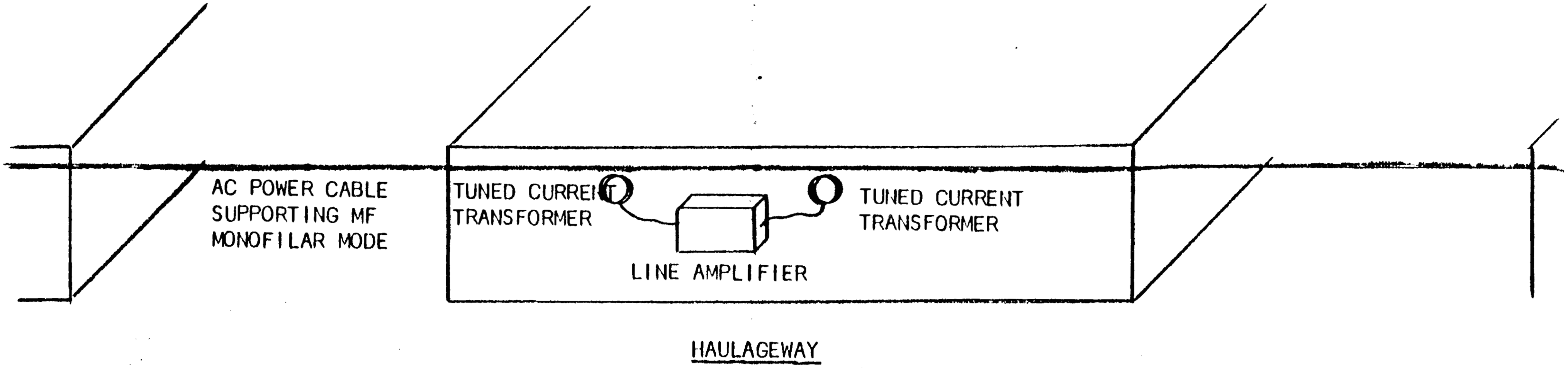


FIGURE 10

ILLUSTRATION OF THE IMPLEMENTATION OF A LINE AMPLIFIER REPEATER

Implementation of the Line Coupler is illustrated in Figure 11 .

The Remote Repeater provides extension of local area quasi-conductor-free range between Portables and Vehiculars serving the local area coverage only type of communications. The Remote Repeater does not necessarily tie directly into any existing mine wiring grid. A particular application where it does tie into a grid through field coupling is associated with section communications where the power center and/or belt is moved often and it is desired to have a semi-permanent repeater which does not depend on particular conductor locations. Normally, a Remote Base will enable section-wide "area coverage" of a panel including the face if the face is within a few hundred feet of the conductors. In large scale room-and-pillaring, where the face may be located 700-800 feet from a conductor or where functional crews may be working over an extended area of about this same size, the use of both a Remote Base and a Remote Repeater may be required to provide section-wide coverage.

The Remote Repeater link end terminations are both antennas with the transmitter being connected to one antenna and with the receiver being connected to the other. The two antennas can be co-located and oriented orthogonal to one another to obtain increased isolation. This will permit receive operation down to the full set-noise-limited receiver noise floor using a large base station type antenna on the receiver. Alternatively, in areas not so quiet or with exceptionally clean radio design, a common single antenna could be employed.

The Remote Repeater is presumed to be powered from a replacable intrinsically safe battery supply.

Implementation of the Remote Repeater is illustrated in Figure 12 .

The basic Line Extender Elements are used to extend the existing mine wiring or to bridge between isolated mine wiring grids on a semi-permanent basis where the cost/complexity of a suitable Repeater Element is not justifiable. In particular, Line Extender Elements can be considered as meeting repeater type requirements in cases where so much isolation exists between link ends that a "single-frequency repeater" can be used. Line Extender Elements are comprised of

- Passive Line Extenders
- Active Line Extenders.

Active Line Extenders may be thought of as being similar to one-way CATV/CCTV line amplifiers where two separate lines are required to provide bidirectional service. Active or Passive Line Extenders provide "link" or "loop" coupling by virtue of being like a length of coax with an antenna on each end. The Implementation of Line Extender elements is illustrated in Figure 13 .

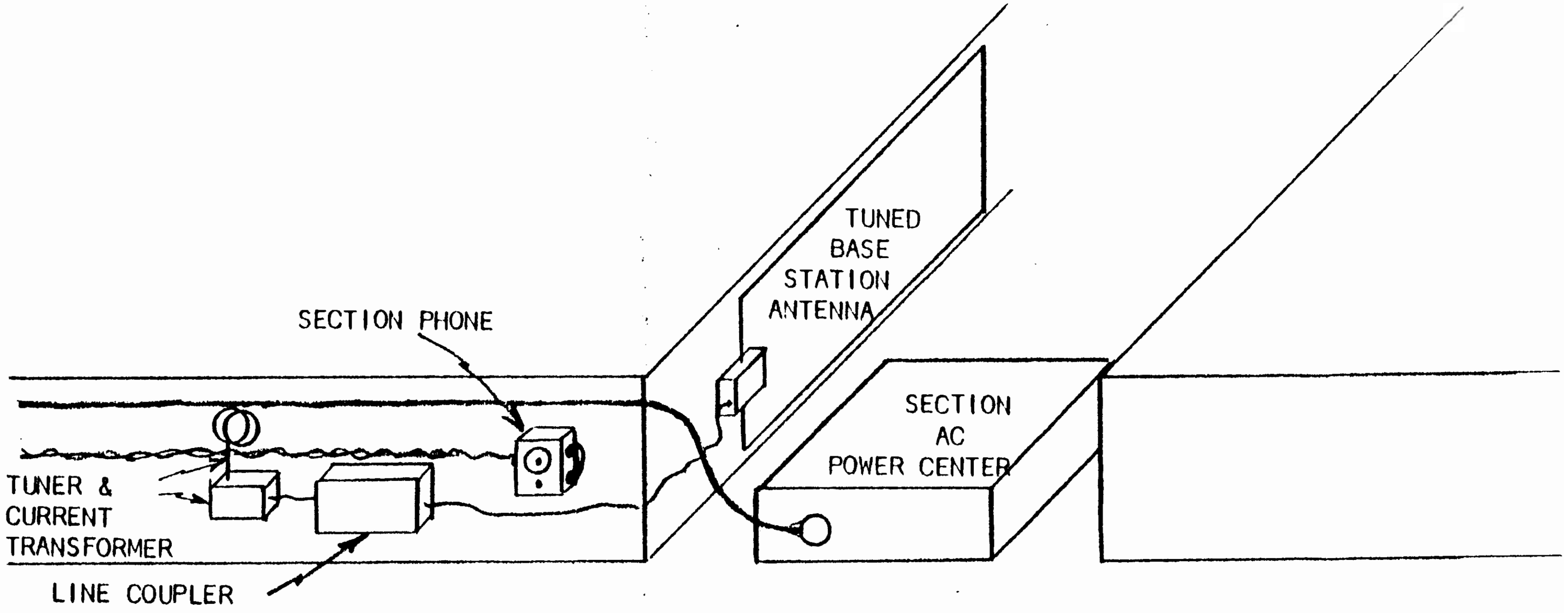


FIGURE 11

ILLUSTRATION OF THE IMPLEMENTATION OF A LINE COUPLER REPEATER

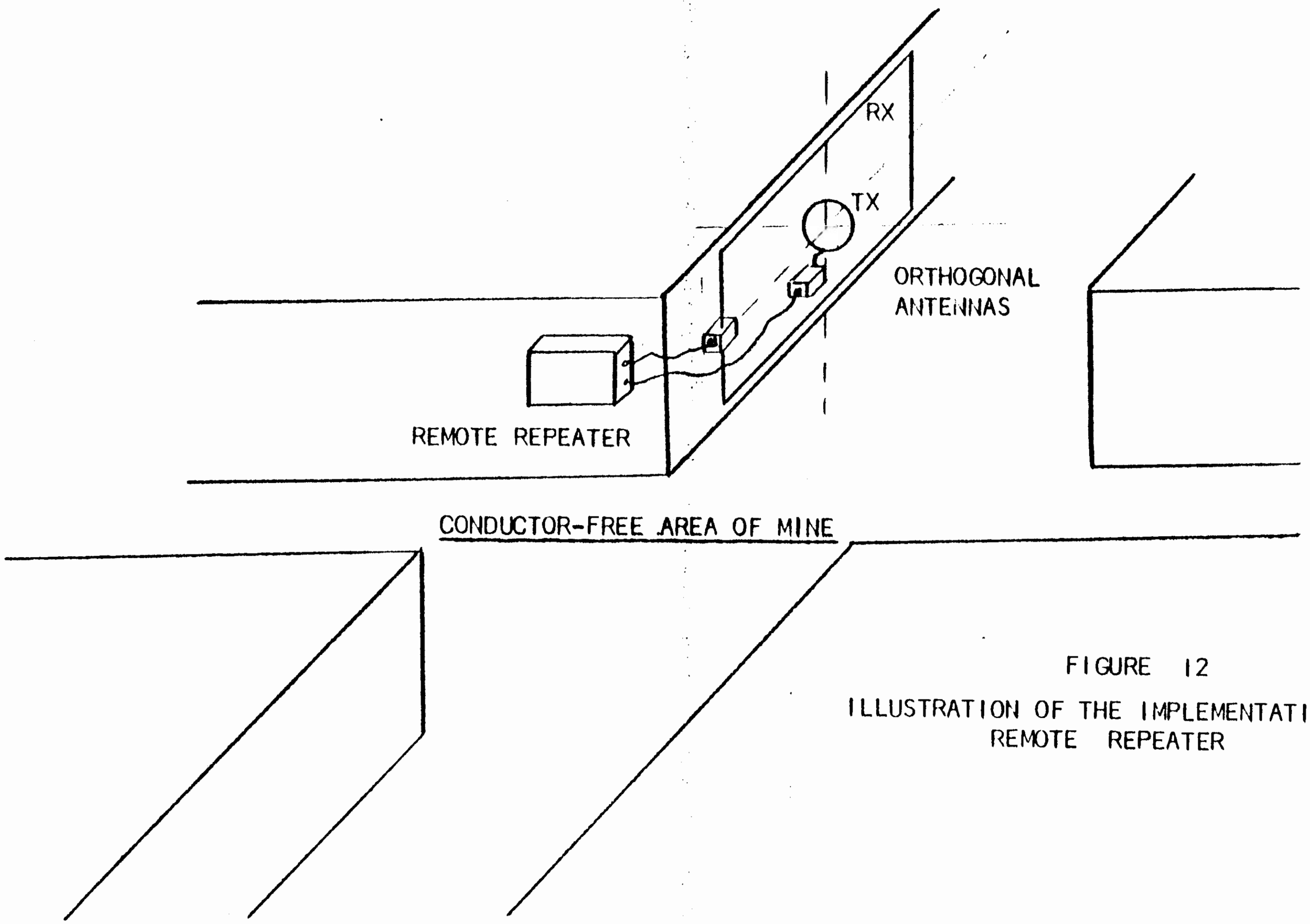
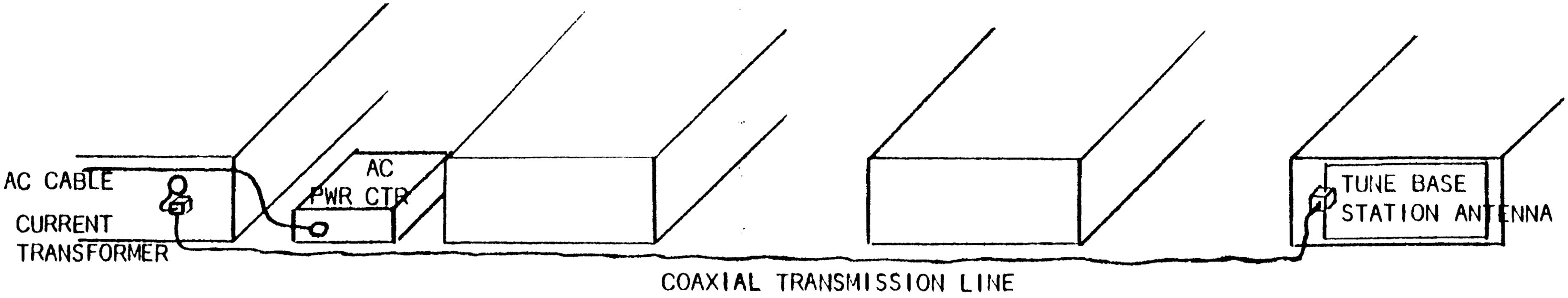


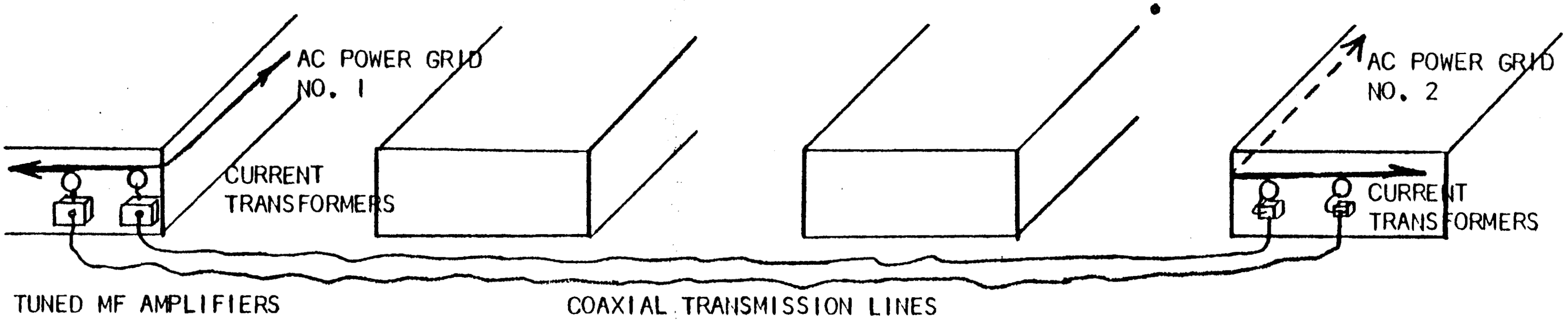
FIGURE 12

ILLUSTRATION OF THE IMPLEMENTATION OF A REMOTE REPEATER



(A)

PASSIVE LINE EXTENDER SHOWN FROM SECTION POWER CENTER FORWARD TOWARD FACE



(B)

ACTIVE LINE EXTENDER SHOWN BRIDGING TWO SEPARATED AC POWER GRIDS

FIGURE 13

ILLUSTRATION OF THE IMPLEMENTATION OF
ACTIVE AND PASSIVE LINE EXTENDERS

A Passive Line Extender is envisioned to consist of a current transformer on one end (coupling into the monofilar conductor) and a large base station antenna on the other end; the ends being joined via a piece of coax. Alternatively, the current transformer could be replaced with a balun transformer directly coupling into the bifilar mode of a phone line. In some mines with short isolated working sections, a Passive Line Extender may be all that is required to provide the local area-to-central dispatcher type communications in lieu of the use of a Remote Base and possibly a Remote Repeater.

Active Line Extenders are formed from Passive Line Extenders by placing a directional tuned amplifier in the coax line. Two such lines are required to provide bidirectional service. The amplifier(s) is presumed to obtain power from the coax, the conductor end of which is tied into a permanent power source. Alternatively, intrinsically safe replacable (rechargable) battery power supplies could be used.

3.2.2 SYSTEM ELEMENT FUNCTIONS

This section provides functional block diagrams of the elements within each system element grouping and a generic discussion of their operation. Key design considerations are pointed out together with an outline of design alternatives.

To facilitate understanding of system element operation, the use of separate transmit and receive modules is made and a separate T/R switch is shown. This form in no way is meant to impose design limitations. For example, transmit excitation and receive tuning/mixing could very well share a common frequency generation scheme and control scheme, etc. For simplicity, power sources are deleted from the diagrams. Certain preferred aspects of overall system design will be postulated in this section in areas where prior experience or obvious advantages show these aspects to be the logical choice. A complete treatment of preferred system design functions, features, and parameters will be given in the next two subsections.

A functional block diagram for the Base Station is given in Figure 14 . Operating system assumptions made in this diagram include:

- Multiple frequency operation of the transmitter
- Single or multiple frequency operation of the receiver
- Provisions for more than one Remote Base link for local area-to-central dispatcher communications; each link with a separate receive audio circuit
- Single frequency (simplex) operation locally to the Base Station; a single-tuned-frequency base station antenna
- Requirement for remote tuning (switching) of the current transformer for central dispatcher-to-mobile unit communications via the monofilar mode on existing mine wiring

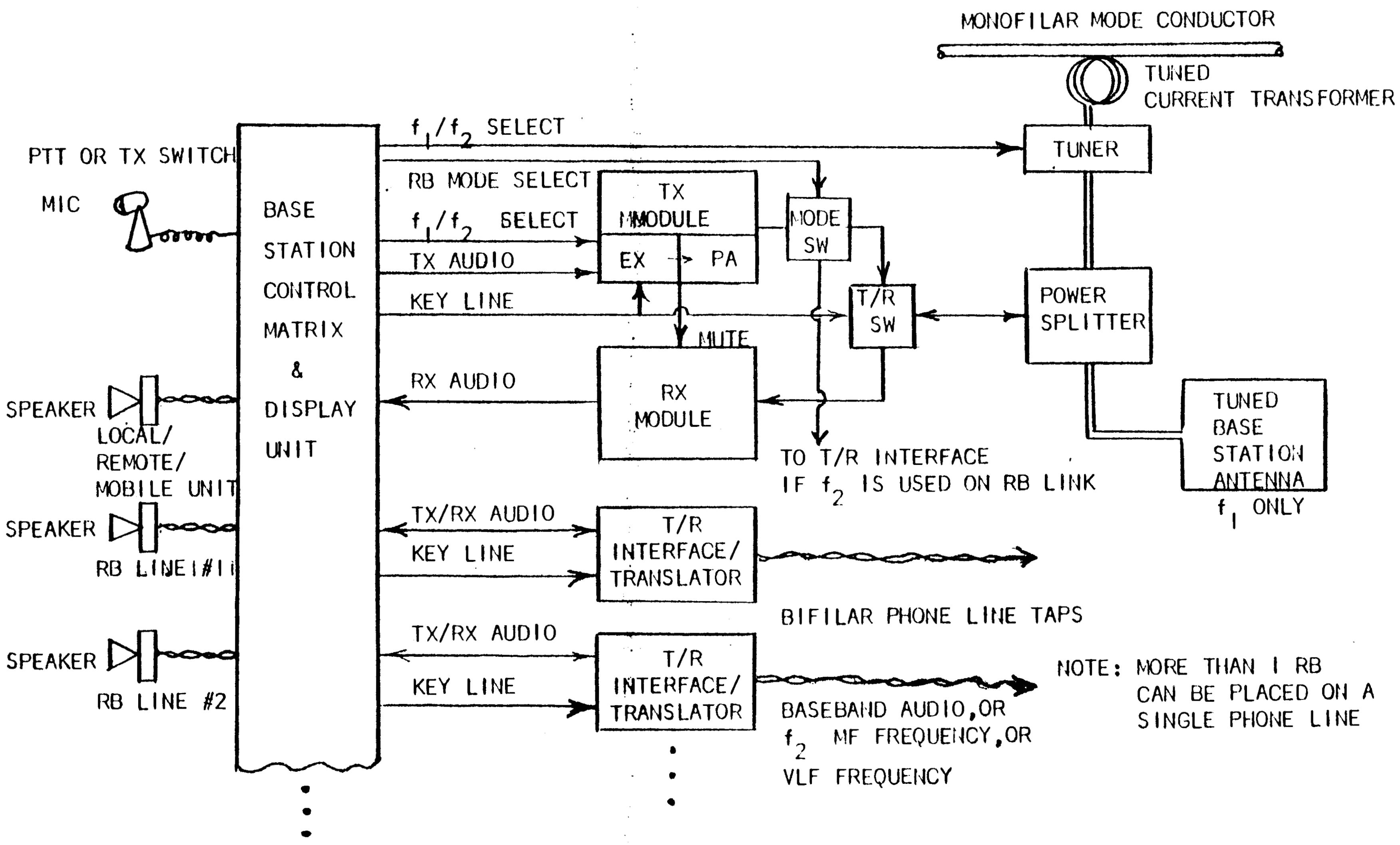


FIGURE 14

FUNCTIONAL BLOCK DIAGRAM OF BASE STATION

It will be important to separate Remote Base and Central dispatcher-to-mobile unit communication links. Separate loudspeaker outputs for these two links are preferred; however, in a simplified system implementation, a single speaker with a visual indicator as to which type (mode) of communications is active would suffice for low traffic density applications.

From the Base Station point of view, the simplest Remote Base Interconnection is a direct termination of the phone line to the switch matrix with the signal and control link being baseband. From the Remote Base point of view, the simplest implementation would involve passive reception and bifilar mode conversion of the direct MF transmit frequency; say, the same frequency as is normally received by the Base Station. This second situation would require that the T/R Interface/Translator be another Rx Module and with a mode selector switch on the control panel to route the Tx Module output to the phone line. Alternatively, the T/R Interface/Translator could be a simple frequency converter with a means provided to key the Remote Base transmitter; the conversion frequency being above baseband. This frequency would probably be chosen either to be "just above baseband" in the 10's of kHz range to minimize transmission loss; or else, at some other MF frequency compatible with the Portables/Vehiculars so that leaky wave operation along the phone line runs could be obtained.

For maximum coupling efficiency, the tuning for the current transformer should occur at the transformer rather than within the Base Station enclosure. This will require a tune line between this enclosure and the tuner.

A single block diagram for the Portable and Vehicular radio operation is given in Figure 15 ; the vehicular antenna connection being shown. The major differences between Portable and Vehicular radio implementations include:

- The vehicular antenna is separate (not attached directly to the Vehicular radio enclosure) thus requiring a 50-ohm interface to permit interconnection via a short length of coaxial cable. The Portable antenna is attached directly to the Portable radio enclusure; thus, the impedance transfer level is essentially the transmit PA output impedance level (or the antenna input resistance level when series tuned).

- The Vehicular radio employs an external loudspeaker for displaying the receive audio; whereas, the Portable receiver audio is most likely incorporated into a speaker mike or else in a small audio transducer integral to the Portable radio package

Packages for Portable and Vehicular radios have previously been illustrated in Figures 6 and 7 respectively. The most important aspects of design for the Portable are expected to be in the packaging and in providing ease of operation.

Operating system assumptions made in the functional block diagram of Figure 15 include:

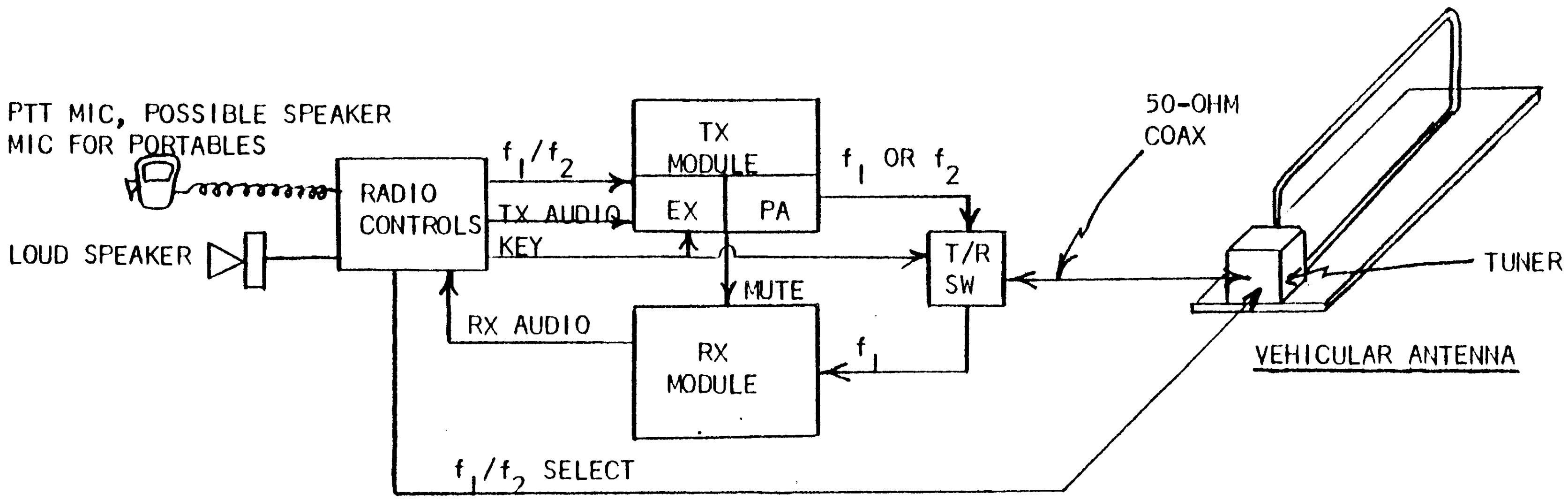


FIGURE 15

FUNCTIONAL BLOCK DIAGRAM FOR PORTABLE OR VEHICULAR RADIOS (VEHICULAR SHOWN)

- Multiple frequency operation of the transmitter
- Single frequency operation of the receiver
- Requirement for tuning of the antenna to accomodate the multiple transmit frequencies (remote tuning in the case of the vehicular antenna).

A functional block diagram for an active Remote Base repeater is geiven in Figure 16 . Operating system assumptions made in this diagram include:

- Single or multiple frequency operation of the MF transmitter
- Single or multiple frequency operation of the MF Receiver

the Remote Base operating on a half-duplex basis;

- The requirement for audio spectral amplitude compensation for possible use in a simulcast mode with the Base Station and/or other Remote Base stations
- A wireline (phone line) interface on the Tx/Rx audio link sides of the MF transmitter and receiver (Tx Module & Rx Module).

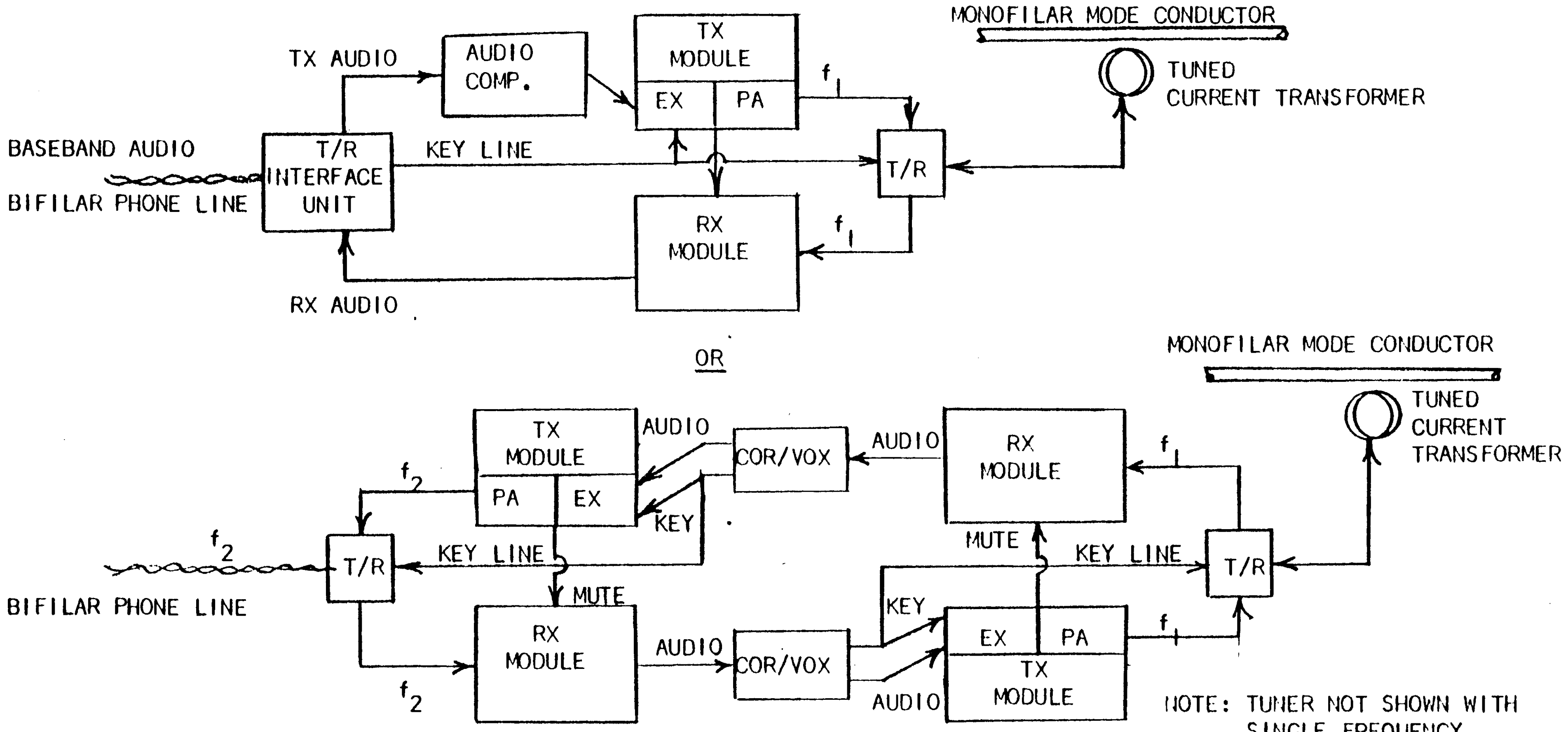
The Remote Base link possibilities have been discussed earlier in this subsection. Within the functional framework of the diagram, the T/R interface could operate at baseband or at some higher low frequency; also, the MF transmit and receive frequencies could be the same or different. This type of repeater configuration (as opposed to the configuration with Rx and Tx audio being joined through a carrier-operated relay (COR) or a VOX circuit) is required to enable simulcast operation.

If the bifilar wireline transmission were to occur at MF so that "leaky feeder" operation along haulageways would be possible (providing a separate "parallel" link to mobile units operating very close to the line) or so that MF could be carried a longer distance than would be possible with the monofilar mode, the Remote Base configuration becomes similar to that of the Line Coupler repeater configuration of Figure . In this case, the base station antenna and the monofilar current transformer are bridged with a balun to provide the wireline interface.

The functional block diagram illustrating the Remote Repeater is given as Figure 17 . This type of repeater is illustrated first for ease of visualization; namely, separate single (and decoupled) antenna terminations for the MF transmitter and receiver. The operating system assumptions made in this diagram include:

- Single frequency operation of the transmitter
- Single frequency operation of the receiver,

the TX and Tx frequencies are different (separated) with the repeater operating on a half-duplex basis;

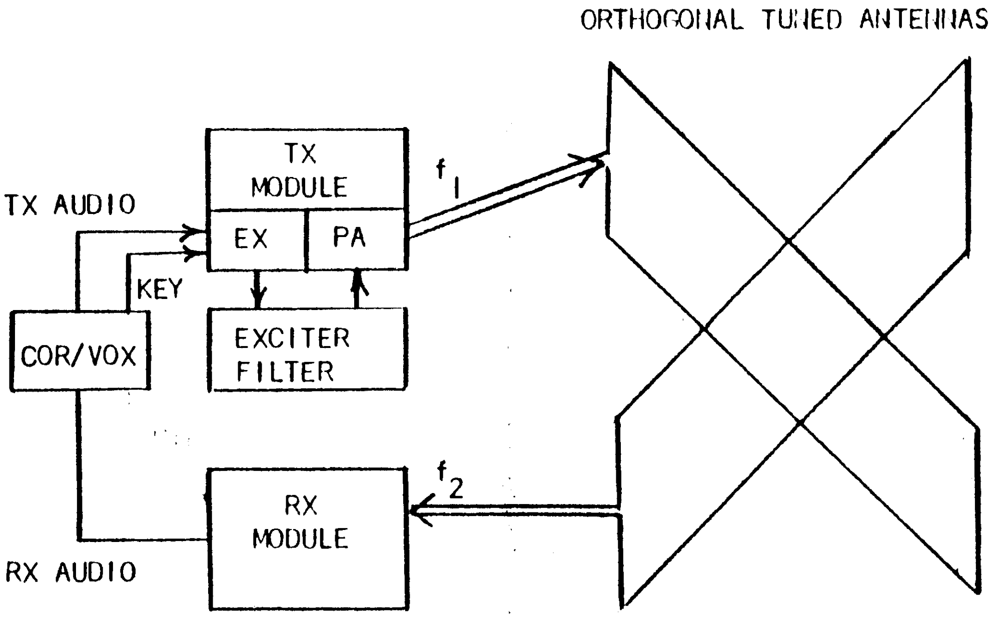


NOTE: TUNER NOT SHOWN WITH SINGLE FREQUENCY TRANSFORMERS

FIGURE 16

FUNCTIONAL BLOCK DIAGRAM OF REMOTE BASE

SHOWING BASEBAND AUDIO AND MF INPUT OPTIONS FROM BIFILAR PHONE LINE



NOTE: TUNER NOT SHOWN WITH
SINGLE FREQUENCY
ANTENNAS

FIGURE 17

FUNCTIONAL BLOCK DIAGRAM OF REMOTE REPEATER

- The transmit/receive isolation is supplied via filtering of the transmit exciter output, modulating spectrum fall-off between transmit and receive frequencies, and via antenna isolation.

- Transmit keying is activated using a carrier-operated relay (COR) or a voice-operated relay (VOX) circuit.

- The use of separate transmit and receive antennas is assumed; each single-tuned to the respective transmit and receive frequencies. These antennas are orthogonally oriented to obtain increased transmit/receive isolation.

The Remote Repeater may be expected to operate in low-noise environments requiring maximum receive system sensitivity (set-noise-limited) to achieve maximum system margin. The receive antenna is chosen to be of the large tuned base station type, having a large capture area, to increase the receiver sensitivity. The orthogonal antenna orientation provides increased transmit/receive isolation consistent with the increased receive system sensitivity required.

The functional block diagram illustrating the Line Amplifier repeater is given in Figure 18 . The operating system assumptions made in this diagram include:

- Single frequency operation of the transmitter

- Single frequency operation of the receiver,

the TX and RX frequencies are different with the repeater operating on a half-duplex basis;

- The transmit/receive isolation is supplied via filtering of the transmit exciter output and via modulation spectrum fall-off between transmit and receive frequencies

- Transmit keying is activated using COR or VOX circuitry

- The use of separate single-tuned current transformers is assumed for transmit and receive channels (shown) for monofilar mode coupling or separate transformers for bifilar mode phone line coupling. Alternatively, for monofilar mode coupling, a double-tuned single current transformer could be used with switched tuning controlled being activated from the transmitter keying function. Both incoming and outgoing link interfaces are served via carrier current flowing in a selected monofilar mode conductor.

The possibility of bridged antenna(s) at the Line Amplifier location is not shown as this would essentially constitute a Line Coupler repeater, which is discussed seprately to follow.

The Line Amplifier probably operates in the noisiest environment and, thus, experiences the least transmit/receive signal margin. There is no clear cut choice, performance wise, between the use of separate or a single current transformer(s) except for the single-tuned vs double-tuned complexity.

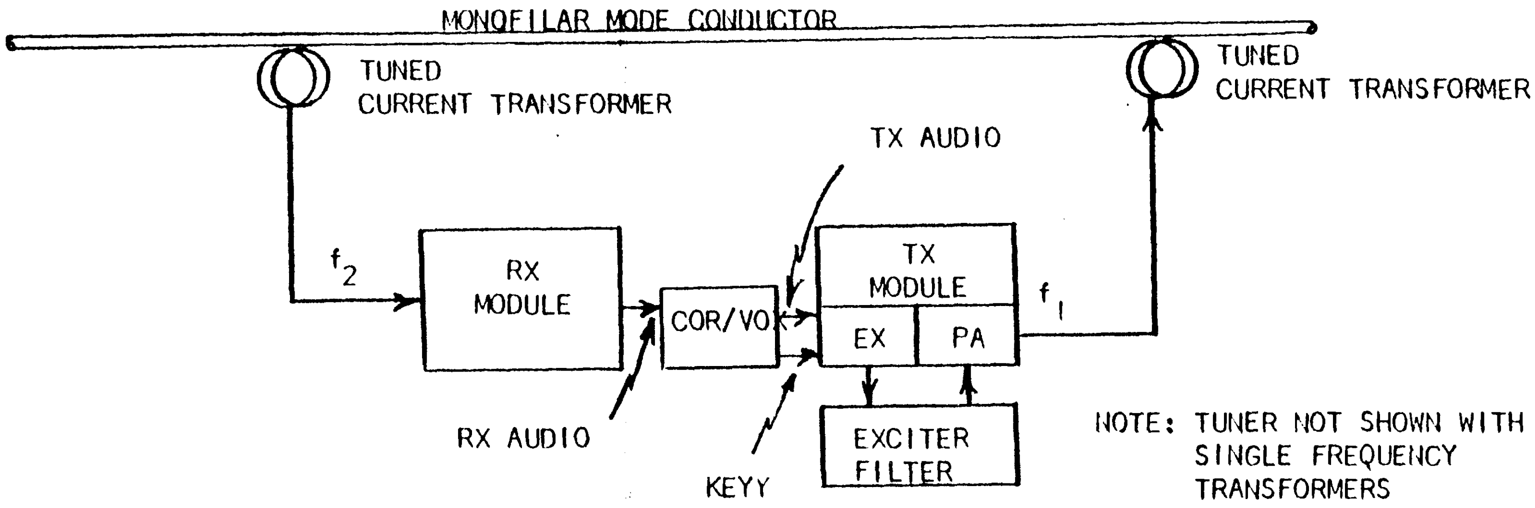


FIGURE 18

FUNCTIONAL BLOCK DIAGRAM OF LINE AMPLIFIER

The functional block diagram illustrating the Line Coupler repeater is given in Figure 19 . The operating system assumptions made in this diagram include:

- Single frequency operation of the transmitter
- Single frequency operation of the receiver,

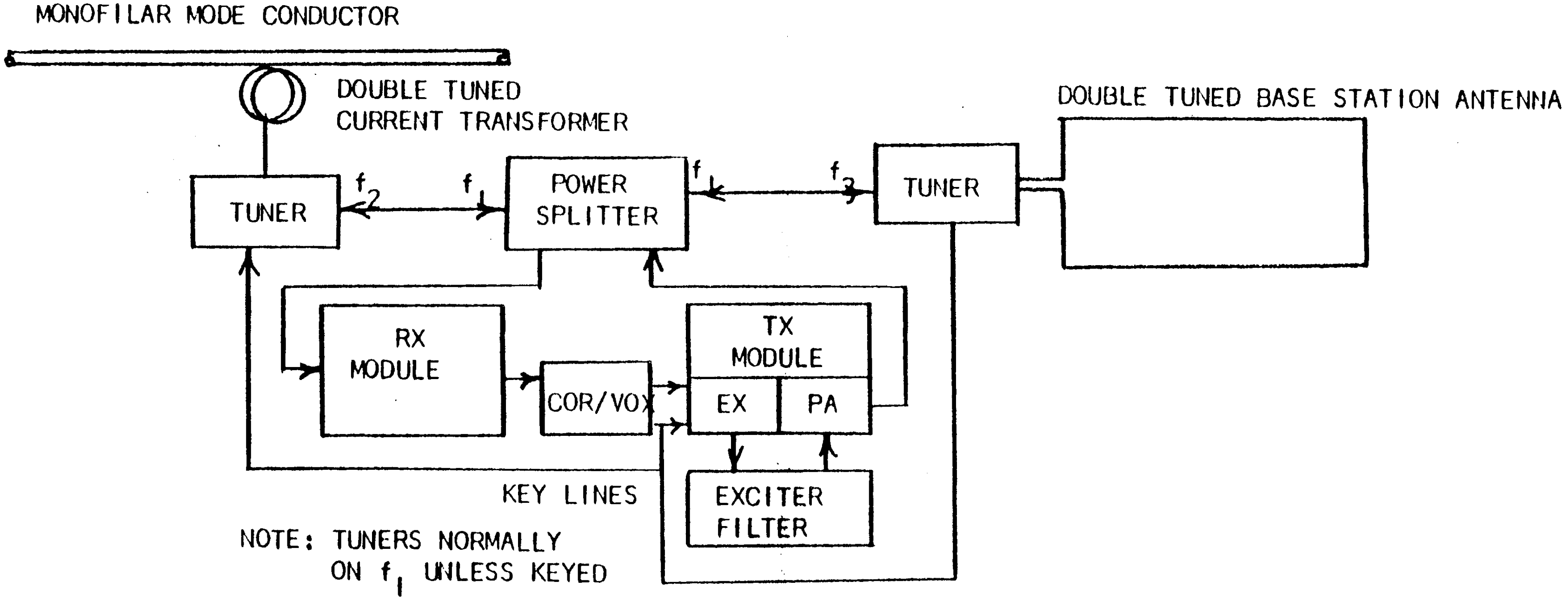
the TX and Rx frequencies are different with the repeater operating on a half-duplex basis;

- The transmit/receive isolation is supplied via filtering of the transmit exciter output and modulating spectrum fall-off between transmit and receive frequencies
- Transmitter keying is activated using COR or VOX circuitry
- The communication circuit links are enabled via carrier current coupling (via a current transformer) into a monofilar mode conductor and via a large double-tuned base station antenna. Alternatively, for long distance local area-to-local area transmission, the coupled link end may interface with the phone line bifilar mode through a transformer. The transmitter and receiver are bridged across both link inputs

A more sensitive one-way repeater could be built with a single-tuned antenna on one link end (most likely the wireless receive mode) and a current tranformer on the other link end (most likely the monofilar or bifilar transmit mode). The transmit link end margins are expected to be roughly symmetrical (i.e., for example, Portable-to-Base Station vs Base Statio-to-Portable) so that bidirectional repeaters only are required. The exception to this (and the reason for mentioning the one-way link possibility) is the possibility of implementing satellite receivers which, in a more complicated Base Station configuration, would permit more careful monitoring and location of traffic in a busy large mine.The use of satellite receivers is not herein considered a part of the baseline system design.structure.

The functional block diagram illustrating the Passive and Active Line Extenders is given in Figure 20 . The operating system assumptions made in this diagram include:

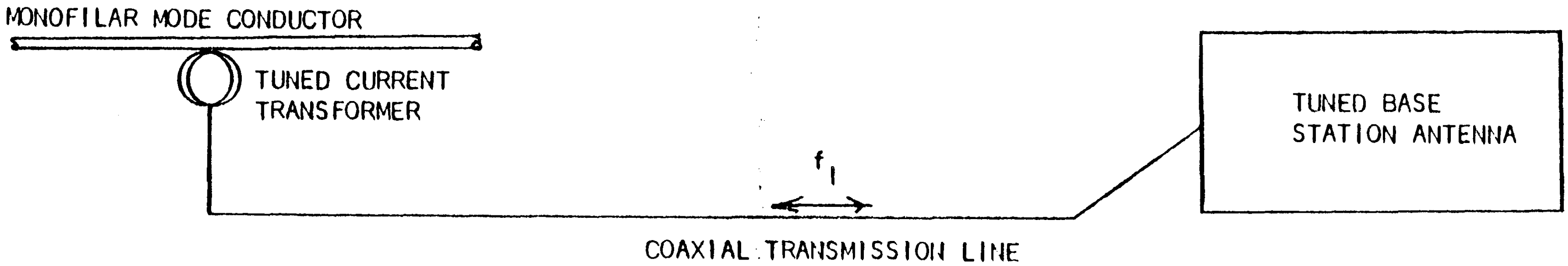
- Active or passive extenders use a current tranformer at one link end and a base station antenna at the other end (except for bridging between AC power grids where two current transformers would be used)
- An Active Line Extender is comprised of two one-way extenders for maximum extension capability; each using a directional tuned amplifier
- Separate directional amplifier frequencies are employed to be compatible with the local area-to-mobile unit or local area-to central dispatcher type of communications being served



NOTE: TUNERS NORMALLY ON f_1 UNLESS KEYED

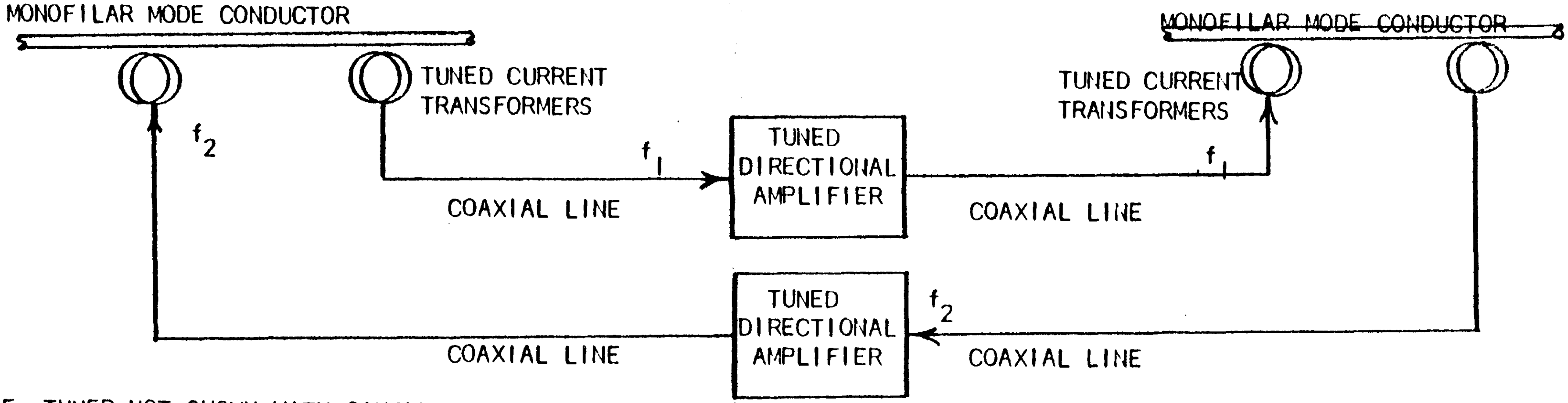
FIGURE 19

FUNCTIONAL BLOCK DIAGRAM OF LINE COUPLER



(A)

PASSIVE LINE EXTENDER



NOTE: TUNER NOT SHOWN WITH SINGLE
FREQUENCY TRANSFORMERS &
ANTENNAS

(B)

ACTIVE LINE EXTENDER

FIGURE 20

FUNCTIONAL BLOCK DIAGRAM OF PASSIVE AND ACTIVE LINE EXTENDERS

In serving local area-to-central dispatcher type of communications in a large mine, the Line Extenders simply extend the monofilar mode range; with operation into a separate Remote Base being assumed.

3.3 PREFERRED SYSTEM CONCEPT & DESIGN BASELINE

The generic configurational groundwork for MF system design in underground coal mines, emphasizing AC trackless haulagemines, has been given in the previous two subsections. This subsection presents the preferred system concept, implementable in part or in whole, which achieves a practical compromise between system simplicity and system operational flexibility.

Care has been taken to provide for the three major types of communication on a minimum interfacing basis by providing "quasi-decoupled modes" of operation in so far as possible. Additionally, the design provides for decoupled transmission between distantly separated local areas as an extension of the local-area-only type of communications; thus, a total of four distinct quasi-decoupled modes are provided for in the design. Proliferation of the design beyond that given in this subsection is expected to occur through the selection of different sets of operating frequencies.

The sifting of some link alternatives put forth in this subsection depend on a more complete understanding of the particular tarnsmission characteristics and prototype equipment design considerations than will be given. These details will be given in later sections of this report.

The design is based on the use of nominally 5-watt radios employing narrowband FM transmission for all Radio Terminal Elements and for all Repeater Elements. In actual equipment design, the maximum common usage of transmit and receive "modules" between all active system elements is assumed.

The design uses some Continuous Tone Coded Squelch (CTCS) decoding and encoding to provide operator simplecity on the part of the Portables and Vehiculars, and to help"decouple" the transmission modes. Use of additional CTCS control is discussed as providing embelishments beyond the basic design; but are not included as part of the basic design because of the recognized size of commercially available encoder and decoder components and because their use may not prove operationally feasible (except of supervisory radios, if two "tiers" of radios are practical) until experience has been gained with an actual operating system.

3.3.1 SYSTEM FREQUENCY PLAN

The frequency plan is a two-frequency plan providing for both simplex and half-duplex types of operation. The frequency plan is the same for all Radio Terminal Elements, with a variation in the Base Station. The frequencies, designated f_1 and f_2, are expected to occur in the 500-1000 kHz range with a minimum of 10% separation and with f_1 being the higher frequency of the two.

The frequency plan options for the Portables and Vehiculars are envisioned as being selectable via a three-position switch on the enclosure as follows:

"Local"	Transmit	f_1	no CTCS
	Receive	f_1	no CTCS
"Base"	Transmit	f_1	CTCS
	Receive	f_1	no CTCS
"Remote"	Transmit	f_2	CTCS
	Receive	f_1	no CTCS

A single tone encoderis used with both transmit frequencies (and a single tone is used throughout the system). Use of the single receive frequency, of course, poses the ambiguity of which "mode" is being received. This is acceptable in this type of service where the operator generally knows to whom he is talking and whether it is "Local" or "Base"; otherwise, it will most often be remote.

The dispatcher has additional visibility with regard to the type of communications being serviced and can differentiate between Remote Base and "Local" or "mobile unit" links. The frequency plan for the Base Station is:

"Local"	Transmit	f_1	no CTCS
	Receive	f_1	no CTCS

Note: on base station antenna or on a coupled monofilar conductor

"Remote Base"	Transmit	f_2	no CTCS, or baseband audio
	Receive	f_2	no CTCS, or baseband audio

Note: on phone line only, bifilar mode

"Remote/Mobile Unit"	Transmit	f_2	CTCS
	Receive	f_1	no CTCS

Note: on coupled monofilar conductor

If provisions are made in the Base Station design for simulcasting and, if Line Coupler elements are linked to the phone line (bifilar mode); then, in the simulcast mode, CTCS should be transmitted on f_2 on the phone line (assuming f_2 is used rather than baseband audio).

The frequency plan for the Remote Base is:

Receive	f_2	no CTCS, or baseband audio on wireline link
	f_1	CTCS on MF link
Transmit	f_2	no CTCS, or baseband audio on wireline link
	f_1	no CTCS on MF link

The frequency plans for the Line Amplifier, Line Coupler, and Remote Repeater are identical, and are:

Receive	f_2	CTCS
Transmit	f_1	no CTCS

As an overlay on this basic frequency plan, additional CTCS tones could be added to provide:

- Paging/Call Alert from the Base Station

  Each or certain Portables and Vehiculars would have a "home" address tone decoder such that if this tone was received, it would audibly or visually signal the operator of the radio of a call

- Private Line (blocking) from selected radios

  Selected supervisory radios would have a tone encoder and each non-supervisory radio would have a tone decoder such that if the tone were sent, it would block the receiver of each radio having the decoder

3.3.2 SYSTEM DESIGN LINK FEATURES

Using the system elements previously defined and discussed, and the frequency plan of the previous subsection, a versatile system design can be performed. An overview of the system design possibilities is given in Figure 21 which illustrates the majority of the link options.

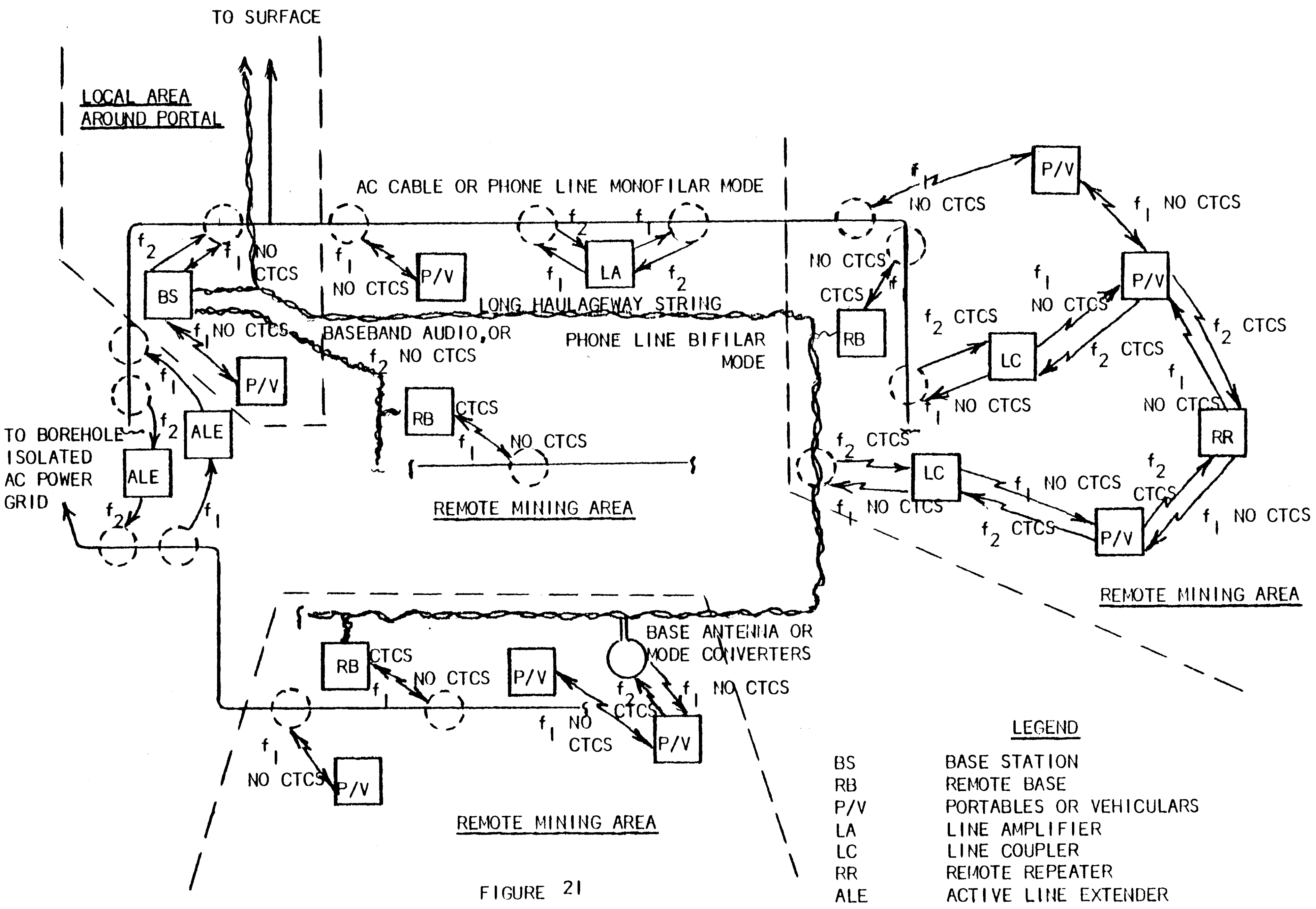
The system provides for four quasi-decoupled types or modes of communications. These are:

- Base Station-to-local area(Portable/Vehicular) communications via the Remote Base repeater.

  The link is provided using the bifilar phone line transmission mode which isolates it from types using monofilar mode coupling and transmission. This link is isolated from long distance local area-to-local area transmission via frequency separation for transmissions originating from a Line Coupler Repeater and by CTCS for transmissions originating from the Base Station

- Long distance Base Station or Portable/Vehicular-to-mobile unit communications via a Line Amplifier repeater

  The link is provided using the monofilar mode transmission on the AC power cable and/or phone line which isolates it from types using the bifilar mode for transmission. This link is isolated from links employing a Line Coupler and the monofilar mode because of frequency separation (two repeaters with like frequency plans cannot be chained)



	LEGEND
BS	BASE STATION
RB	REMOTE BASE
P/V	PORTABLES OR VEHICULARS
LA	LINE AMPLIFIER
LC	LINE COUPLER
RR	REMOTE REPEATER
ALE	ACTIVE LINE EXTENDER

FIGURE 21

OVERVIEW OF COMMUNICATION LINK POSSIBILITIES FOR MEDIUM FREQUENCY SYSTEM

- Extended range local-area-only type of communications via a Line Coupler repeater, coupled to a monofilar conductor

  Same rationale applies as for the above mobile unit monofilar link.

- Extended range local area-to-local area communications via a Line Coupler Repeater, coupled to the bifilar phone line mode

  Same rationale applies for isolation as for the above Base Station-to-local area link.

Additionally, local area simplex communications are somewhat isolated from communications from the local area to the Base Station via the Remote Base through the use of CTCS.

Of course, CTCS does not provide much isolation under dense traffic conditions; and,due to the common receive frequency, there will be interferance between "Local" and "Remote" transmissions and between "local-area-only" transmissions.

The major local area-to-central dispatcher communication link possibilities are illustrated in Figure 22 . The primary link is via the bifilar phone line transmission through the Remote Base. Other secondary monofilar mode possibilities are shown.

The major local area/central dispatcher-to-mobile unit communications link possibilities are illustrated in Figure 23 .All possibilities involve the use of at least a section of monofilar transmission along which the mobile units are presumed to be. Besides the primary all-monofilar-mode options, hybrid links including Remote-Base-excited monofilar mode and isolated power grid crossconnections using Active Line Extenders are shown.

The major local-area-only (or between local areas) communications link possibilities are illustrated in Figure 24 . These links are arranged in order of shortest range to longest range in decending order on the diagram page. The shorter range links employ direct wireless transmission or passive coupling into wiring. The longest range links employ purposeful coupling into the bifilar transmission mode on the phone line.

The configuration of particular systems will depend upon the

- Size of the mine

- Type of mine

- Size of the areas requiring communications and their locations with respect to conductors

- Mine topology; plus arrangement and number of existing mine wiring conductors

- Mining format; how often the wiring changes, and how the functional working crews are deployed.

The means of configuring the systems is the topic of the next subsection of this report.

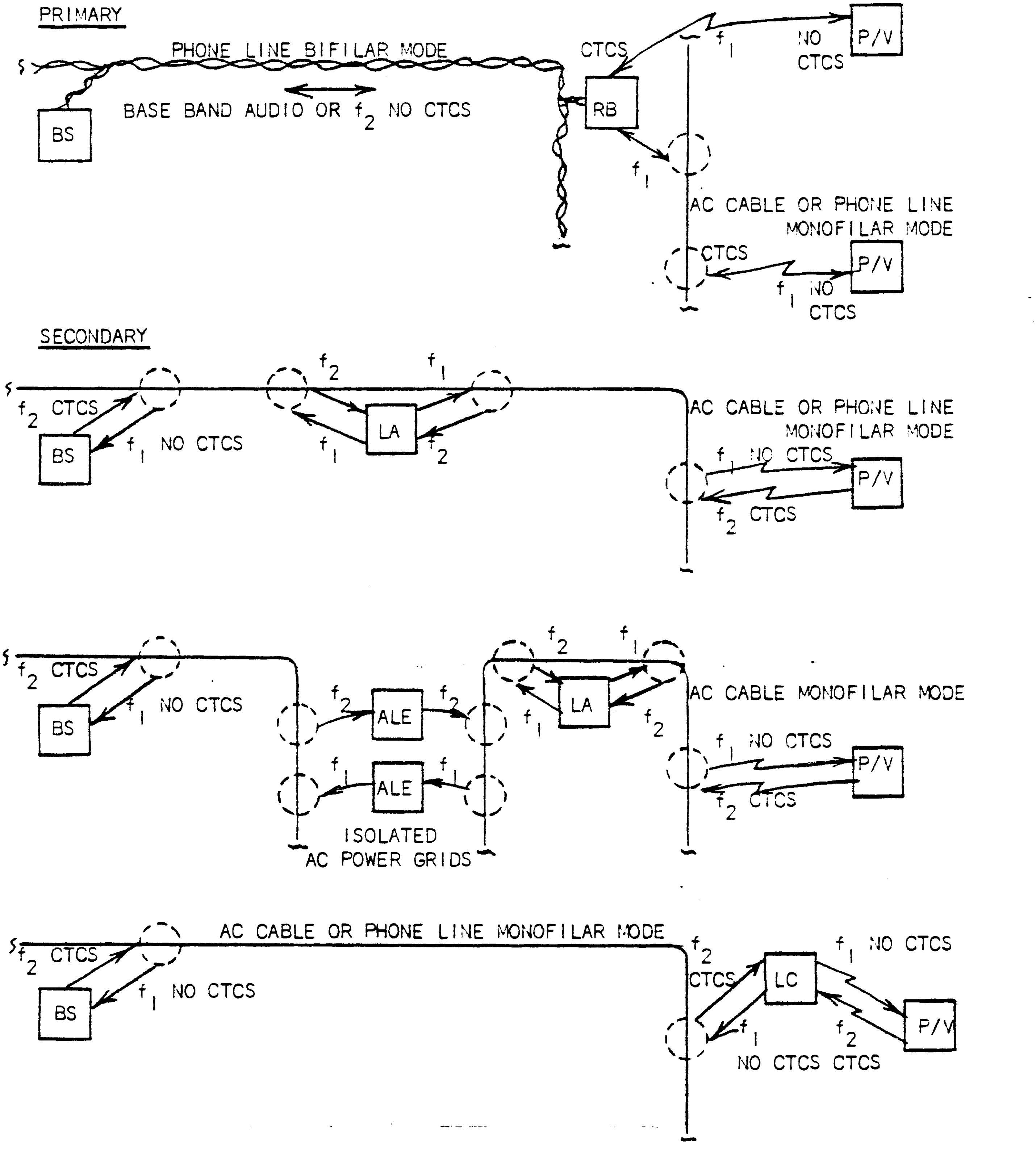


FIGURE 22

SYSTEM LINK POSSIBILITIES

LOCAL AREA-TO-CENTRAL DISPATCHER

LEGEND

BS	BASE STATION
P/V	PORTABLES OR VEHICULARS
RB	REMOTE BASE
ALE	ACTIVE LINE EXTENDER
LA	LINE AMPLIFIER
LC	LINE COUPLER

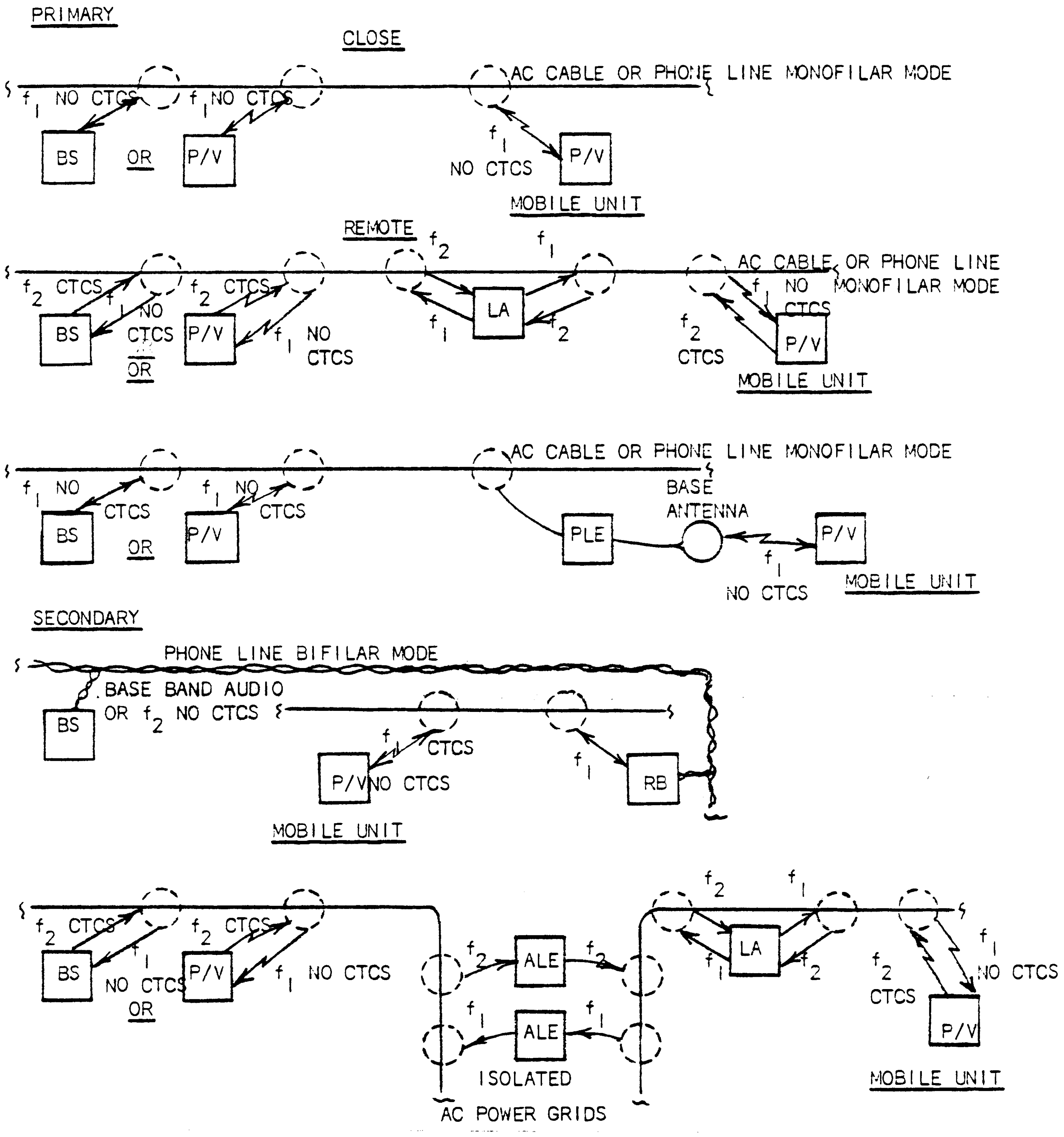


FIGURE 23

SYSTEM LINK POSSIBILITIES

LOCAL AREA/CENTRAL DISPATCHER-MOBILE UNITS

LEGEND

BS	BASE STATION
P/V	PORTABLES OR VEHICULARS
RB	REMOTE BASE
ALE	ACTIVE LINE EXTENDER
LA	LINE AMPLIFIER
PLE	PASSIVE LINE EXTENDER

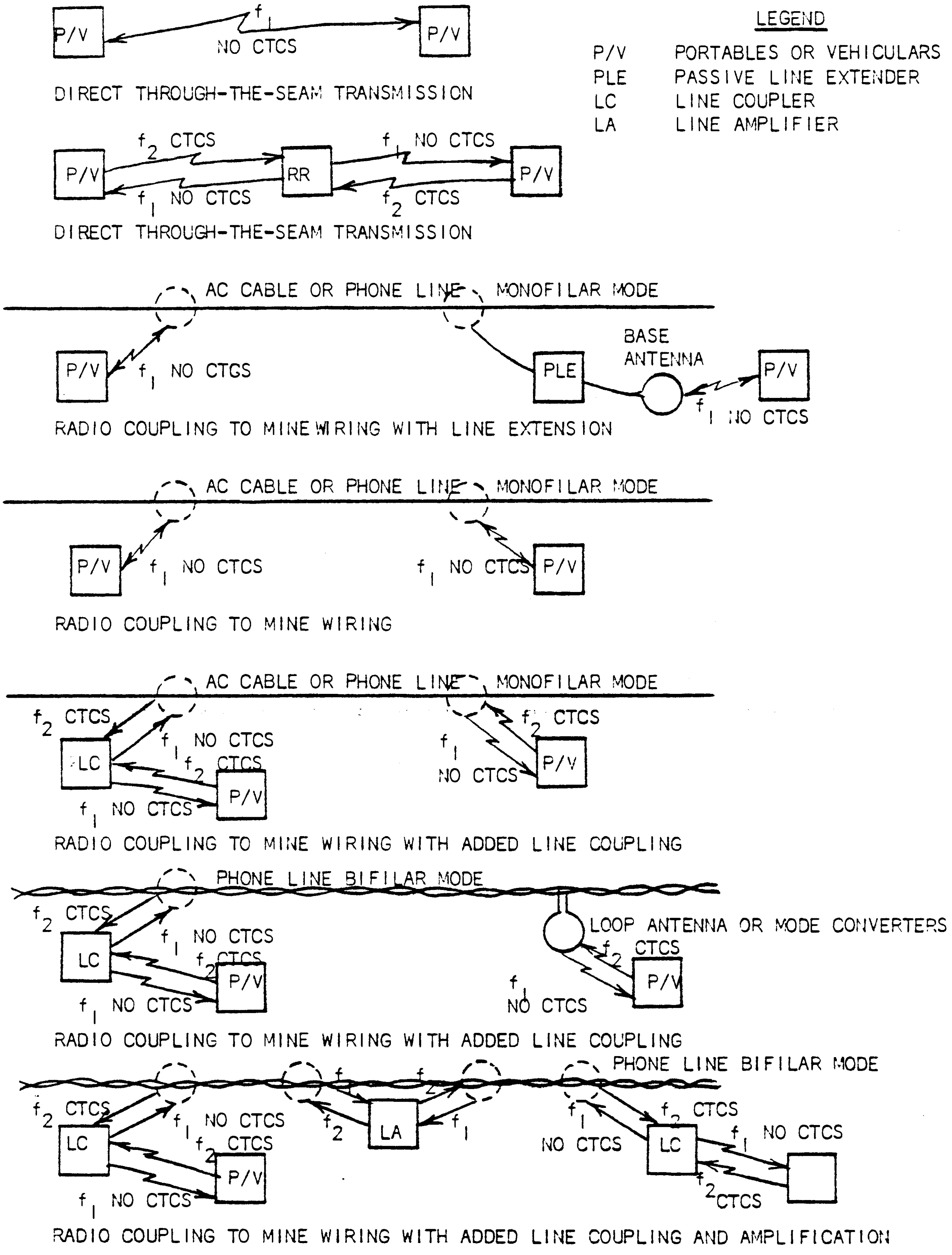


FIGURE 24

SYSTEM LINK POSSIBILITIES

LOCAL-AREA-ONLY OR BETWEEN LOCAL AREAS

3.4 SYSTEM PERFORMANCE ANALYSIS TECHNIQUE

Details of the technology "tools" required to predict and analyze system performance are given in Section 5.0. This section discusses the technique for system performance analysis using these tools, providing the basis for a particular "strawman" analysis to be given in the next subsection.

The first step in system analysis is to define the critical equipment parameters. Based on the system definition of previous subsections and technical specifications to be given in the next section, the equipment parameters are:

Frequency, choose 890 kHz as typical
Transmit power 5 watts
Portable transmit NIA 1.5
Vehicular transmit NIA 0.82
Portable NA 1.25, R = 3.5 ohms
Vehicular NA 1.67, R = 22 ohms
Portable antenna area 0.208 m^2, N = 6
Vehicular antenna area 0.139 m^2, N = 12
Base Station antenna area 14.4 m^2, N = 1

Receiver noise figure 6 dB
Modulation type, FM voice, ± 3 kHz deviation (m = 1)
Portable receive system sensitivity -33.7 dB above 1 uamp/meter
12 dB SINAD
Vehicular receive system sensitivity -27.0 dB above 1 uamp/meter
12 dB SINAD
BaseStation receive system sensitivity -49.3 dB above 1 uamp/meter
12 dB SINAD
Thermal Noise floor -120.3 dB above 1 uamp/meter
Repeaterfrequency spacing 10% or 75 kHz, whichever is greater
condition: no degradation in receiver sensitivity

The next step is to define the environmental parameters

Seam; determine scatter gain, conductor attenuation, and quasi-conductor-free attenuation
Type of mine; choose AC/trackless haulage, this determines that "face area" noise along conductors is appropriate
Conductor ensemble surge impedance; choose Z_o = 50 ohms
Average "close" separation of antenna centers from the conductor center
Portables 2 meters
Vehiculars 3 meters
Base Station transmit coupling level; choose -28 dB limit
Base Station receive antenna-to-conductor spacing 0.3 meters
Conductor carrier current SWR design criteria; choose ± 10 dB
Attenuation increase per conductor tap; choose 3 dB/single tap
5 dB/double tap

The remainer of this section will address the choice of the Upper Freeport seam, with:

$$G_s = \frac{4.042\, f_{MHZ}^{0.181}}{Z_0 \sqrt{R_T}\; R_R} = \frac{0.03958}{\sqrt{R_T}}$$

α = 0.0213 dB/meter @ 1 MHz
= 0.01896 dB/meter @ 890 kHz
Face noise = -27.5 dB above 1 uamp/meter @ 890 kHz
Note: face noise and set noise for vehicular operation are near-equal @ 890 kHz

The next operation is to estimate system margin for several types of operation vs lateral(transverse) range of the transmitter from the conductor assuming zero attenuation along the conductor ensemble. Also included is the system margin estimates for quasi-conductor-free operationvs range.The conductor proximity data must be prepared using separately the "remote" (scatter gain) and "close" (current coupling coefficient) theories, plotting curves prepared from these theories, and joining these curves in the transition region of lateral range.

An example of theconductor-proximity computations for Vehicular-Vehicular (V-V) operation is as follows:

Remote Coupling-

R_T	G_s	H_i	$G_s \times H_i$	E_s	MARGIN
15	-43.3	+44.4	+1.1	-27.5	+28.6
30	-46.3	+32.4	-13.9	-27.5	+13.6
45	-48.1	+18.8	-29.3	-27.5	- 1.8
60	-49.3	+ 5.4	-43.9	-27.5	-16.4
90	-51.0	-16.6	-67.6	-27.5	-40.1

where, R_T is the range from the transmit antenna center to the conductor ensemble center in meters
G_s is the scatter gain ratio in dB
H_i is the incident magnetic field strength in dB above 1 uamp per meter from an NIA = 0.82 transmitting source
E_s is the face noise level in dB above 1 uamp per meter

Close Coupling-

	R_T	R	C_R	C_T	I_L	E_s	I_I	I_s	MARGIN
	15			-79.3	0.49	-27.0	52.9	1.5	+36.0
	7.5			-67.2	0.49	-27.0	213.8	1.5	+48.1
rib edge	4.83			-59.6	0.49	-27.0	513.1	1.5	+55.7
	3.9	0.57	-42.7	-55.9	0.49	-27.0	785.6	1.5	+59.4
	2.9	0.30	-37.1	-50.3	0.49	-27.0	1496.9	1.5	+65.0
	2.0	0.22	-34.4	-47.6	0.49	-27.0	2042.1	1.5	+67.7

where, R_T is the range from the transmit antenna center to to the conductor center, meters

C_R is the receive current coupling coefficient obtained from graphical field mapping, n = 64, derived from Figure

Note: C_R is used only to calibrate C_T as the field mapping coefficient is deemed more accurate than the simple formula and the relationship between transmit and receive coefficients is relatively constant

C_T is the transmit current coupling coefficient computed as

$$C_T = \frac{C_T(\text{ field formula})}{C_R(\text{ field formula})} \times C_R \text{ (field mapping)}$$

<u>then</u> scaled as $1/R_T^2$ for ranges beyond the rib edge (taken to be located at 4.83 meters lateral range)

I_L is the transmit antenna current, amps

E_s is the set-noise sensitivity level in dB above 1 uamp/meter

I_1 is the conductor carrier current in amps

I_s is the conductor noise current in dB above 1 uamp

The quasi-conductor-free margin is computed using the Upper Freeport seam measured results (Margaret #11) shown in Figure 33 adjusted for actual NIA and the corresponding face-noise or set-noise field strength levels.

The system margins for zero dB line attenuation (along the monofilar conductor) and quasi-conductor-free margins, each for several Radio Terminal Element types, are given in Section 5.1 in Figure 30 . Note in this figure that the "remote" and "close" coupling regions are identified along with the transition region in which the $1/R^2$ fall-off was assumed. The actual field strength fall-off for short lateral ranges beyond the rib edge, once the "remote" and "close" curves are joined, is less than the $1/R^2$ law assumed. The actual fall-off law in this region is very close to the $1/R^{1.58}$ law measured in the Rose Valley mine.

To enable the conductor proximity results to be easily used for system analysis, the curves of the above referenced figure are used to prepare curves of lateral range away from conductors vs range along the monofilar conductor string. Continuing the example of Vehicular operation in the Upper Freeport seam, curves are shown in Figure 25 for V-V operation with 0 dB corresponding to no taps, 5 watts, ± 10 dB SWR, and 3-meter fixed range of one radio terminal from the conductors at 890 kHz. These same curves can be used for V-B operation by taking the +16 dB curve to correspond to 0 dB. Using the curves, a contour of lateral range vs range along conductors can be plotted. If there are taps/branches involved, the curves are used as follows:

> for single wide-spaced taps (for example) the attenuation is estimated to be 3 dB/tap. If there are 4 taps between the transmitter and receiver for V-V operation, we would use the -12 dB curve; for V-B operation, we would use a +4 dB curve.

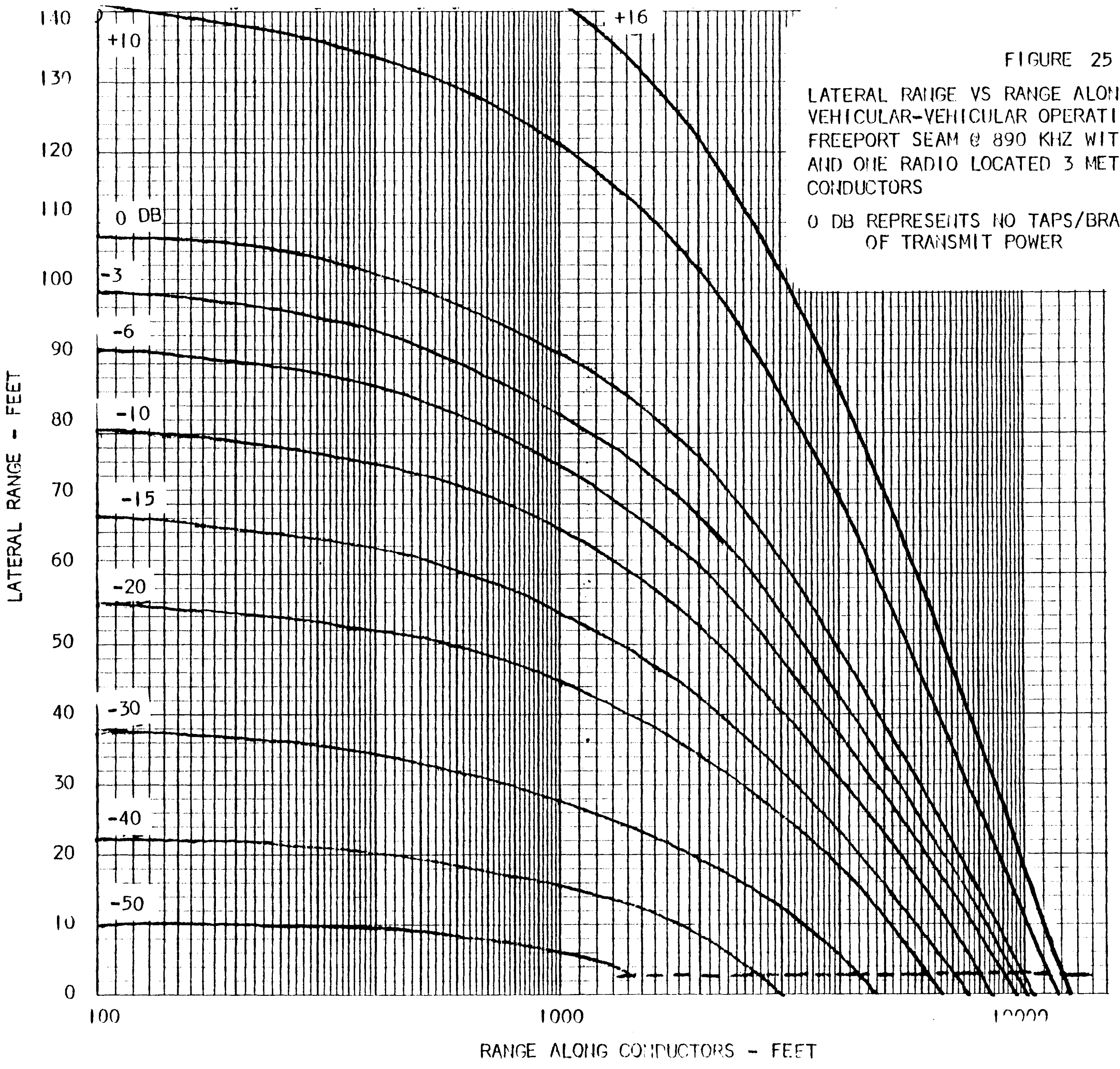


FIGURE 25

LATERAL RANGE VS RANGE ALONG CONDUCTORS FOR VEHICULAR-VEHICULAR OPERATION IN UPPER FREEPORT SEAM @ 890 KHZ WITH ± 10 DB SWR AND ONE RADIO LOCATED 3 METERS FROM CONDUCTORS

0 DB REPRESENTS NO TAPS/BRANCHES FOR 5 WATTS OF TRANSMIT POWER

3.5 STRAWMAN SYSTEM DESIGN EXAMPLE

The preceeding calculations and analysis technique will be used in this subsection to estimate the Vehicular-Vehicular(V-V) and Vehicular-Base Station (V-B) operation in a particular mine; the Helvetia Coal Co. Lucerne #8 mine. This mine is familiar to PMSRC and is one for which the Bureau has an ongoing communications system test-bed program under cooperative agreement with the mine. The author visited this mine during August, 1977, and performed a an electromagnetic field mapping at medium frequency in this mine at that time. A summary mine map was prepared illustrating the status of mining operations, topologically, together with assumed area coverage regions for a trackless haulage MF system as of late 1977. Also shown are areas to be mined in the near future. This summary mine map is given as Figure 26. The assumed desirable communication coverage area is given by crosshatching on the figure. The lateral haulageway coverage area assumed was governed by communications in all fresh air entries, with the result

145 feet lateral range in South Mains
80 feet lateral range in North Mains
80 feet lateral range in sections.

The required area in sections included the size of the room-and-pillar areas extending about 400 feet on either side of a center line. The acceptable lateral range coverage in haulageways has been taken to be

80 feet in all haulageways, nominal
65 feet minimum
Note: the 65 feet minimum reflects the range required 1 entry removed from the conductor entry as the pillars are nominally on 65-foot centers.

Also shown on the map are rectangular areas showing rooms to be mined (as of that date) and dashed lines representing expected future extensions of the AC power cable and beltways.

The exact operational status of Lucerne #8 as of the time of this writing and that expected at a future time when demonstration hardware will be available for testing are not known. The following analysis, therefore, assumes all dashed AC power cable and beltway extensions to be active.

The analysis of V-B and V-V transmission in this mine are illustrated respectively in Figures 27 and 28 . The lateral range predicted at selected locations adjacent to the coverage contours and especially near the ends of particular power cable/beltway runs.

The V-B coverage illustrates the placement of Line Amplifier or Remote Base repeaters to give mine-wide coverage.

Specific conclusions afforded by this analysis include:

(1) The maximum through-the-seam (quasi-conductor-free) range expected is 108 meters (354 feet).

(2) If both Radio Terminal Elements of a pair are closely coupled to conductors, approximate mine-wide coverage is expected V-B, and Vehiculars will be able to communicate with other Vehiculars (V-V) over either the North Mains or the South Mains areas without repeaters.

(3) V-V coverage without repeaters with one radio located one entry removed from conductors is limited to about 2500 feet or less.

(4) V-V coverage without repeaters with both radios removed one entry from conductors is limited to about 1000 feet or less.

(5) With a Base Station assumed to be located in the portal area, and to maintain nominal one-entry-away coverage with vehicles, a Line Amplifier or a Remote Base Repeater is required 2500 feet away in the North Mains and 3750 feet away in the South Mains.

(6) With therepeater spacing of (5), a lateral range in excess of 80 feet is assured over all haulageway Mains, in excess of 60 feet at the end of all Butt Sections (Submains) panels, and in excess of 50 feet at the extreme ends of room-and-pillar area assuming the AC cable runs this far (this should assure at least 60-65 feet of lateral range at all section power center locations).

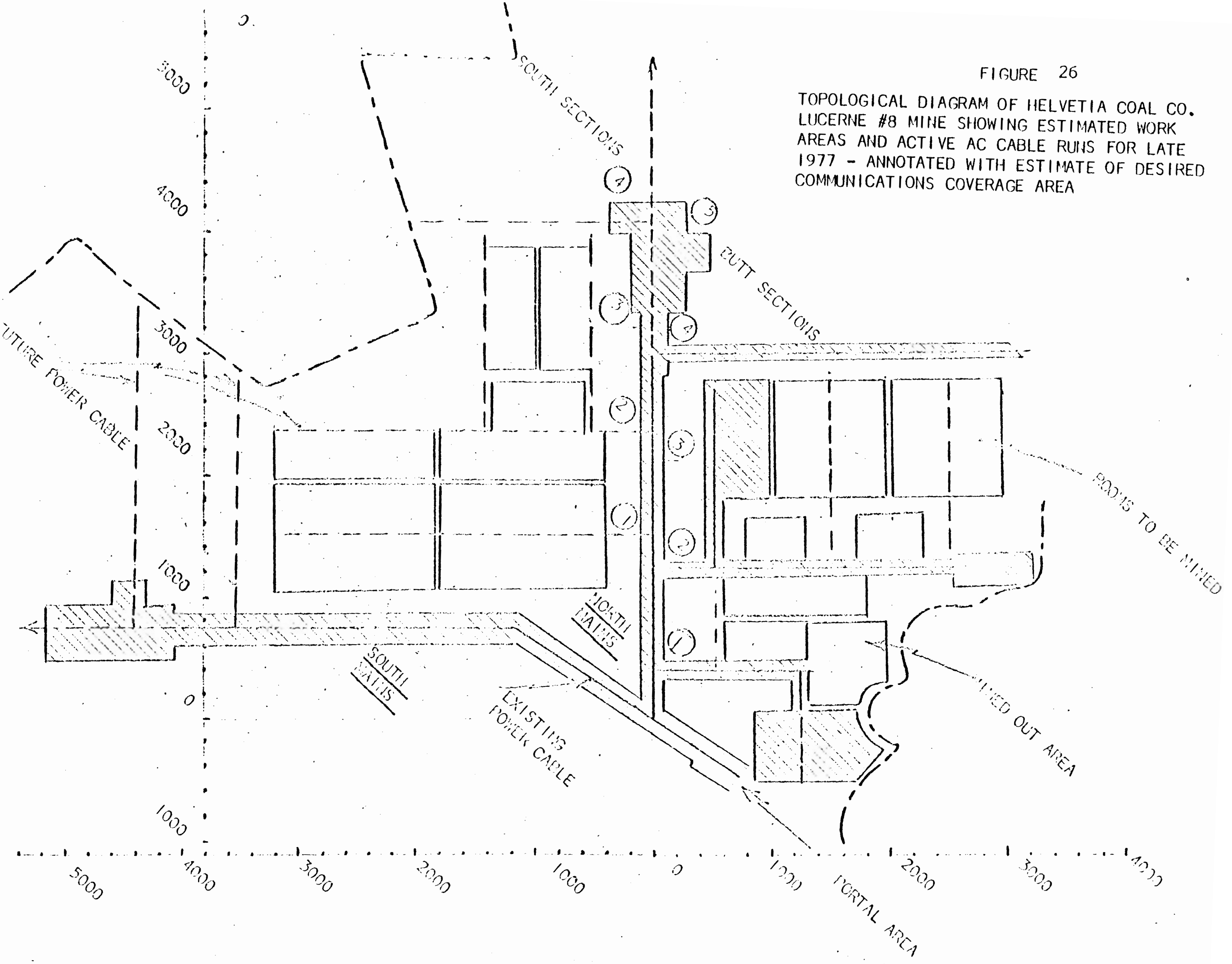


FIGURE 26

TOPOLOGICAL DIAGRAM OF HELVETIA COAL CO. LUCERNE #8 MINE SHOWING ESTIMATED WORK AREAS AND ACTIVE AC CABLE RUNS FOR LATE 1977 - ANNOTATED WITH ESTIMATE OF DESIRED COMMUNICATIONS COVERAGE AREA

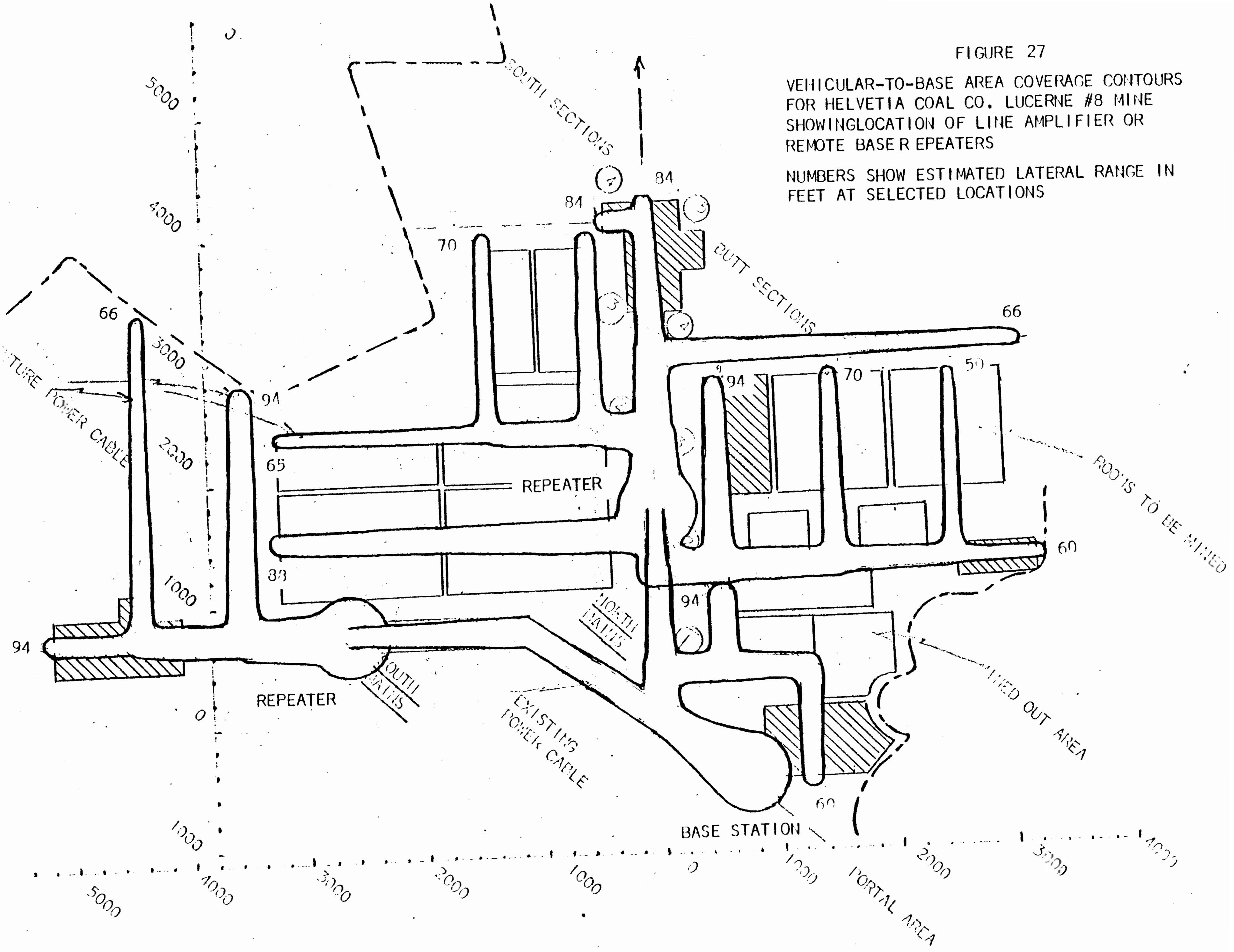


FIGURE 27

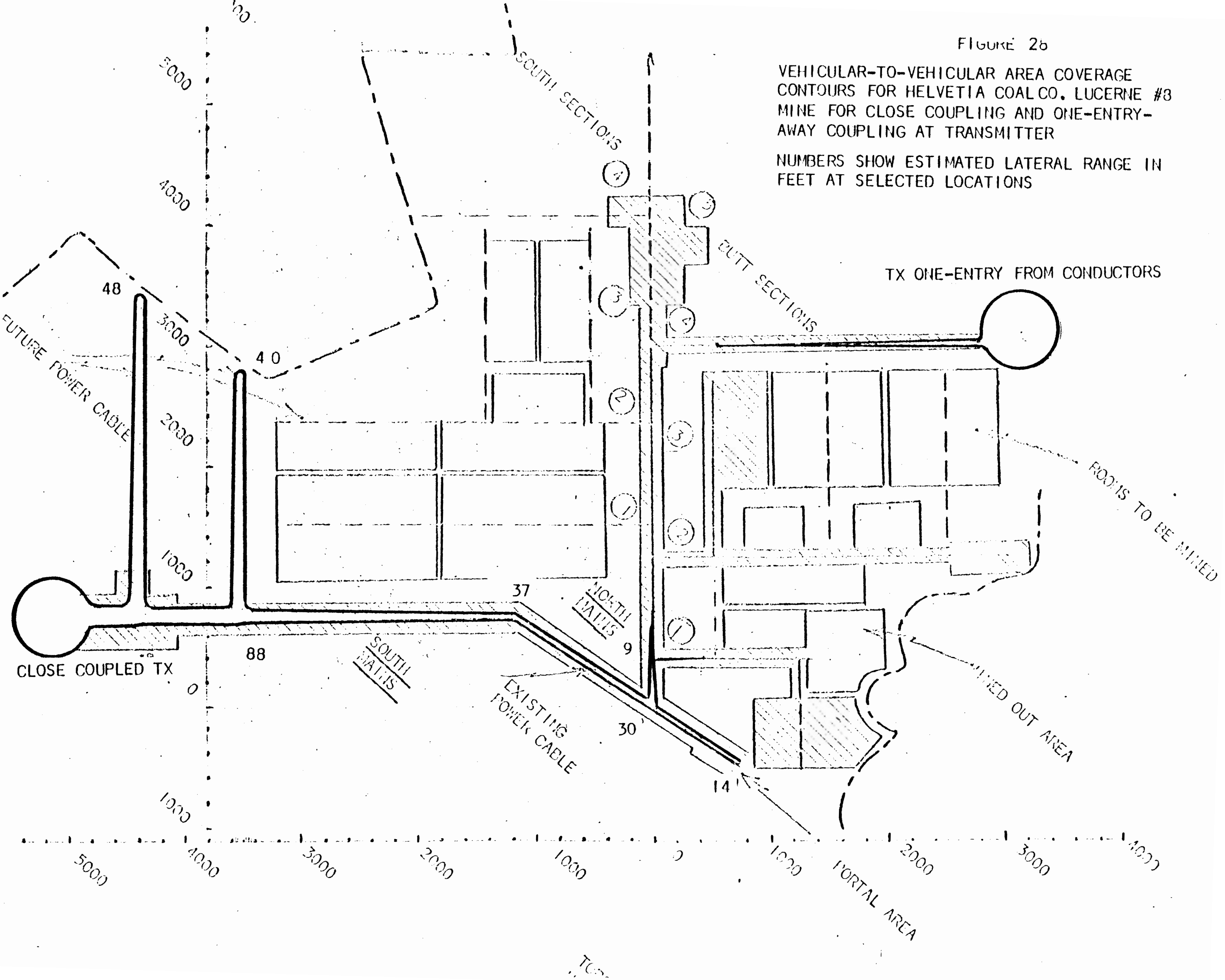
VEHICULAR-TO-BASE AREA COVERAGE CONTOURS FOR HELVETIA COAL CO. LUCERNE #8 MINE SHOWINGLOCATION OF LINE AMPLIFIER OR REMOTE BASE R EPEATERS

NUMBERS SHOW ESTIMATED LATERAL RANGE IN FEET AT SELECTED LOCATIONS

FIGURE 26

VEHICULAR-TO-VEHICULAR AREA COVERAGE CONTOURS FOR HELVETIA COAL CO. LUCERNE #8 MINE FOR CLOSE COUPLING AND ONE-ENTRY-AWAY COUPLING AT TRANSMITTER

NUMBERS SHOW ESTIMATED LATERAL RANGE IN FEET AT SELECTED LOCATIONS



4.0 MF SYSTEM ELEMENT SPECIFICATIONS

Functional details of the System Elements required for a mine-wide trackless haulage medium frequency wireless communication system, generally meeting the requirements for a general purpose system applicable to many types of underground mines, have been given in Section 3.0. The purpose of this section is to summarize certain key functional and performance specifications for System Elements which are apparent as a natural consequence of the technology.

4.1 PORTABLE RADIO

Functional-

Provision for channelized operation; changing channels requiring simple adjustments internal to the radio not accessable via the external controls)

Per channel:

Reception on a single frequency, f_1 , the lower frequency of an f_1/f_2 pair

Transmit on either f_1 (simplex) or f_2 (half duplex), as selectable on the front panel

Frequency plan- provides for 3 selectable front panel operating modes

"Local"	transmit	f_1 no CTCS
	receive	f_1 no CTCS
"Base"	transmit	f_1 CTCS
	receive	f_1 no CTCS
"Remote"	transmit	f_2 CTCS
	receive	f_1 no CTCS

single tone encoder for use with both transmit frequencies

provision for addition of CTCS tones for

"Call Alert"	home address tone decoder
"Private Line"	blocking tone decoder on all radios; blocking tone encoder on selected supervisory radios

Provision for externally adjustable squelch

Provision for flexible, tuned, bandolier antenna with direct connection to transmitter power amplifier; also for f_1/f_2 switching. For switching:

normally on f_1, f_2 Tx "mode" selection on front panel enables switch "line" to antenna, actual switching controlled by Tx key

Antenna "retuning" for other channels controlled by internal adjustments

Normal operation via audio transducer on Portable case and PTT key on Portable case; provision for speaker mike operation with noise cancelling microphone; front panel keying control and sidetone for tone signalling

General-

Frequency Range minimum of 4 channels per radio	300 - 1000 kHz
Modulation Type	FM voice (m = 1) or tone signalling
Intrinsically safe design	
Power Supply	rechargable nickel-cadmium battery with minimum 8-hour battery life; or external cap lamp battery
Environmental	-20 deg C to +60 deg C sealed waterproof high-impact plastic case

Transmitter-

Power Level	5 watts
Modulation	narrowband FM voice (m = 1) ± 3 kHz deviation
Exciter	phase-locked-loop type for voice modulated waveform: 12 dB/octave roll-off above 10 kHz 10 dB bandwidth 8 kHz nominal
Frequency Stability	0.0082% or better
Signalling Tone	single tone in 700-100 Hz range
VSWR Protection	transmitter shall be operable into any load without damage

Receiver-

Noise Figure	6 dB maximum
Receive System Sensitivity (including antenna)	-33.7 dB or better above 1 uamp/meter
Image and IF Rejection	Better than 60 dB relative to 0.2 uvolt

AGC	accomodate impulse noise environment with maximum 3 dB gain reduction 18 dB peaks above background noise of 333-1000 usecond duration every 2-6 milliseconds
Tone Signalling	300 Hz nominal IF filter activating visual indicator and sidetone

Antenna-

Flexible, multi-turn loop antenna attached directly to radio

Nominal Area	0.208 m^2
Nominal NA	1.25 m^2 turns
NIA from 5-watt Tx	1.5 nominal

Provides fixed resistive padding to 12 kHz minimum 3 dB bandwidth, fixed resistance adequate to provide current limiting for intrinsic safety from a 4.5 VDC battery, per UL-913

4.2 VEHICULAR RADIO

Same specifications as for Portable radio with the following changes/ exceptions:

Provision for rigid external antenna, connection via untuned length of 50-ohm coaxial cable plus a switching key line

Normal operation via PTT noise conceling external microphone and a separate externally mountable loudspeaker

Power Supply	13.6 VDC from vehicle battery or 270 VDC trolley sourve; 12 volt internal standby battery with automatic switchover provision

Receiver-

Receive System Sensitivity (including antenna)	-27.0 dB or better above 1 uamp/meter

Antenna-

Rigid multi-turn loop antenna with self-contained matching and f_1/f_2 switching; antenna winding protected by an electrostatic shield

Nominal Area	0.139 m^2
Nominal NA	1.67 m^2 turns
NIA from 5-watt Tx	0.82

Provides fixedresistive padding inherent in winding to 12 kHz minimum

3 dB bandwidth, the high impedance design providing inherent intrinsic safety protection from a nominal 12 VDC source

4.3 BASE STATION

Functional-

Provision for channelized operation; changing channels requiring simple adjustments internal to the radio(not accessable via the external controls)

Provision for multiple-link operation; direct transceive operation from Base Station location, provision for control or more than one additional Remote Base Repeater; separate loudspeakers for each link

Per channel:

Reception on either f_1, f_2, or baseband audio

Transmit oneither f_1, f_2, or baseband audio

Frequency plan- provides for 3 selectable front panel operating modes

"Local"	transmit	f_1 no CTCS
	receive	f_1 no CTCS
"Remote Base"	transmit	f_2 no CTCS, or baseband audio
	recieve	f_2 no CTCS, or baseband audio
"Remote/Mobile Unit"	transmit	f_2 CTCS
	receive	f_1 no CTCS

single tone encoder for use with both transmit frequencies

provision for additional CTCS tones for

"Call Alert"	home-tone encoders for each Portable/Vehicular radio on which Call-Alert is implemented
"Private Line"	blocking tone encoder; possible blocking tone decoder

Provision for externally adjustable squelch

Normal operation viatable microphone with integral or foot-actuated PTT switch; separate loudspeakers for direct transceive and each Remote Base link

Provision for direct termination of mine phone line taps for Remote Base link control

Provision for either monofilar mode (conductor coupled) or direct radiation on transceive link; or simultaneous excitation of both conductor coupled and direct radiation transmission

General-

Same as for Portable/Vehicular except for

Power Supply	115 VAC local source with 12 VDC battery backup
Environmental	-20 deg C to +60 deg C table-mountable case

Transmitter-

Same as for Portable/Vehicular

Receiver-

Same as for Portable/Vehicular except for

Receive System Sensitivity (including antenna)	-49.3 dB or better above 1 uamp/meter when base station antenna is used

Antennas-

Multi-turncurrent transformer for monofilar mode coupling with self-contained matching and switching

N,A,I parameters similar to Portable

Single-turn tuned antenna, tuned to f_1 only,

Nominal Area	14.4 m^2

4.4 REPEATER RADIOS

For all f_1/f_2 repeaters, the frequency separation per channel shall be a minimum of 10% or 75 MHz, whichever is greater

4.4.1 REMOTE BASE

Functional-

Option providing for either baseband audio or f_2 on control link to Base Station via bifilar phone line mode

Per channel:

Frequency plan-

receive	f_2 no CTCS, or baseband audio on wireline link f_1 CTCS on MF link

	transmit	f_2 no CTCS, or baseband audio on wireline link
		f_1 no CTCS on MF link
Power Supply		117 VAC with rechargable battery backup for 24-hour operation at 15% repeat, 85% standby, with an external indication of battery condition

For test and maintainance, provision for local operation from internal handset with noise cancelling microphone

General-

Same as for Portable/Vehicular except for power supply (per above) and

Sealed waterproof and rust resistant wall-mountable case

Transmitter-

Same as for Portable/Vehicular except for:

Exciter filtering	Provide additional filtering of phase-locked-loop exciter output so as to achieve a minimum of 24 dB/octave roll-off above 10 kHz
Note:	composite voice modulation spectrum and exciter filtering should provide a roll-off above 10 kHz of 36 dB/octave

Receiver-

Same as for Portable/Vehicular

Antenna-

Single-frequency-tuned current transformer (f_1 only) with N,A,I parameters similar to Portable antenna

4.4.2 LINE AMPLIFIER, LINE COUPLER, & REMOTE REPEATERS

Specifications are the same as for Remote Base except for

Functional-

Connectivity to antennas/current transformers differ for each type; the reader is referred to Section 3.2.2 for these differences.

Per channel:

Frequency plan-

receive	f_2 CTCS
transmit	f_1 no CTCS

4.5 ALTERNATIVE ANTENNAS/CURRENT TRANSFORMERS

Consisting of:

Terminated dedicated wire coupler

Magnetic current probe (similar to Stoddard current probe)

the characteristics of these devices are a matter of detailed design, if used, and remain to be determined

Fixed multi-turn loops

these antennas/transformers will have parameters similar to those of the portable antenna; these representing "field-expedient" coupling devices.

4.6 PASSIVE LINE EXTENDERS

Specifications to be determined

5.0 COMPENDIUM OF FOUNDATION TECHNOLOGY ELEMENTS

This section presents summaries of data, theories, measurements,and analyses comprising the foundation resources for the characterization of MF systems. Familiarity with the contents of this section will provide the reader with an overview of the state of MF technology. This overview can serve as a baseline for extension of the technology.

To enable MF system performance computations in coal mines, data and/or theories are required in the following topical areas:

- Quasi-conductor-free transmission - magnetic field strength vs range in coal seams vs frequency
- Magnetic field coupling to mine wiring conductors - current coupling coefficient between transmit/receive antennas and conductors vs transverse range and frequency for the seams of interest
- Monofilar mode conductor attenuation - the attenuation of a "matched" transmission system vs frequency for each seam of interest
- Monofilar mode standing wave ratio and junction losses - estimates made from conductor-proximity field strength measurements and from magnetic field strength mappings
- Bifilar mode phone line attenuation characteristics including junction losses - assumed to be seam invariant
- Electromagnetic noise - quasi-conductor-free and monofilar mode noise estimates related to the type of mine, mining operations, and to operationally significant locations in mines; also, bifilar mode noise on phone lines
- Type of modulation used and noise bandwidth
- List of typical practical equipment parameters
    - NIA and NA of antennas vs power level; effect of antenna orientation
    - Operating power level
    - Operating frequency
- Receive system sensitivity

Data will be provided in each of these topical areas in the subsections to follow.

5.1 MF PROPAGATION

The measurement of quasi-conductor-free magnetic field strength vs range and frequency and analytical fitting of the measured data to a model has been performed in 11 mines comprising 7 seams and roughly (ref. 1-15) 4 different geographic areas. The analyses of the measured data has provided values for the major constituitive parameters of rock (overburden/underburden) and coal seam conductivities. The quasi-conductor-free transmission characteristics can, thus, be determined either from measured curves or from model computations for the coal seams which have been addressed.

The quasi-conductor-free transmission has been characterized as a quasi-TEM mode between lossy parallel plates (the overburden and underburden rock) with a lossy dielectric (the coal seam).(ref. 24,28-31)

The analytical results provide the basis for computing conductor coupling via a technique called scatter gain which considers the complete end-to-end path (transmitter to receiver) effects,(ref. 9, 15) excluding monofilar mode attenuation, from a remote transmitter (far enough away so that the TEM mode characteristics are established). The scatter gain is the ratio of the received magnetic field strength in proximity to a conductor located near the receiver to the field strength in absence of the conductor. The range assumes the receiver lies directly on the shortest path from the transmitter to the conductor (perpendicular to an assumed long straight conductor ensemble). The receiver can, then, be translated along the conductor ensemble taking account of monofilar mode attenuation. The scatter gain ratio is an easily measurable quantity and the validity of its use has been carefully established in three mines.

The monofilar mode conductor attenuation is estimated from the quasi-static limit of the propagation constant of the lowest order TM mode on a lossy coaxial transmission line which has been conformally mapped into a conductor over an infinite plane interface. Use of this analytical technique again depends on knowledge of the rock conductivity as derived from the theoretical propagation model.(ref.23)

Close coupling to conductors vs transverse range from the conductors (assumed to be within the entry containing the conductors) depends on the detailed geometry of the entry crossection and on the conductor configuration occurring in the entry, including vehicles (if any). The current coupling coefficient is different, of course, for the transmit and receive cases. An important factor is that the maximum practical transmit,monofilar mode coupling achievable is bounded. Coupling measurements have been performed for a simulated in-mine situation on the surface, and coupling coefficients have been computed for complex entry crossectional geometries using graphical field mapping. Bridging the close and remote coupling cases correctly requires estimates of the geometric fall-off law for moderately short distances away from the conductor(s). An analysis based on comparing measured and computed results has been performed and composite close/ remote coupling curves have been developed.

A prime motivator for early propagational R & D in the MF frequency range has been the selection of optimum or near-optimum operating frequencies. There is an optimum frequency range both for quasi-conductor-free and conductor-proximity operation from a remote transmitter. A fortuitous aspect of MF transmission is that the near-optimum operating frequencies are nearly the same for the two types of transmission. The frequency dependence characteristics have been estimated by performing system calculations and determining the maximum communication range for each frequency; the optimum frequency being that which gives maximum comonnication range.

The bifilar mode attenuation characteristics of a phone line in a large AC mine have been measured and analyzed and these results(re. 49) suggest that statistically in long runs with many taps/junctions, the junction losses approach 3 dB/tap; also, moderate runs give about 6 dB/tap. On a per-tap basis, the losses can be significantly greater.

MF propagation information and characteristics given in this subsection will proceed from the most general and/or most significant to the most detailed.

5.1.1 SUMMARY CHARACTERISTICS

The maximum communication range characteristics vs frequency for the several seams provide the broadest overview of potential MF system local area performance coverage without the use of repeaters or of bifilar mode transmissions. Much greater range, even without repeaters, cab be achieved, of course, with close coupling to conductors. These maximum communication range curves were developed considering a transmit NIA of 2.5 and receive system sensitivities commensurate with the Collins prototype FM radios in median-mine-noise and set-noise-limited operation; a set-noise limited sensitivity of -35.5 dB above 1 uamp/meter being assumed. These curves should be used to compare seams and ranges generically. The original NIA of 2.5 was that expected from a 20-watt Portable into a separate(not integral) antenna matched to 50 ohms. We have since determined that a Portable radio NIA of 1.5 developed from an approximate 5-watt transmiiter using a more efficient antenna is more representative. Also, we have since determined that median-mine-noise, while an easily definable statistic, has limited operational significance. Curves of maximum communication range are shown in Figure 29 representing all seams in which testing was conducted.

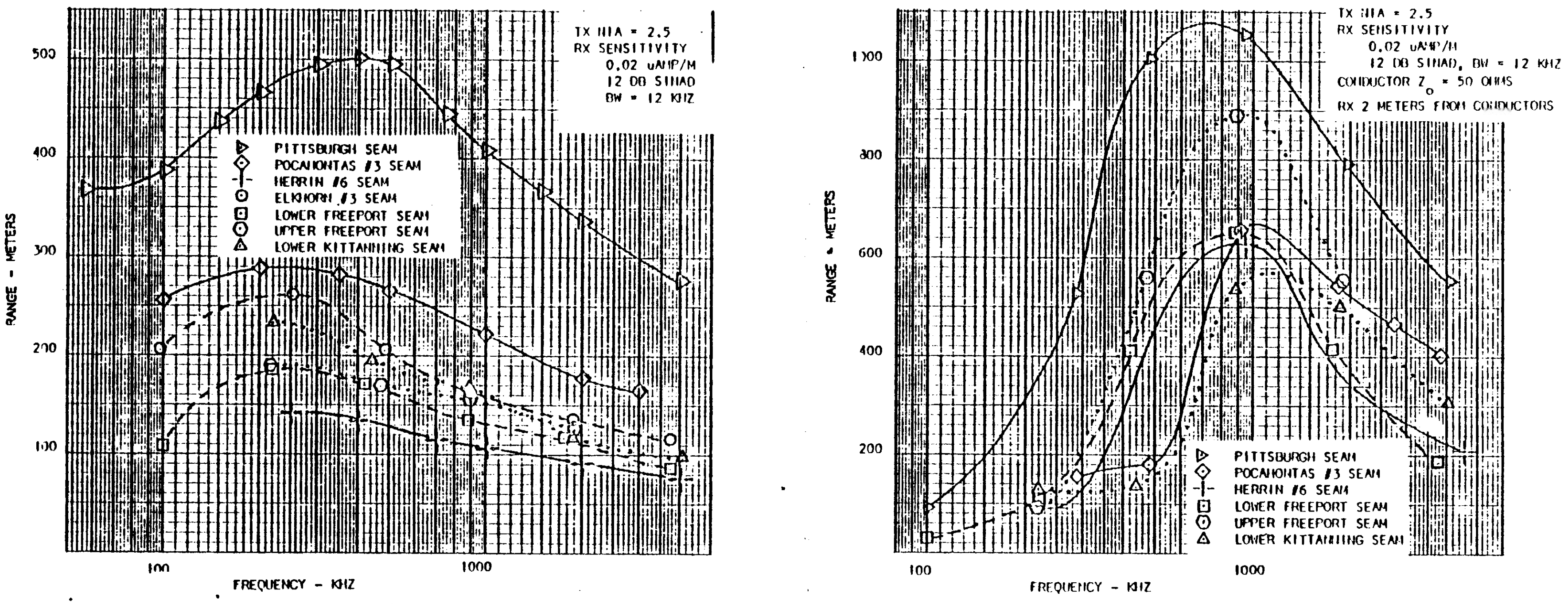
The ultimate communication range is more nearly apparent by considering curves of excess signal margin vs either range between radios employing direct through-the-seam transmission in absence of conductors; or else, vs transverse range from an assumed monofilar conductor ensemble (bridging between the close and remote coupling theories). Curves have been prepared for the Upper Freeport seam for several combinations of Radio Terminal Elements without repeaters at a representative frequency of 890 kHz.

FIGURE

SUMMARY MAXIMUM COMMUNICATION RANGE DATA
FOR SEVEN COAL SEAMS UNDER MEDIAN-MINE-
NOISE AND SET-NOISE LIMITS

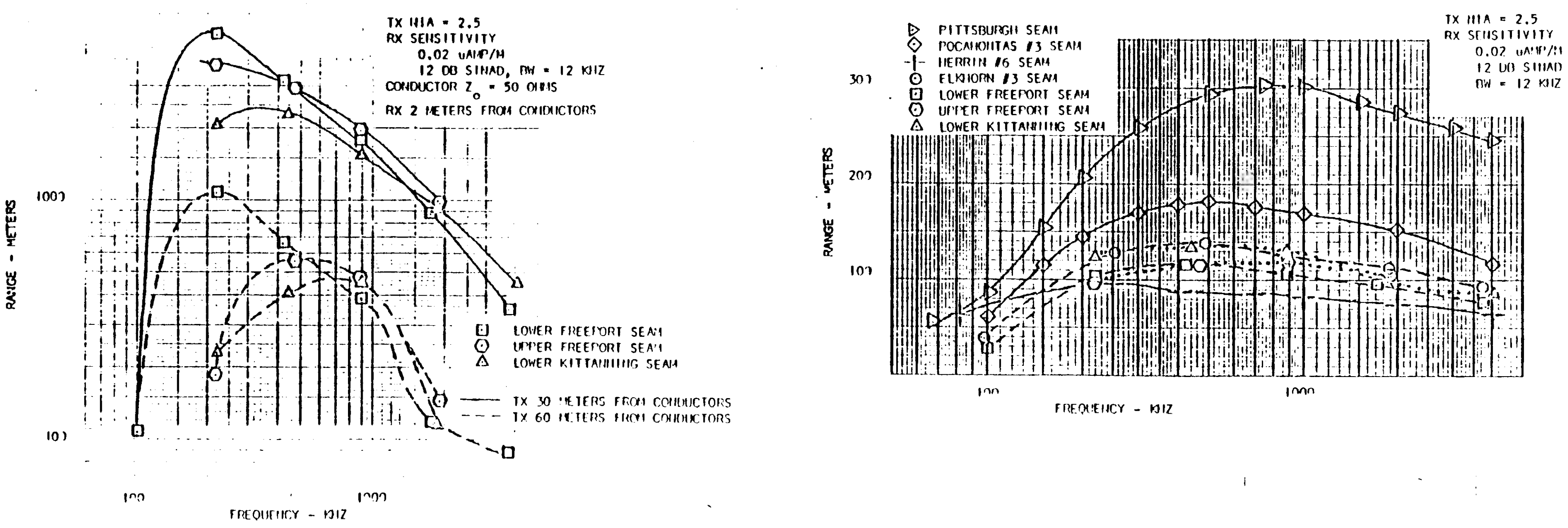
MAXIMUM COMMUNICATION RANGE VS OPERATING FREQUENCY IN CONDUCTOR-FREE AREAS OF COAL MINES - SET NOISE LIMIT

MAXIMUM COMMUNICATION RANGE VS OPERATING FREQUENCY IN COAL MINES IN PROXIMITY TO CONDUCTOR(S) - TX LOCATED REMOTELY - MEDIAN MINE NOISE



MAXIMUM COMMUNICATION RANGE VS OPERATING FREQUENCY IN COAL MINES IN PROXIMITY TO CONDUCTOR(S) - TX LOCATED REMOTELY - SET NOISE LIMIT

MAXIMUM COMMUNICATION RANGE VS OPERATING FREQUENCY IN CONDUCTOR-FREE AREAS OF COAL MINES - MEDIAN MINE NOISE



The excess signal margins from these curves are convertable to range estimates employing a known factor of dB/meter of attenuation along a monofilar conductor ensemble or else known dB/100 feet factor for direct through-the-seam transmission. Assumptions embodied in the curves include:

• Power level	all RTE's 5 watts
• Portable	transmit NIA = 1.5, I = 1.2 amps
• Vehicular	" " "0.82, I = 0.49 amps
• Base Station	tightly coupled, 1.2 amps in current transformer -28 dB transmit current coupling coefficient (max coupling limit)
• Receiver range	Portable avg. 2 meters from conductors Vehicular avg. 3 meters from conductors
• Noise type	face-noise-limited or set-noise-limited typical for AC mines Portable face-noise-limited Vehicular set-noise-limited (face and set noise levels nearly equal)
• Receive sensitivity (6 dB noise figure receiver assumed)	Portable -33.7 dB above I uamp/meter Vehicular -27.0 " " " " " Base Station-49.3 " " " " "

The excess signal margin vs range curves are given in Figure 30 . For conductor attenuation, the factor is 0.01896 dB/meter @ 890 kHz. For quasi-conductor-free attenuation, the factor is 17.7 dB/100 feet. The excess signal margins are, of course, higher for direct through-the-seam transmission because there is no coupling loss into and out of conductors. Once current is coupled into conductors (the monofilar mode is excited), then the attenuation along the conductors is much lower. A summary of quasi-conductor-free attenuation rates vs frequency for 6 seams and 10 mines is given in Figure 31 .

A final summary of expected maximum monofilar mode communication ranges follows, as computed for the Upper Freeport seam.

For a continuous conductor string without standing waves or taps/branches and for Radio Terminal Elements with the above cited close coupled spacings for both transmitter and receiver (antenna centers to conductor ensemble center), the maximum communication ranges along the conductor string are:

(I) In an AC mine

Radio type	Range Along Conductors
P-P	4019m (2.50 miles)
V-V	3428m (2.13 miles)
B-B	6096m (3.79 miles)

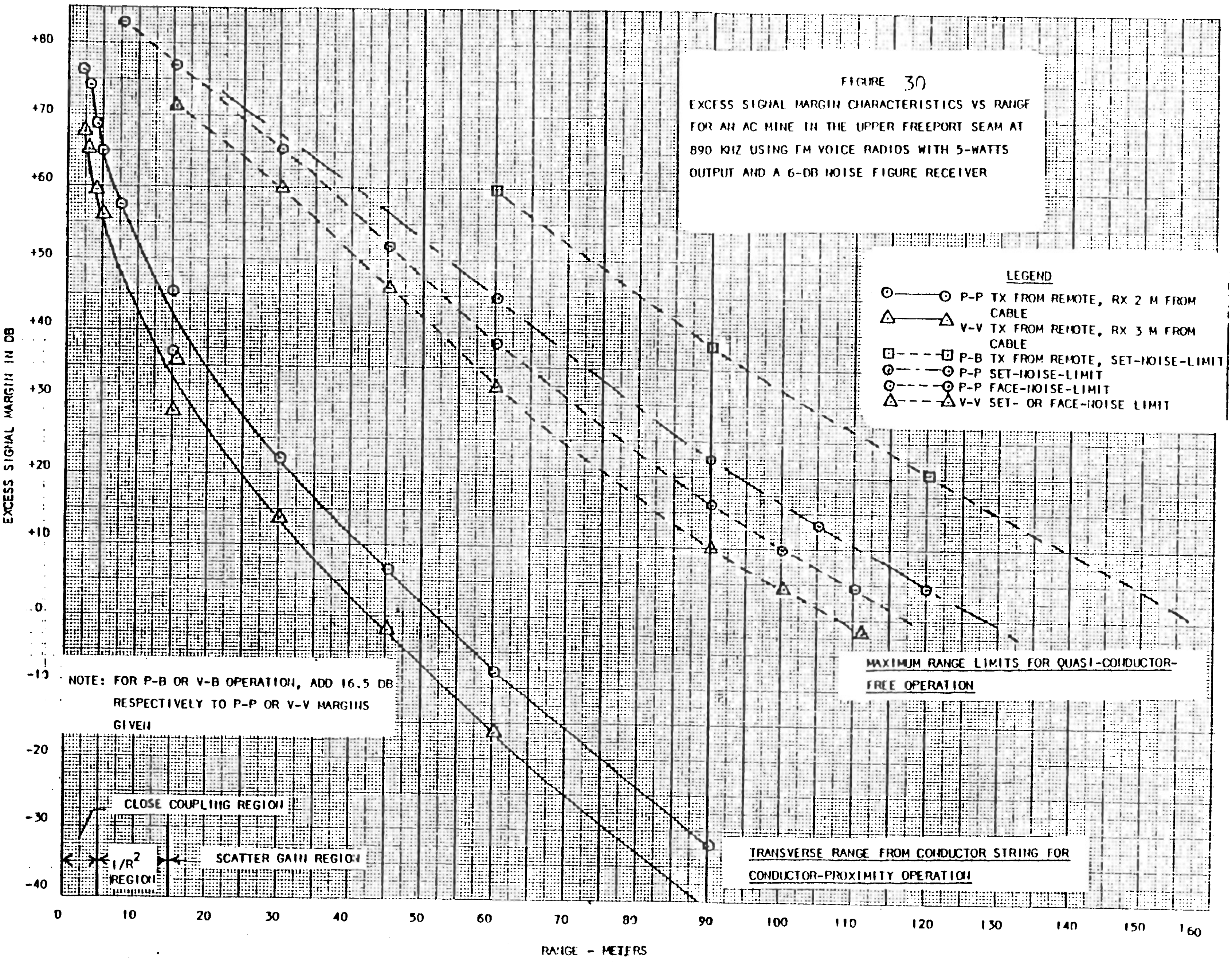


FIGURE 30

EXCESS SIGNAL MARGIN CHARACTERISTICS VS RANGE FOR AN AC MINE IN THE UPPER FREEPORT SEAM AT 890 KHZ USING FM VOICE RADIOS WITH 5-WATTS OUTPUT AND A 6-DB NOISE FIGURE RECEIVER

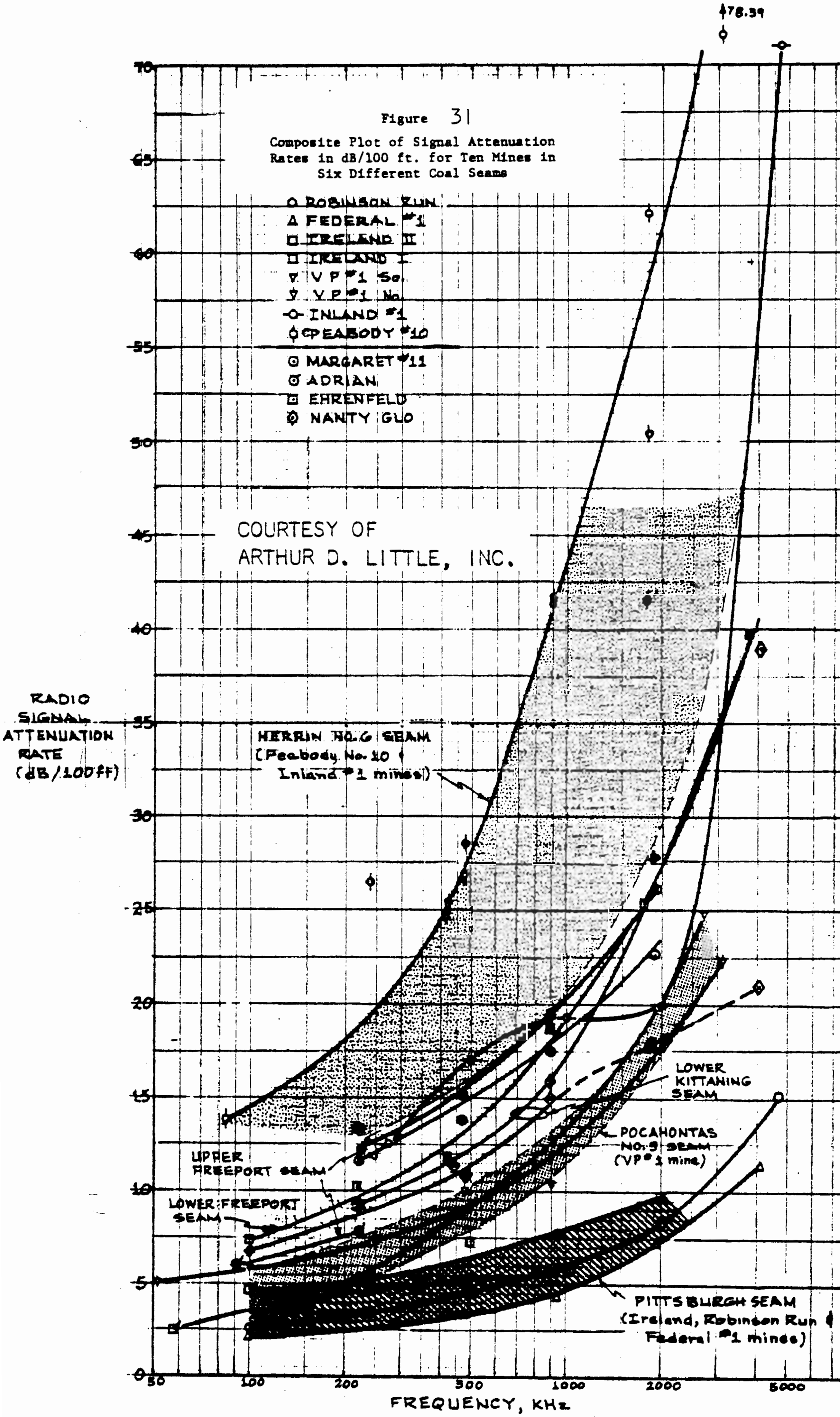


Figure 31

Composite Plot of Signal Attenuation Rates in dB/100 ft. for Ten Mines in Six Different Coal Seams

(2) In a DC mine w/belt haulage

Radio type	Range Along Conductors
P-P	2727m (1.69 miles)
V-V	2136m (1.33 miles)
B-B	4805m (2.99 miles)

(3) In a DC mine with tracked haulage & no trolleyphone interferance

Radio type	Range Along Conductors
P-P	1013m (0.63 miles)
V-V	422m (0.26 miles)
B-B	3091m (1.88 miles)

the mine type differences being the noise levels experienced; these operationally significant types to be shown in Section 5.2.

Close examination of a great deal of magnetic field strength data has resulted in the following expectations for monofilar mode standing wave levels and tap losses:

For standing waves

± 3 dB in long haulageways with tap spacing of at least 1000 feet

± 4 dB in submains with approximate 400 foot tap spacings, single tap

± 6 dB in submains with approximate 400 foot tap spacings, double tap

± 6 dB in conductor-dense areas in sections near center of sections

± 10dB in conductor-dense tracked, belted sections with service tracks

Note: ± 10 db was also measured in Lucerne #8

For taps/junctions

-3 dB/single tap

-5 dB/double tap

For a large scale overview, the following average conditions may be assumed:

I each NS or EW mains split	-3 dB
I each submain split	-3 dB

(A) For haulage areas

2 each double taps	-10 dB	
or		plus ± 6 dB VSWR
4 each single taps	-12 dB	

giving an aggragate approximate loss to consider of -22 to -24 dB with respect to a flat untapped line

(B) For section areas

2 each single taps	-6 dB	plus ± 10 dB VSWR

giving an aggragate approximate loss of -22 dB

Note that the assumption for both haulageway and section areas produce about the same loss estimate of -22 dB in signal margin due to the combination of standing wave and junction effects under average conditions. Under this assumption, the closely coupled maximum communication range estimates along conductor strings without repeaters becomes:

(1) In an AC mine

Radio type	Range Along Conductors
V-B	3138m (1.95 miles)
P-P	2859m (1.78 miles)
V-V	2268m (1.41 miles)
B-B	4937m (3.06 miles)
P-B	3729m (2.32 miles)

(2) In a DC mine w/belt haulage

P-P	1566m (0.97 miles)
V-V	976m (0.61 miles)
B-B	3644m (2.26 miles)
P-B	2437m (1.51 miles)
V-B	1846m (1.15 miles)

Bifilar mode conductor attenuation for flat twisted pair phone lines, without taps/branches,vs frequency is summarized for different wire guages in Figure 32 . Phone line attenuation measurements at MF frequencies including taps, to-date, are limited in extent, but indicate the effects of statistical averaging over long runs at high MF frequencies (near 1000 kHz) for a large number of taps. In average terms, for numbers of taps greater than 1-2 and less than about 10, the available data indicates 6 dB/tap (based on current split). For larger numbers of taps, the average attenuation per tap is expected to approach 3 dB/tap.

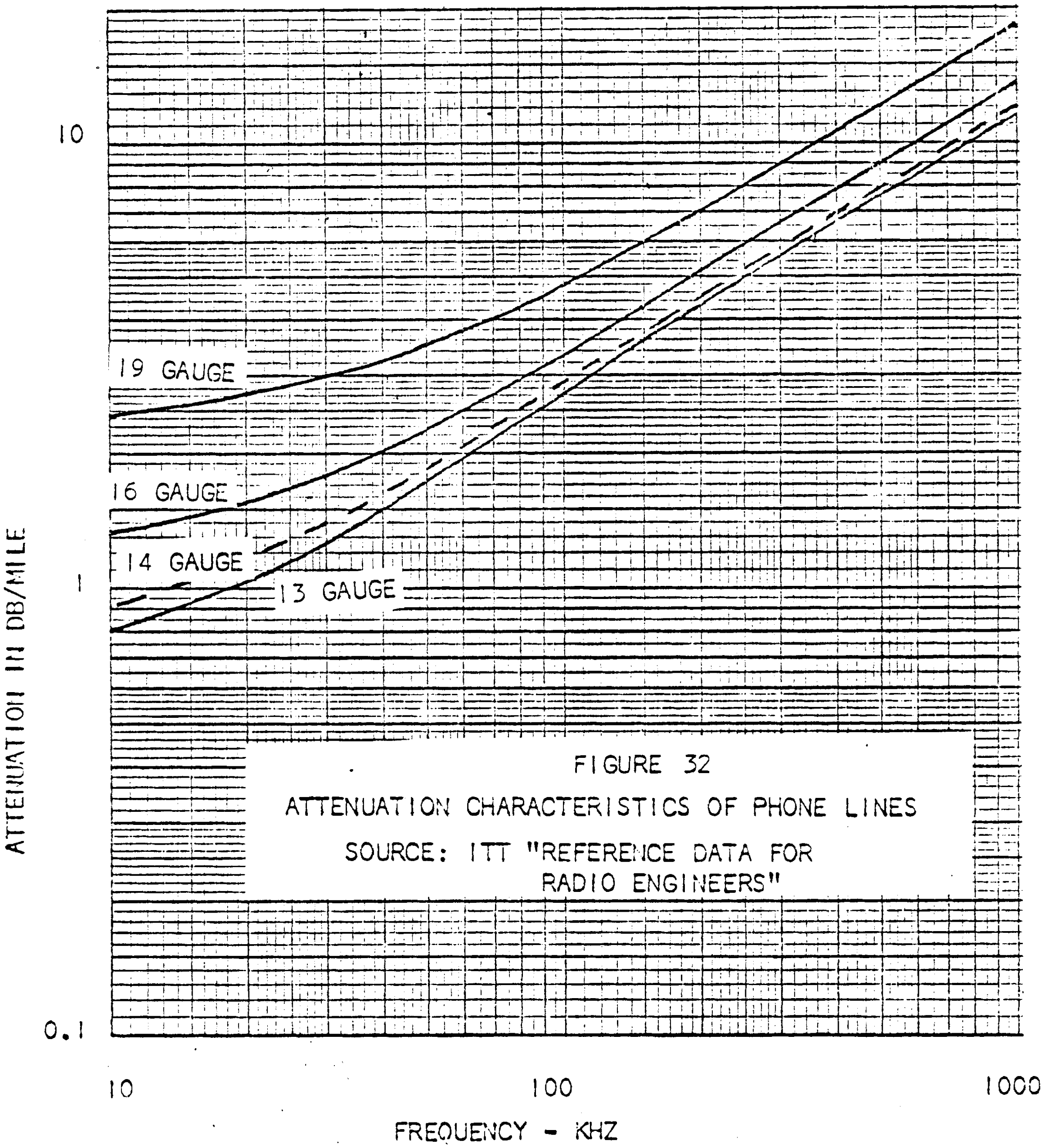


FIGURE 32

ATTENUATION CHARACTERISTICS OF PHONE LINES

SOURCE: ITT "REFERENCE DATA FOR RADIO ENGINEERS"

5.1.2 QUASI-CONDUCTOR-FREE TRANSMISSION & CONSTITUITIVE PARAMETER ANALYSIS

Representative families of curves of magnetic field strength vs range and frequency for each of the seven seams are given in Figure 33 for an assumed transmit NIA = 2.5. These curves may be used directly to obtain range attenuation estimates.

The quasi-TEM mode 3-layer model analysis put forth by Arthur D. Little, Inc. consists of: (ref. 24,28)

$$H = \frac{NIA\ (\alpha^2 + \beta^2)^{3/4}}{(8\pi)^{\frac{1}{2}}\left[(h + \delta_r)^2 + \delta_r^2\right]^{\frac{1}{2}}} \cdot \frac{e^{-\alpha r}}{\sqrt{r}} \quad \text{amperes/meter}$$

Where, r is the range in meters

α, β are respectively the real and imaginary parts of the propagation constant given by

$$\alpha + i\beta = \sqrt{\left[\frac{2(1 + 1)}{\sigma_r \delta_r} + i w \mu_0 h\right]\left[\frac{\sigma_c}{h} + \frac{i w \epsilon_c}{h}\right]}$$

h is the seam height in meters

δ_r is the overburden/underburden skin depth in meters

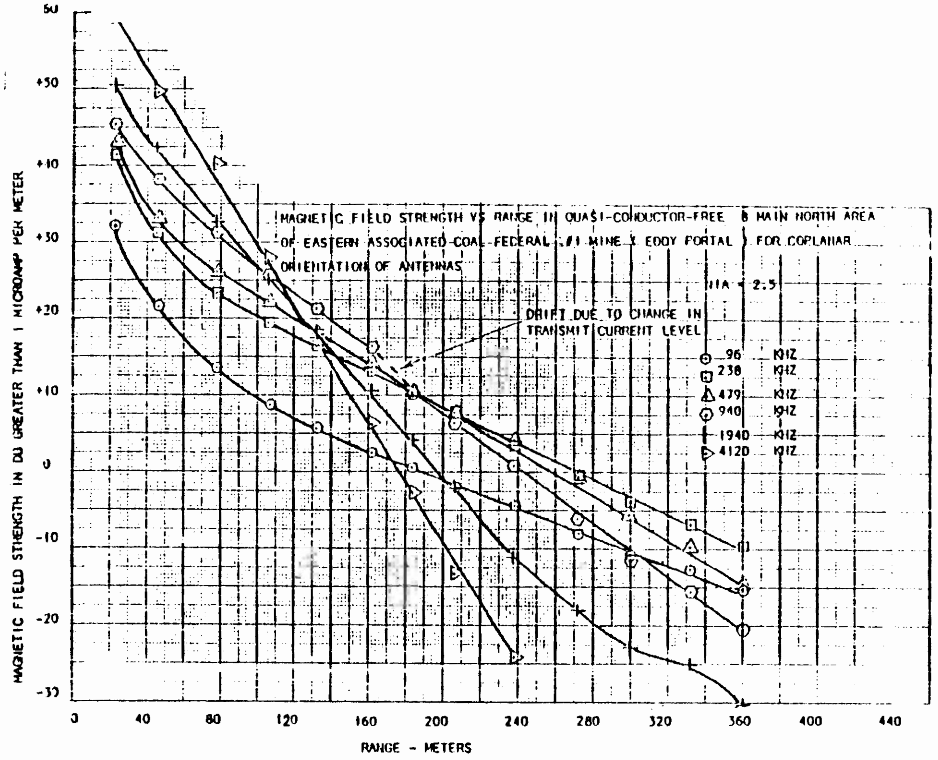
$$= \left(\frac{1}{\pi u_0\ f \sigma_r}\right)^{\frac{1}{2}}$$

σ_c, σ_r are respectively the coal seam and rock conductivities

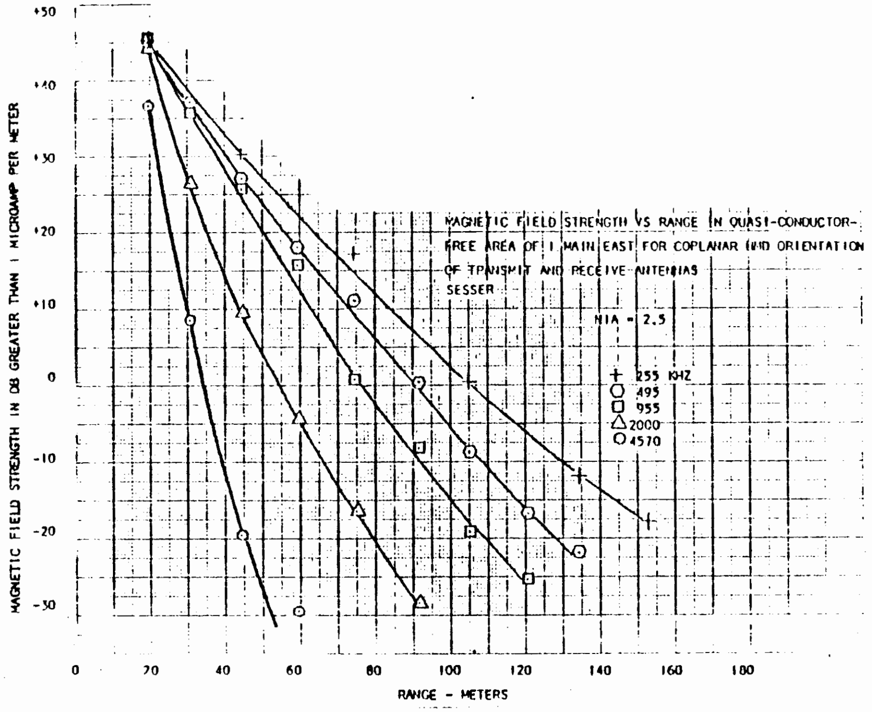
ϵ_c is the dielectric constant of the coal taken to be always equal to 6

This model has been demonstrated to reproduce the measured data accurately beyond a range of approximately $1/\alpha$ in the 200-900 kHz range to within about 6 dB or less.

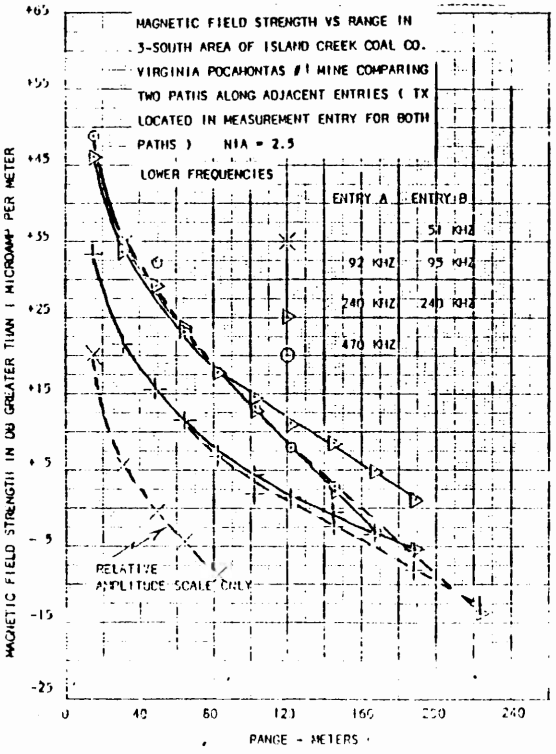
Careful curve fitting has produced the following rock and coal seam conductivities as shown in Table I . Using the above formulation with representative conductivities from the table for the seam of interest, range attenuation estimates may be made in lieu of using the measured data.



PITTSBURGH SEAM



HERRIN #6 SEAM



COPLANAR ORIENTATION OF BOTH ANTENNAS

——— Measured in Entry A; one entry away from air line (to the left proceeding away from transmitter) and one entry away from solid coal block (to the right proceeding away from transmitter)

— — —Measured in Entry B adjacent to solid coal block and two entries away from air line (to the left proceeding away from transmitter)

POCAHONTAS #3 SEAM

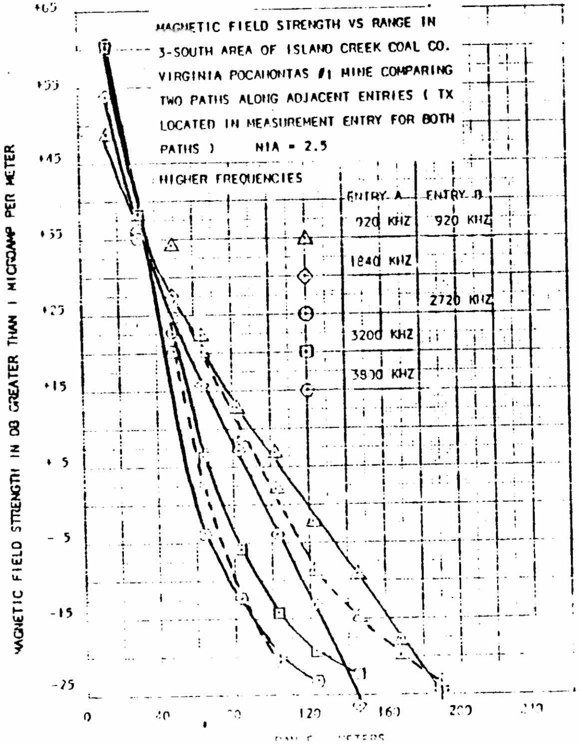
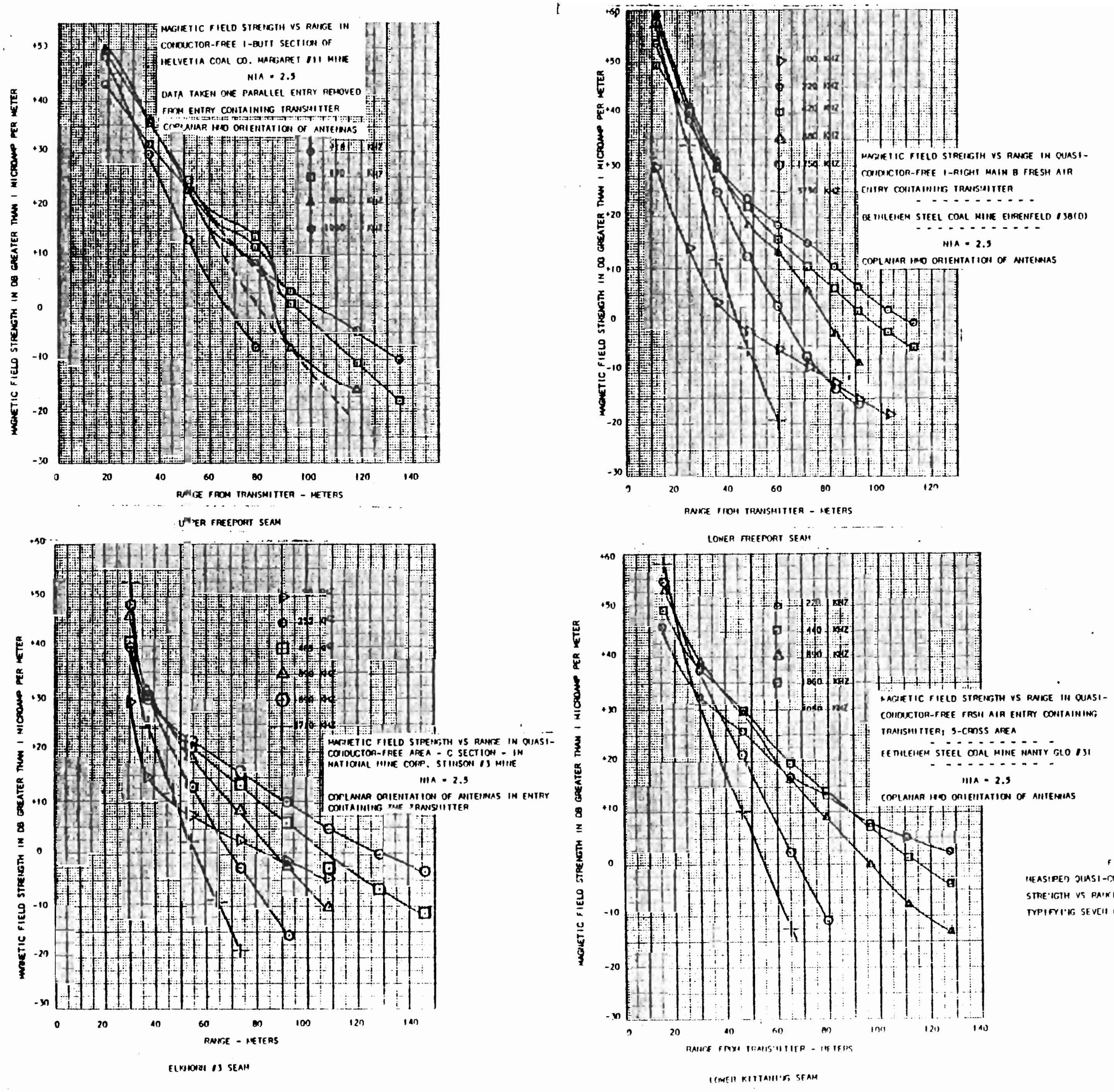


FIGURE 33
MEASURED QUASI-CONDUCTOR-FREE MAGNETIC FIELD STRENGTH VS RANGE AND FREQUENCY CURVES TYPIFYING SEVEN COAL SEAMS



MAGNETIC FIELD STRENGTH VS RANGE IN CONDUCTOR-FREE I-BUTT SECTION OF HELVETIA COAL CO. MARGARET #11 MINE

NIA = 2.5

DATA TAKEN ONE PARALLEL ENTRY REMOVED FROM ENTRY CONTAINING TRANSMITTER

COPLANAR HMD ORIENTATION OF ANTENNAS

UPPER FREEPORT SEAM

MAGNETIC FIELD STRENGTH VS RANGE IN QUASI-CONDUCTOR-FREE I-RIGHT MAIN B FRESH AIR ENTRY CONTAINING TRANSMITTER

BETHLEHEM STEEL COAL MINE EHRENFELD #38(D)

NIA = 2.5

COPLANAR HMD ORIENTATION OF ANTENNAS

LOWER FREEPORT SEAM

MAGNETIC FIELD STRENGTH VS RANGE IN QUASI-CONDUCTOR-FREE AREA - C SECTION - IN NATIONAL MINE CORP. STINSON #3 MINE

NIA = 2.5

COPLANAR ORIENTATION OF ANTENNAS IN ENTRY CONTAINING THE TRANSMITTER

ELKHORN #3 SEAM

MAGNETIC FIELD STRENGTH VS RANGE IN QUASI-CONDUCTOR-FREE FRSH AIR ENTRY CONTAINING TRANSMITTER; 5-CROSS AREA

BETHLEHEM STEEL COAL MINE NANTY GLO #31

NIA = 2.5

COPLANAR HMD ORIENTATION OF ANTENNAS

LOWER KITTANNING SEAM

FIGURE 33 (CONT)

MEASURED QUASI-CONDUCTOR-FREE MAGNETIC FIELD STRENGTH VS RANGE AND FREQUENCY CURVES TYPIFYING SEVEN COAL SEAMS

TABLE I

DERIVED COAL SEAM AND ROCK CONDUCTIVITIES FROM CURVE FITTING TO MEASURED DATA USING THE ADL 3-LAYER ANALYSIS MODEL

COAL MINE	SEAM	CONDUCTIVITY COAL, MHO/M	CONDUCTIVITY ROCK, MHO/M
IRELAND (1ST VISIT)	PITTSBURGH	2.0×10^{-4}	1.09
		1.4×10^{-4}	0.3
IRELAND (2ND VISIT)	PITTSBURGH	1.0×10^{-4}	0.054
INLAND STEEL #1(SESSER)	HERRIN #6	1.0×10^{-3}	0.22
CONSOL #95 (ROB. RUN)	PITTSBURGH	0.3×10^{-4}	0.085
FEDERAL #1 (EDDY)	PITTSBURGH	0.26×10^{-4}	0.084
VP #1	POCAHONTAS # 3	3×10^{-5}	0.01 3-SOUTH, ENTRY A
		3×10^{-5}	0.0077 3-SOUTH, ENTRY B
		6×10^{-5}	0.017 2-NORTH, #1 PLOW
PEABODY #10	HERRIN #6	4×10^{-3}	0.3 1MAIN SOUTH, 1ST WEST 2ND NORTH
		2.5×10^{-3}	0.3 1-SOUTH 5½ EAST/ 1-SOUTH JUNCTION
MARGARET #11	UPPER FREEPORT	1.6×10^{-4}	0.013 TX, RX IN SAME ENTRY
		1.2×10^{-4}	0.006 TX, RX ONE ENTRY APART
ADRIAN	UPPER FREEPORT	3.4×10^{-5}	0.0019
NANTY GLO	LOWER KITTANING	6.2×10^{-5}	0.0072 5-CROSS
		6.6×10^{-5}	0.011 MAIN N
EHRENFELD	LOWER FREEPORT	6.3×10^{-5}	0.0054
STINSON #3	ELKHORN #3	3.0×10^{-5}	0.0041

The quasi-TEM mode of transmission is excited using the HMD (horizontal magnetic dipole)orientation of the transmit and receive loop antennas which is that with the loop planes oriented vertically. The maximum coupling between transmit and receive antennas is obtained when the loop antennas are further oriented so that they are coplanar. This geometry is illustrated in Figure 34 . The least coupled set of antenna orientations are with both antennas VMD (vertical magnetic dipole) with the loop planes horizontal. One would expect that if both antennas were oriented HMD but with the loop planes perpendicular, there would be no coupling. This is not the case, however, and this type of orientation produces coupling typically 11 dB below the optimum coplanar case. All further discussions of quasi-conductor-free transmission will assume the optimum coplanar antenna orientations.

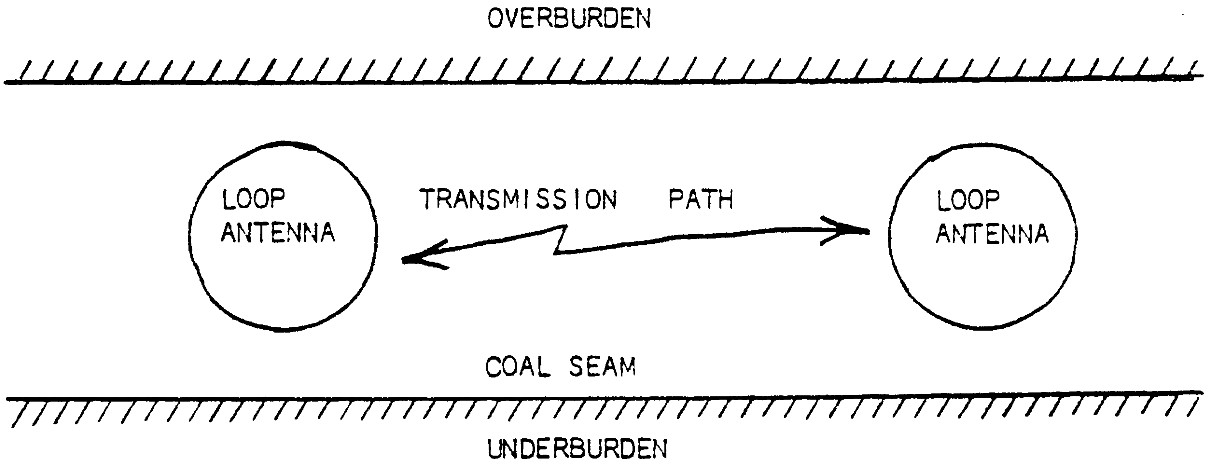


FIGURE 34

COPLANAR LOOP ORIENTATION GEOMETRY FOR OPTIMUM TRANSMISSION USING QUASI-TEM COAL SEAM MODE

5.1.3 CONDUCTOR PROXIMITY TRANSMISSION

The simplest technique for computing the communication range in the presence of conductors involves the use of the scatter gain ratio. This ratio is that of the magnetic field strength at the receiver with the conductor(s) present to that with the conductor(s) absent. When the transmitter and receiver lie on a straight line path which is perpendicular to the conductor string, as illustrated in Figure , the scattered field strength, compared to the minimum required field strength in the presence of noise, gives the signal margin available to overcome conductor attenuation when the receiver is, then, translated along the conductor(s). When the receiver is translated so far that the aggragate attenuation along the conductor string equals the signal margin, then the maximum range is reached for the particular set of distances chosen for the transmitter and receiver away from the conductor(s). The "full" scatter gain formula, derived using ADL's 3-layer model as a basis, is given by:

$$G_S = \frac{11.97}{Z_o \left(h + \delta_r \right) \sqrt{R_T}\, R_R \left(\alpha^2 + \beta^2 \right)^{\frac{1}{4}}}$$

Where, R_T is the range from the remote transmitter antenna center to the conductor string center in meters .
R_R is the comparable range for the receive antenna
α, β are the real and imaginary components of the propagation constant previously defined
Z_o is the surge impedance of the monofilar transmission line which, in most instances, is close to 50 ohms in value

Simple "short formula" scatter gains have been derived which reflect a (ref.9.15) minor correction, if necessary, to achieve agreement between computed and measured data. The short formula scatter gain ratio is of the form:

$$G_S = \frac{F_1 \; F_2}{Z_o \sqrt{R_T}\; R_R}$$

Where, F_1 expresses the frequency dependence of the full formula
F_2 expresses the frequency dependence correction to achieve agreement with the measured scatter gain frequency dependence (if necessary)

A collection of the particular seam short formulas for the scatter gain ratio is given in Table 2 . The following steps are involved in the computation of magnetic field strength in the presence of conductors:

TABLE 2

SUMMARY OF SHORT FORMULAS FOR SCATTER GAIN CALCULATION VS COAL SEAM

SEAM	FORMULA
PITTSBURGH	$G_S = \dfrac{9.53}{Z_o\sqrt{R_T}\ R_R}$
POCAHONTAS #3	$G_S = \dfrac{3.76\ f_{MHZ}^{0.075}}{Z_o\sqrt{R_T}\ R_R}$
HERRIN #6	$G_S = \dfrac{7.0\ f_{MHZ}^{0.25}}{Z_o\sqrt{R_T}\ R_R}$
LOWER FREEPORT	$G_S = \dfrac{4.324\, f_{MHZ}^{-0.374}}{Z_o\sqrt{R_T}\ R_R}$
UPPER FREEPORT	$G_S = \dfrac{4.042\, f_{MHZ}^{0.181}}{Z_o\sqrt{R_T}\ R_R}$
LOWER KITTANNING	$G_S = \dfrac{2.634\, f_{MHZ}^{0.2071}}{Z_o\sqrt{R_T}\ R_R}$

(1) Choose ranges, R_T and R_R, of the transmit and receive antennas respectively from the conductor(s); the shortest possible perpendicular distances

(2) Obtain the magnetic field strength at the conductor location assuming the conductor to be absent, using R_T as the range (quasi-conductor-free field strength curves; or else, ADL's model), properly scaled to account for the actual transmit NIA

(3) Multiply the field strength of (2) by the scatter gain ratio (or add dB) as computed for the seam of interest from the table

(4) Reduce the field strength of (3) by the attenuation corresponding to the translation distance, if any, of the receive antenna location along the conductor from the shortest path location

The monofilar mode conductor attenuation is given approximately by the following normalized attenuation constant expresion:

$$\alpha/k = \frac{\pi/8}{\left[\ln\frac{2a}{a_i}\left(\ln\frac{2a}{a_i} - \ln\frac{2.517}{\delta r}\right)\right]^{\frac{1}{2}}}$$

Where, a is the distance from the conductor center to an assumed flat infinite conducting interface (distance to the rock predominates)
a_i is the conductor radius

Taking $k = 2\pi/\lambda$ and multiplying by 8.686 to change nepers to dB, the attenuation constants are readily expressible in dB/meter at any particular frequency of interest.

Short formulas for the particular seam attenuation constants are given in Table 3 using $a/a_i = 9$ and $Z_o = 50$ ohms.

Except for very short ranges constituting close coupling, the optimum orientation of the remote transmitting antenna for conductor coupling is with the loop plane perpendicular to the conductor.

To illustrate the values typically taken on by the scatter gain ratio and to show correspondance to measured data, particular comparisons of measured and computed scatter gain are given in Table 4 .

TABLE 3

SUMMARY OF SHORT FORMULAS FOR CONDUCTOR ATTENUATION VS COAL SEAM (BASED ON SINGLE CONDUCTOR GEOMETRY)

SEAM	FORMULA
PITTSBURGH	α = 0.02665 DB/M @ 1 MHZ
POCAHONTAS #3	α = 0.02277 DB/M @ 1 MHZ
HERRIN #6	α = 0.02916 DB/M @ 1 MHZ
LOWER FREEPORT	α = 0.02130 DB/M @ 1 MHZ
UPPER FREEPORT	α = 0.02171 DB/M @ 1 MHZ
LOWER KITTANNING	α = 0.02171 DB/M @ 1 MHZ

NOTE: ASSUME α IS PROPORTIONAL TO FREQUENCY

TABLE 4

COMPARISONS OF MEASURED AND COMPUTED SCATTER GAINS IN THREE MINES

COMPARISON OF MEASURED & COMPUTED SCATTER GAINS
MARGARET #11 MINE - UPPER FREEPORT SEAM

FREQ(KHZ)	R_T(M)	R_R(M)	MEASURED G_S(DB)	FULL FORM CALCULATED G_S(DB)	MEAS/CALC Δ(DB)	SHORT FORM CALCULATED G_S(DB)	MEAS/CALC Δ(DB)
900	4.3	0.25	-26.0	-15.6	10.4	NOTE: AC POWER CABLE MUST HAVE BEEN OPEN CIRCUITED NEAR THE MEASUREMENT AREA	
AC POWER "	14.0	0.25	-41.5	-20.7	20.8		
CABLE " ONLY	10.4	3.7	-57.5	-42.8	14.7		
"	28.4	0.25	-18.0	-23.8	5.8	-18.5	0.5
PHONE LINE	25.0	3.0	-39.5	-44.8	5.3	-39.5	0
& BELT SUPPORT "	9.8	0.25	-22.0	-19.1	2.9	-13.9	8.1

NOTE: CALCULATION ASSUMPTIONS

$h = 1.30$ M

$\sigma_c = 16 \times 10^{-5}$ MHO/M

$\sigma_r = 7.2 \times 10^{-3}$ MHO/M

$Z_o = 50$ OHMS, FULL FORMULA
25 OHMS, SHORT FORMULA

COMPARISON OF MEASURED & COMPUTED SCATTER GAINS
EHRENFELD #38 MINE - LOWER FREEPORT SEAM

FREQ(KHZ)	R_T(M)	R_R(M)	MEASURED G_S(DB)	FULL FORM CALCULATED G_S(DB)	MEAS/CALC Δ(DB)	SHORT FORM CALCULATED G_S(DB)	MEAS/CALC Δ(DB)
220	26.2	0.25	-21.0	-26.0	5.0	-18.5	2.5
470	"	"	-21.7	-25.1	3.4	-21.0	0.7
880	"	"	-28.5	-24.6	3.9	-23.0	5.5
220	20.4	5.8	-44.7	-52.2	7.5	-44.7	0
470	"	"	-47.0	-51.3	4.3	-47.2	0.2
880	"	"	-49.2	-50.9	1.7	-49.2	0

NOTE: CALCULATION ASSUMPTIONS

$h = 1.12$ M

$\sigma_c = 6.3 \times 10^{-5}$ MHO/M

$\sigma_r = 5.4 \times 10^{-3}$ MHO/M

$Z_o = 50$ OHMS

COMPARISON OF MEASURED & COMPUTED SCATTER GAINS
NANTY GLO #31 MINE - LOWER KITTANNING SEAM

FREQ(KHZ)	R_T(M)	R_R(M)	MEASURED G_S(DB)	FULL FORM CALCULATED G_S(DB)	MEAS/CALC Δ(DB)	SHORT FORM CALCULATED G_S(DB)	MEAS/CALC Δ(DB)
440	23.8	0.25	-31.0	-23.4	7.6	-28.8	2.2
890	"	"	-23.9	-22.9	1.0	-27.5	3.6
1860	"	"	-19.3	-22.7	3.4	-26.2	6.9
4050	"	"	-22.4	-22.7	0.3	-24.8	2.4
440	17.5	6.25	-56.0	-50.0	6.0	-55.4	0.6
890	"	"	-55.5	-49.5	6.0	-54.1	1.4
1860	"	"	-52.8	-49.3	3.5	-52.8	0
4050	"	"	-53.3	-49.3	4.0	-51.4	1.9

NOTE: CALCULATION ASSUMPTIONS

$h = 1.04$ M

$\sigma_c = 6.2 \times 10^{-5}$ MHO/M

$\sigma_r = 7.2 \times 10^{-3}$ MHO/M

$Z_o = 50$ OHMS

A different analysis is required for "close coupling" when the transmit and/or receive antennas are within the entry containing the conductor(s) or else generally within one entry of the conductor entry. For very close coupling within the conductor entry, the coupling coefficient is a function of the transverse crossectional details approximating the quasi-static field distribution over the crossection considering the antenna (transmit case) or the monofilar conductor (receive case) to be the "DC" source. For simple geometry where the distance from an assumed single conductor to the antenna center is smaller than the entry crossectional dimensions, the field fall-off is approximately 1/r and the corresponding transmit and receive current coupling coefficients are given by:

$$C_R = \frac{2\pi f \times 10^{-7} AN}{R\, r}$$

Where, R is the loop antenna series resistance, ohms
r is the range in meters
A is the antenna area in meters^2
N is the number of turns

$$C_T = \frac{2\pi f \times 10^{-7} AN}{2 Z_o\, r}$$

Where, Z_o is the monofilar line surge impedance
("matched monofilar line assumed)

A more detailed treatment of close conductor coupling will be given in Section 5.4. As a practical matter, the maximum coupling value for transmitting, C_T, is bounded and is of the order of -28 dB; this value having been confirmed both analytically and empirically.

Beyond the very close range, where the range is comparable to or greater than the entry crossectional dimensions and much greater than the separation between the monofilar conductor(s) and the nearest "return current" conducting surface, the field geometrically falls off at a much faster rate. Assymptotically, the field in this intermediate range can fall off at a $1/r^2$ rate because this is the rate at which the field of a line source imaged in a conducting interface falls off along the interface. Based on measurements performed in the Rose Valley mine, the geometric fall-off law was found to be $1/r^{1.58}$. Considering the summary data for the Upper Freeport seam previously shown in Figure , which bridged between the remote coupling and the close coupling, the composite curve falls off 14 dB between 7.5 and 15 meters (15 meters transverse range being the pivotal transition range for this seam). Computing the fall-off for $1/r^{1.58}\, e^{-\alpha r}$, taking α to be 17.7 dB/100 feet, the fall-off is 13.86 dB. The bridging between regions for the curves of Figure 30 assumed 1/r geometric fall-off to the edge of the entry and $1/r^2$ geometric fall-off beyond for the close coupling before the composite curve(s) was drawn.

Measurements have been performed in conductor-dense section area panels and in conductor-dense haulageways as excited from a central transmitter at one end of the area in oder to investigate the "area coverage" provided from multiple-excited conductor ensembles. This has been accomplished by measuring the field strength at many points; sufficient, in detail, to define mappings or contours of field strength. Such a set of measurements was performed in the Upper Freeport seam in the Helvetia Coal Co. Lucerne #8 mine. A field map for this mine is illustrated in Figure 36 .

A final consideration in the conductor-proximity transmission area is the expected performance of a Passive Line Extender. Assume that this extender is coupled into a monofilar conductor using a current transformer with the parameters of a Portable antenna and with a base station antenna at the input end, as shown in Figure 35 . Assume that the maximum coupling of -28dB is achieved with the current transformer. Consider the example to be appropriate for the Upper Freeport seam so that the greatest range at which a Portable can normally field-couple into the conductor is 54 meters. For this case, the excess signal margin above that required, M, is given by:

$$M = \frac{3.766 \times 10^4 \, w\mu A H_i}{\sqrt{R_{loop}} \; R_P}$$

Where, H_i is the incident magnetic field

A is the base station antenna area (one turn assumed), taken = 14.4 m^2

R_{loop} is the base station loop antenna series resistance taken = 66 ohms

R_P is the portable antenna series resistance taken = 3.5 ohms

The maximum range (between base station and portable antennas) to permit a usable signal to be coupled into the monofilar conductor is 68 meters, assuming no transmission line loss.

5.2 ELECTROMAGNETIC NOISE/INTERFERENCE

Noise representing operationally significant situations has only recently been obtained in the MF region for both monofilar mode and bifilar mode (ref.49 phone line transmission. Prior to this, the only available resource for MF noise was an extrapolation of lower frequency (below 200 kHz)(ref.43-47) monofilar mode noise data obtained by NBS .These extrapolations are illustrated in Figure 37 . Consequently, previous system performance estimates were made using median-mine-noise from this curve, conveniently defined as

$$H_{MMN} = 175.8 - 32.5 \log_{10} f(hz) \quad \text{dB above one microamp/meter in a 12 kHz bandwidth,} \quad \text{(ref.43)}$$

or set noise. Median-mine-noise was known to be pessimistic for use in

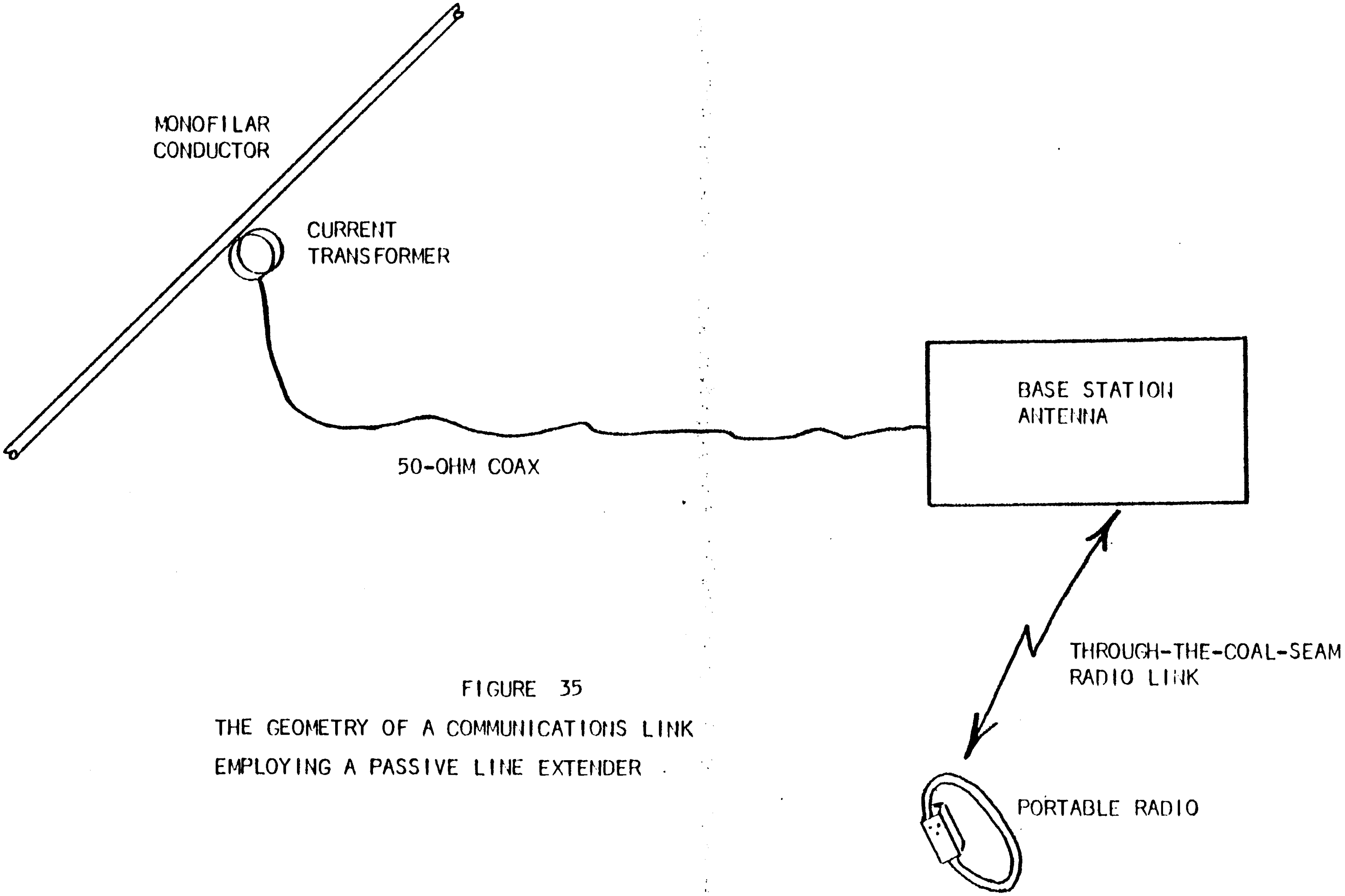


FIGURE 35

THE GEOMETRY OF A COMMUNICATIONS LINK
EMPLOYING A PASSIVE LINE EXTENDER

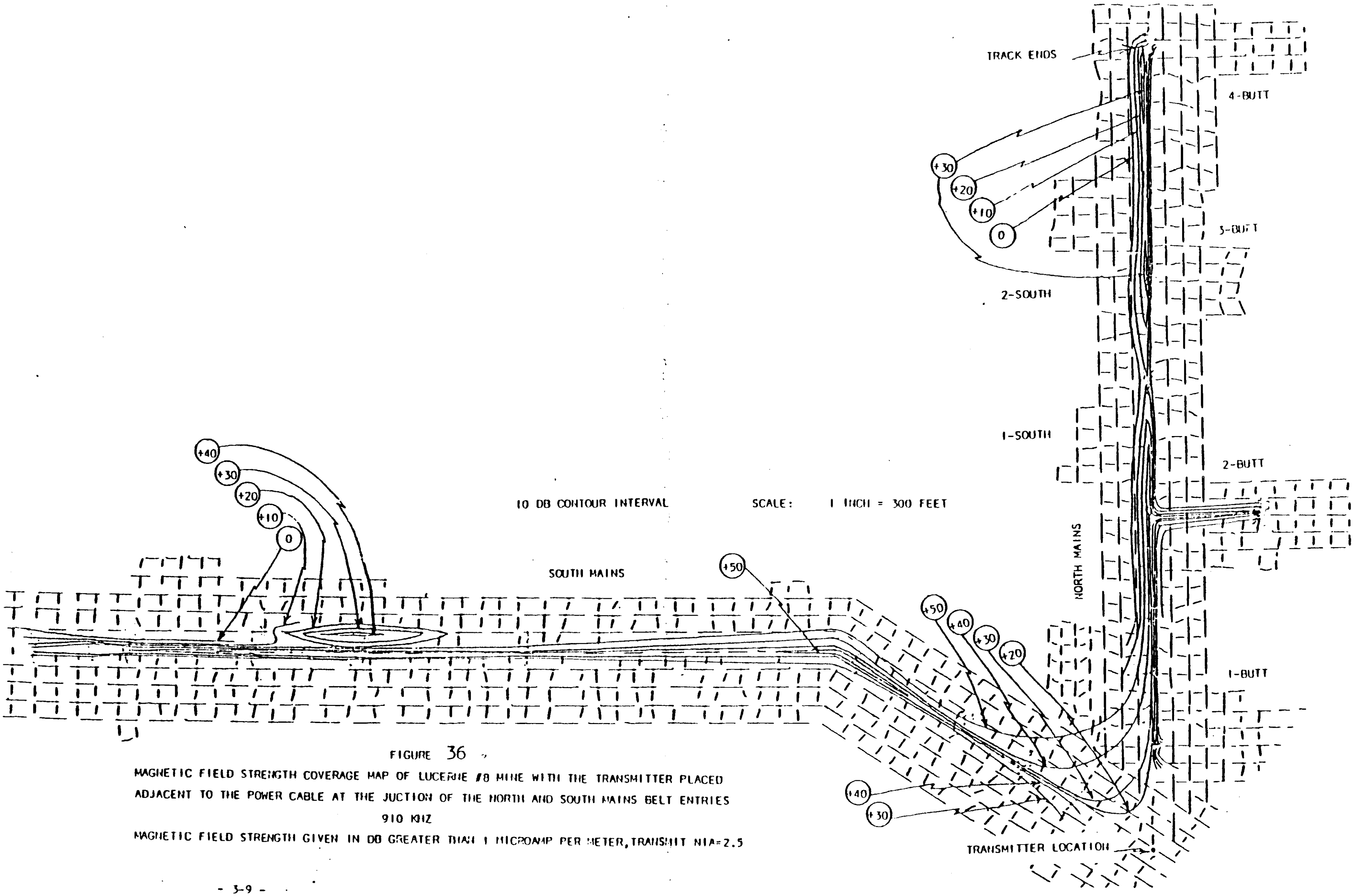


FIGURE 36

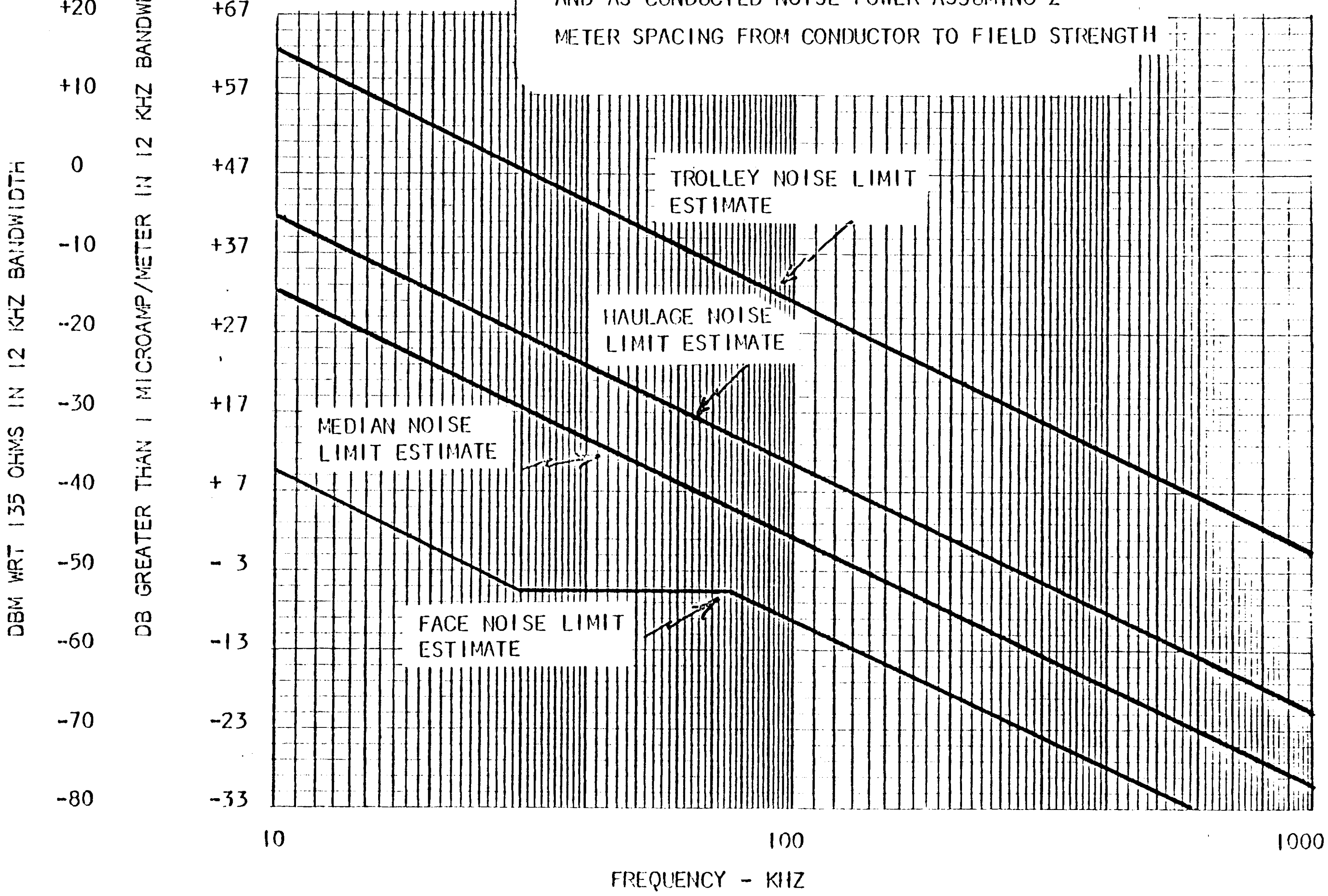
MAGNETIC FIELD STRENGTH COVERAGE MAP OF LUCERNE #8 MINE WITH THE TRANSMITTER PLACED ADJACENT TO THE POWER CABLE AT THE JUCTION OF THE NORTH AND SOUTH MAINS BELT ENTRIES

910 KHZ

MAGNETIC FIELD STRENGTH GIVEN IN DB GREATER THAN 1 MICROAMP PER METER, TRANSMIT NIA=2.5

FIGURE 37

SUMMARY OF ORIGINAL NBS MEASURED NOISE DATA
IN COAL MINES EXTRAPOLATED ABOVE 200 KHZ
EXPRESSED AS FIELD STRENGTH (ORIGINAL)
AND AS CONDUCTED NOISE POWER ASSUMING 2
METER SPACING FROM CONDUCTOR TO FIELD STRENGTH



mines because even in DC mines in quasi-conductor-free areas, field strength measurements were set-noise-limited; the measuring equipment sensitivity being of the order of -40 dB above one microamp/meter. Thus, previous system calculations were also made using the set-noise-limit for comparison purposes.

The recently obtained monofilar mode data is appropriate for use in the entry containing the conductors, with the set-noise-limit deemed as being appropriate for use at remote coupling locations (where the scatter gain technique applies). The new noise data has further been partitioned according to DC and AC mines; and, further, in DC mines for tracked and trackless haulage and also accounting for average trolleyphone interferance levels. Although representing a limited sampling of several areas in only two mines, the new monofilar mode data is in good agreement with the large body of NBS obtained data below 200 kHz; thus,adding confidence to the new data.

The new monofilar mode data is shown in Figure 38 . Note,in particular, that a single curve is appropriate for use in AC mines and, thus, for trackless haulage communications situations. Fortuitously, there is an abrupt roll-off in the noise frequency slope for AC mines at frequencies above 200 kHz.

The bifilar mode noise levels have also been partitioned according to operationally significant situations in AC mines with a single set of curves being appropriate for DC mines. The noise data in DC mines, in particular, has significant impulsive content so that the broadband noise" bandwidth rule" cannot be applied. Rather, the data is presented in terms of 30, 3, 0.3 kHz 6 dB bandwidths and the 30 kHz 6 dB bandwidth is appropriate for use with narrowband FM medium frequency radio systems.

The DC mine bifilar mode noise data is given in Figure 39 . The corresponding AC mine data is given in Figure 40 .

A system embodying the use of repeaters and/or Remote Base stations will result in interferance fringes in generally well-defined areas of the mine due to the simultaneous transmission from two or more sources. These fringes will occur when the potentially interfering signals are nearly of the same amplitude. The following interferance cases are possible:

- Reception of "simulcast" type of signal where the same "message" is being broadcast simultaneously from two or more transmitters. This may consist of the simultaneous broadcast from a Base Station and/or one or more Remote Base stations; or else, the reception of direct and "repeated" signals or the reception of two or more repeated signals.

  In this type of transmission, using FM, the mean square phase deviation between sources must be less than a certain value in order to receive a given "grade" or quality of transmission.

FIGURE 38

CORRECTED NOISE CURVES FOR COAL MINES BASED ON NBS MEASURED FIELDSTRENGTH DATA CORRECTED USING INSTANTANEOUS COMMON MODE NOISE DATA FROM HAREWOOD AND SESSER MINES - FIELD STRENGTH APPROPRIATE FOR 2 METER SPACING FROM PHONE LINE

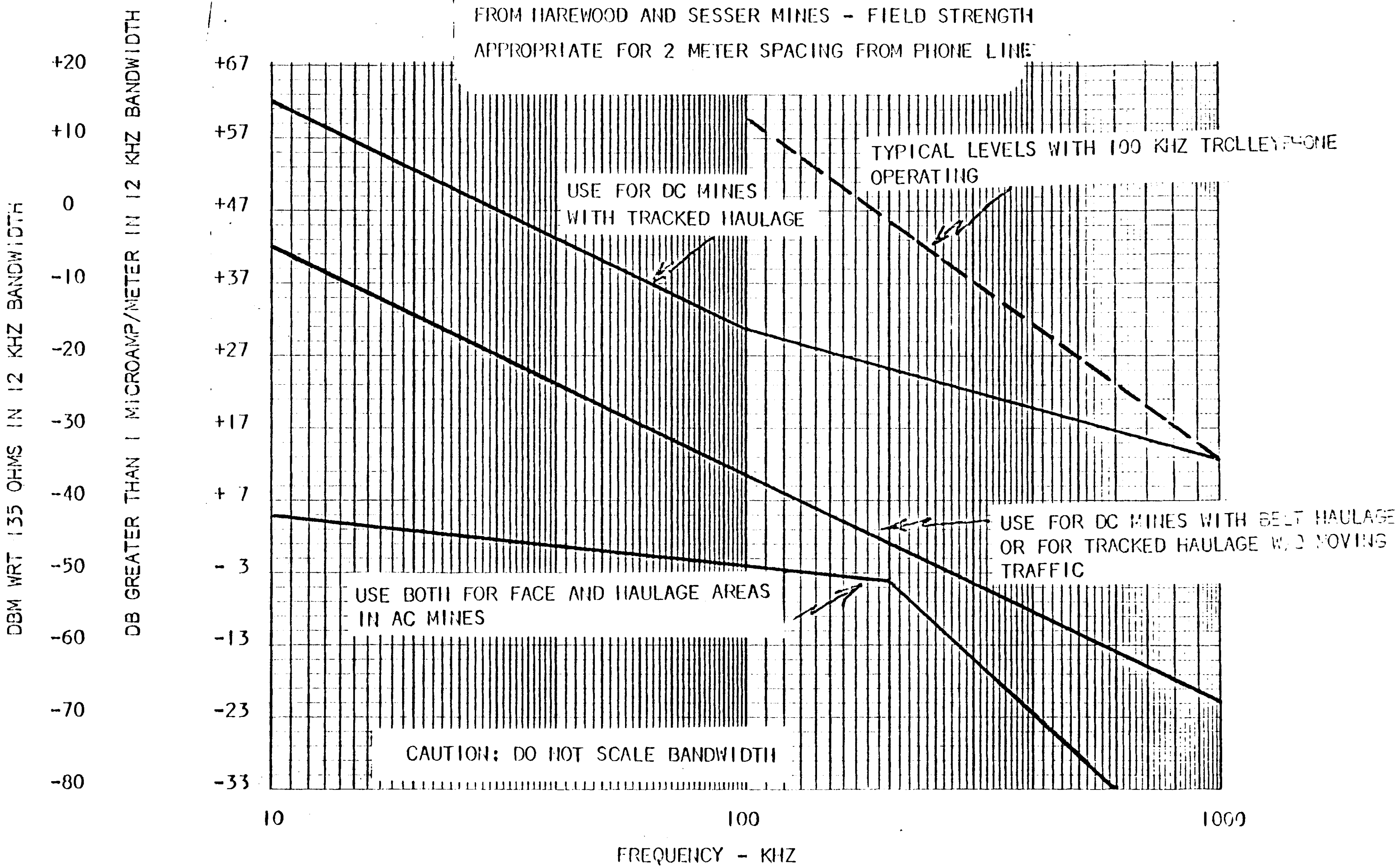


FIGURE 39

AVERAGE DIFFERENTIAL MODE INSTANTANEOUS NOISE LEVELS ON PHONE LINE IN HAREWOOD MINE - CHARACTERISTIC OF DC MINE WITH 100% TRACKED HAULAGE - PHONE LINE WAS 16-3 ROMEX (GND FLOATING) AND NOT TWISTED PAIR

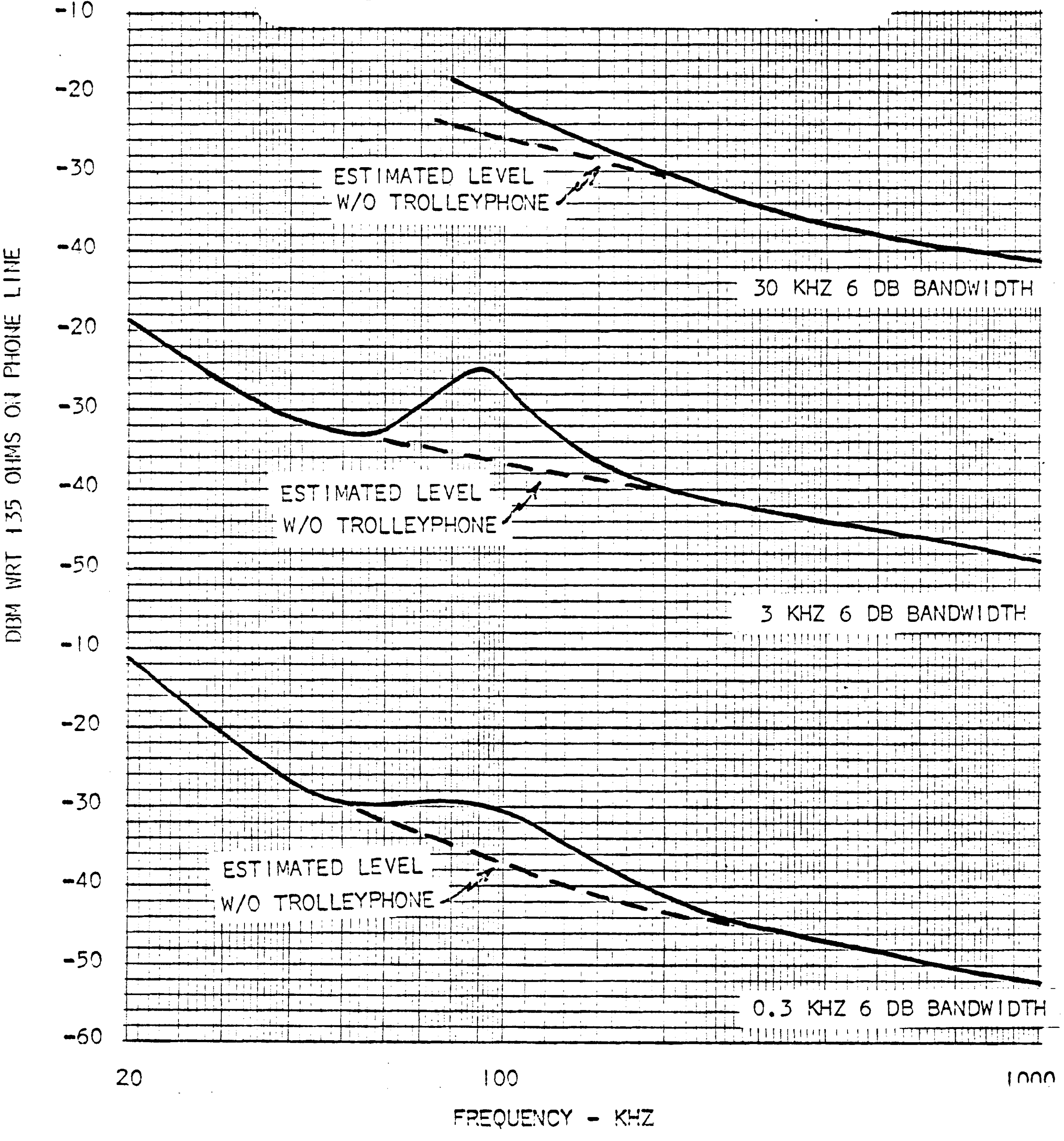
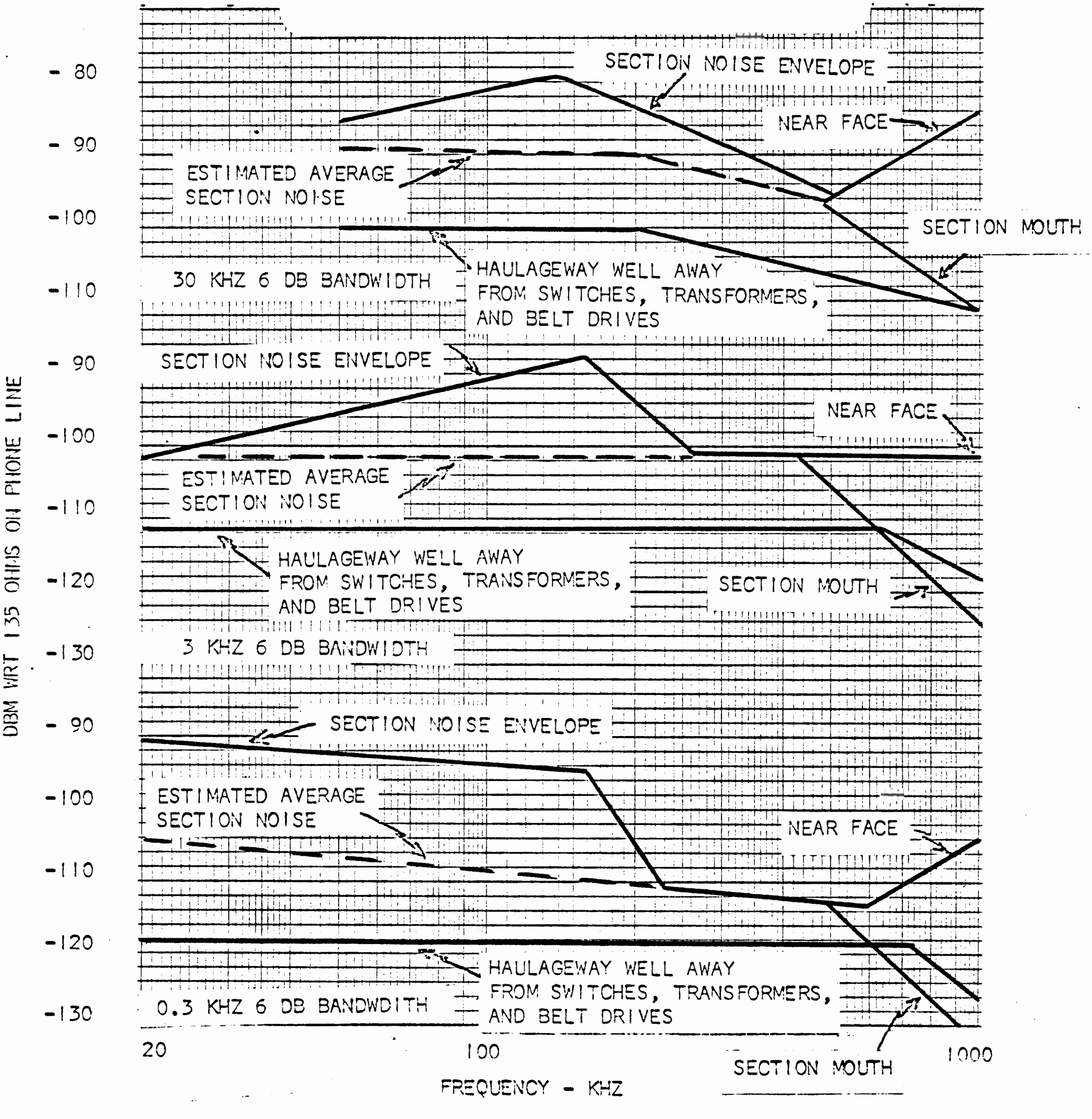


FIGURE 40

AVERAGE DIFFERENTIAL MODE INSTANTANEOUS NOISE LEVELS ON PHONE LINE IN SESSER MINE - CHARACTERISTIC OF AC MINE WITH 100% BELT HAULAGE - PHONE LINE IN SAME ENTRY AS AC POWER CABLE



- Reception of two different signals from two sources transmitting at the same time because they presumably cannot hear each other.

  In this type of transmission, using FM, one signal must be greater in amplitude by a predetermined value to ensure a given grade of service; the amplitude limiting the maximum phase deviation which can occur, this phase deviation being the same as that for the simulcast type of transmission.

Generally, because of the way in which systems will be laid out, regions of potential interferance can be "designed" in to lie in mine areas of minimal operational significance. Also, for the second type of interferance, the FM capture effect will minimize the interferance zone sizes.

For simulcast transmission via path segments employing the monofilar mode, the phase "slip" which can cause "beat notes" in the interferance region will probably be affected by phase path differences due more to imhomogeneities in the coal seam rather than by transmitter frequency off-set or audio phasing control. The only sure way to determine the degree of the problem is by experiment.

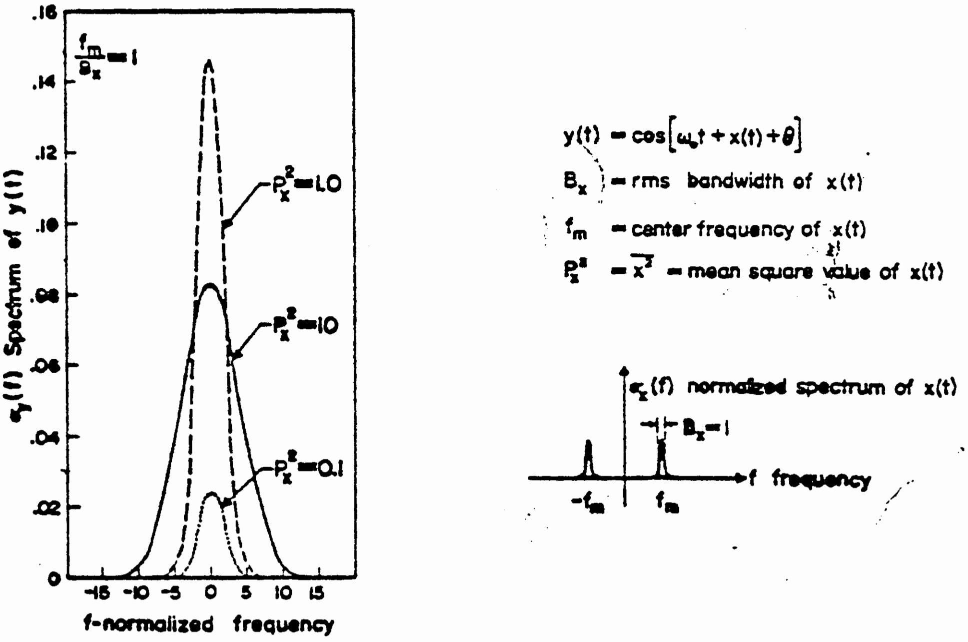
Because the wavelengths are much longer at MF than for VHF(In the land mobile service), the transmitter frequency stability could be relaxed somewhat from the suggested 0.00015%; however, this degree of stability is easy to meet.

Let us define the mean square phase error which can be tolerated while still meeting the 12 dB SINAD (13.5 dB Hamshur S/N) type of service requirement.

Abramson has considered the case of a carrier phase modulated by a (ref.) Guassian random process under both baseband and narrow band conditions. He gives a formula for computing the spectral density of such a modulation process which is a function of the center frequency-to-bandwidth ratio and the mean square phase deviation, P_x^2 . For the case of 1 bit/Hz of bandwidth (in digital terms, the bandwidth equalling the signalling rate), the above ratio is essentially unity and there is a curve for this case which is shown here in Figure 41a. The spectrum shows a carrier of amplitude exp($-P_x^2$) in the center of a continuous spectrum of peak amplitude

$$\frac{e^{-P_x^2}}{4}(P_x^2) + \frac{e^{-P_x^2}}{8}(P_x^2)^2 + \frac{e^{-P_x^2}}{24}(P_x^2\ )^3 + \ldots\ldots$$

A curve of this peak amplitude vs P_x^2 is shown as Figure41b . For small deviations, this spectrum has essentially the same shape as the original modulation process (amplitude modulation). For larger deviations, the spectrum becomes much wider than that of the original process and takes on a Gaussian shape via the central limit theorem. Let us consider the the spectrum of the FM radio signal in the presence of interferance to be the convolution of this spectrum with the above spectrum. We now need



$y(t) = \cos[\omega_0 t + x(t) + \theta]$

B_x = rms bandwidth of x(t)

f_m = center frequency of x(t)

$P_x^2 = \overline{x^2}$ = mean square value of x(t)

Figure 41 a

Normalized Spectrum of a Carrier Angle-modulated by a Narrow Band Gaussian Random Process
(A spectral line at frequency f_0 of average power $e^{-P_x^2}$ is omitted from these figures)

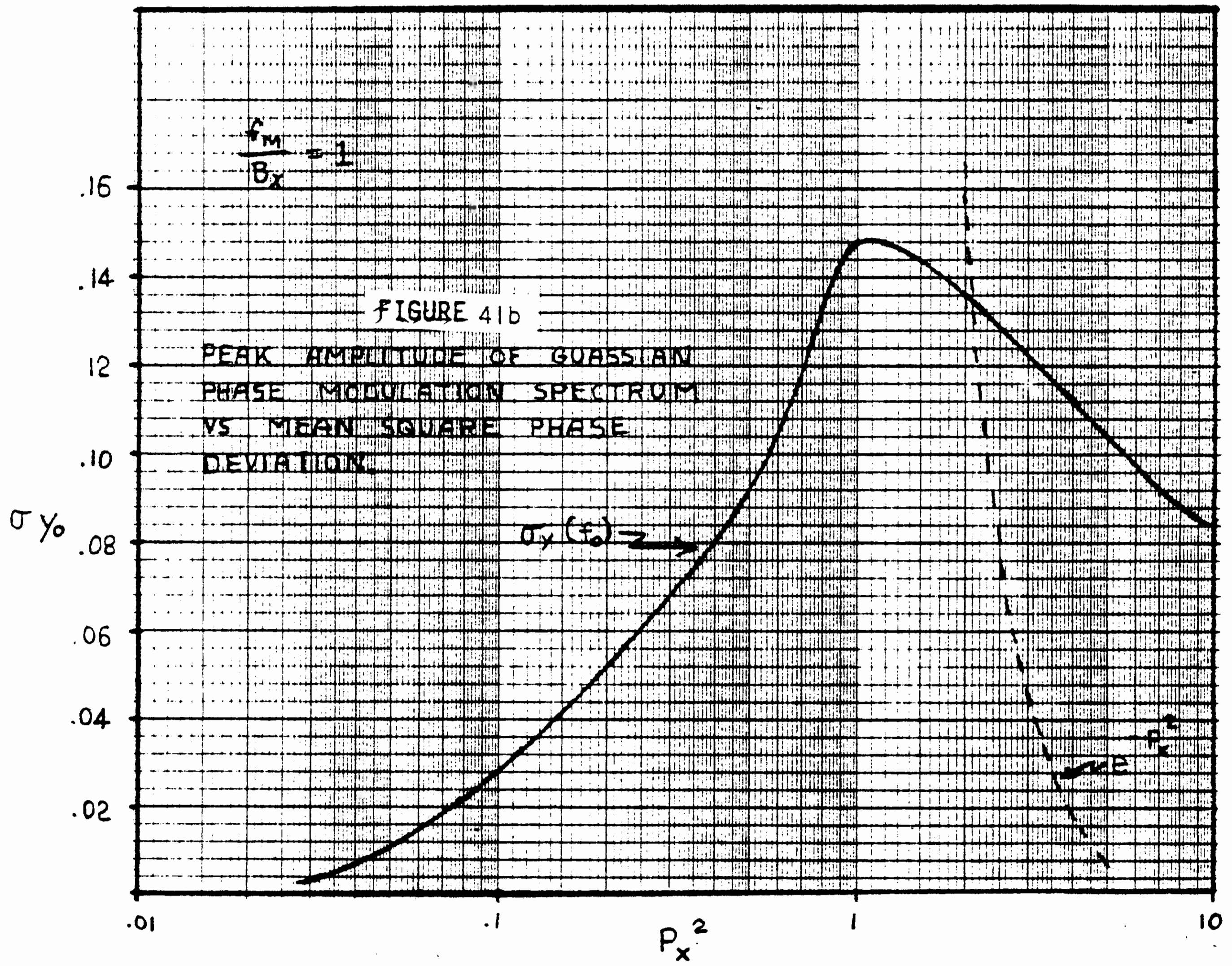


FIGURE 41b

PEAK AMPLITUDE OF GUASSIAN PHASE MODULATION SPECTRUM VS MEAN SQUARE PHASE DEVIATION.

to know the effect of this convolution on the peak amplitude of the continuous "noise/interference" spectrum so that we can ratio the signal spectrum of peak amplitude exp($-P_x^2$) to this spectrum to get a signal-to-interference ratio. If the noise spectrum is much wider tha the signal spectrum, then the peak amplitude of the convolved spectrum is, for unity signal amplitude,

$$S_{*0} = B_2 \, S_{10}$$

Where, B_2 is the signal bandwidth

S_{10} is the original peak before convolving

As this bandwidth is equal to that of the interference process and is equal to unity from the normalization of Figure 41a, the convolved peak is equal to the original peak and Figures41a&41b apply directly for ratioing. If the resultant noise/interference spectrum is equal in bandwidth to the signal spectrum, then the peak amplitude of the convolved spectrum is (again assuming unity amplitude for the peak of the signal spectrum)

$$S_{*0} = B_2 \, S_{10} \int S_{nl} \, df$$

Where, S_{nl} is the spectrum of the interference normalized to both unity peak and bandwidth

It is reasonable to expect that the value of this integral will be about 1/2 so, under that assumption, 3 dB must be added to the desired signal to noise ratio before using Figures 41a& 41bto obtain a value of P_x^2 .

The remaining problem is then to bound P_x^2 in terms of the required values of the desired signal strength and an assumed interfering signal strength in a radio sense. Assume the interference is of the second type with the desired signal amplitude being B and the amplitude of the interfering signal being A. This is shown in the "undulating" phasor triagle of angle modulation, Figure 42 . If the angle between B and the resultant of A & B is taken to be P_x, then a ratio of B/A can be interpreted as a signal-to-interference ratio. The value of P_x so determined will also be the value which must be beaten in terms of phase error(due to frequency offset and phase path difference) in order to permit communications through a simulcast finge region.

If the required S/N is taken to be 13.5 dB for 12 dB SINAD, then we must look up 13.5 + 3 = 16.5 dB on Figure 41b, or

$$\frac{e^{-P_x^2}}{\sphericalangle(y)} = 44.7 \ .$$

This gives an rms phase deviation, P_x , of 15.7 degrees which, interpreted as a signal-to-interference ratio, is 11.4 dB. For the second type of interference, this defines the capture ratio to ensure 12 dB SINAD. As a practical matter, a readible signal can be obtained for a ratio more nearly 6 dB. Wider band FM would result in even a smaller capture ratio

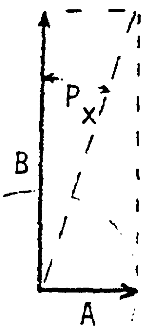


Figure 42

Familiar Phase Modulation Triangle For Two Signals as is our normal experience with FM radio broadcast reception.

Consider the 15.7 degree rms phase deviation in terms of the requirements it will impose for simulcast operation. Let us first evaluate the "slip" in carrier frequency to produce this rms phase error. The slip is 1.04333 wavelengths. Assume a monofilar mode $\alpha/k = 3$ so that a wavelength at 1 MHz is approximately 300 feet. If a desired communication range of 3 miles is assumed, then the number of wavelengths is about 53 so that the "slip" per wavelength is 0.00082. Considering that the desired maximum frequency off-set would be at least an order of magnitude less, the required frequency accuracy is 0.0082%. This assumes complete homogeneity in the monofilar mode constitutive characteristics.

In terms of audio phase to cause the same effect, the phase equals

$$\frac{2\pi(\Delta f = \text{deviation})}{f_m}\text{, radians}$$

where f_m is the modulating frequency. For a mean modulating frequency of 1 kHz, the audio modulating frequency must be controlled to within 14.6 Hz maximum.

5.3 ANTENNA CONSIDERATIONS

Designs for MF wireless radio system antennas include:

- Portable antennas
- Vehicular antennas
- Base Station antennas
- Current transformers

Until recently, only two types of antenna designs were available corresponding to the older prototype system radio equipments. Both the South African ECAM and Collins Portables used a grouping of wires (without particular regard for spacing or orientation) inside a rigid tubular oval shaped enclosure. The antennas had nominally 7 turns. The Collins antenna had 7 ohms of series resistance before matching (@ 520 kHz), approximately 0.2 m^2 of area, and a Q of 44. The ECAM antenna was tuned to 335 kHz. Both these antennas were matched to 50 ohms at a single frequency. With 20 watts of input power, the Portable antennas could achieve a magnetic current moment (NIA) of about 2.5 ampere.meter^2.turns.

The other antenna type was a large single-turn rectangular Base Station antenna, approximately 2 meters by 7.2 meters which could develop a transmit NIA of 14 with a 20-watt radio and which would enable increased receive system sensitivity in quiet areas of a mine.

The major difficulty with these early Portable antennas was that the parallel resonant frequency was low enough that performance near the high end of the MF region (of the order of 1000 kHz) began to degrade significantly. This is illustrated graphically in the Impedance data shown in Figure 43 . The use of spaced optimally arranged turns (so as to minimize and distribute the winding capacitance) was expected to reduce the impedance level and improve the available tuned bandwidth characteristics over a range of MF frequencies. Additionally, the possibility of an integral connection between a Portable radio package and the antenna is expected to improve performance through the elimination of a transformer and/or matching circuitry, with an attempt being made to series-tune the antenna and drive it essentially directly from the PA output impedance level.

A design algorithm was developed for use with multi-turn loop antennas to enable optimization of antenna parameters. This algorithm, given to follow, was first used to design a suitable mechanically rugged antenna for vehicular use.

The antenna inductance, L , is given by

$$L = \frac{L_o}{1 - \left(\frac{f}{f_r}\right)^2}$$

where, L_o is the low frequency inductance given by

$$L_o = 0.02339\, n^2 \left[(s_1 + s_2) \log_{10} \frac{2 s_1 s_2}{nD} - s_1 \log_{10} (s_1 + g) - s_2 \log_{10} (s_2 + g) \right] + 0.01016\, n^2 \left[2g - \frac{(s_1 + s_2)}{2} \right]$$

microhenries

s_1, s_2 are the side lengths in inches

g is the diagonal in inches

n is the number of turns

D is the wire separation in inches

f_r is the self resonant frequency given by

$$f_r = \frac{1}{2\pi \sqrt{L_o C}}$$

C is the distributed capacitance of one turn and is

$$C = \frac{\ell}{\cosh^{-1}\left(\frac{D_1}{d}\right)(36 \times 10^9)}$$

ℓ is the length of one turn in meters
d is the wire diameter in inches
D_1 is the effective wire separation in inches
D_1 is greater than D by about 17%

The antenna resistance, R , is given by

$$R = \frac{R_o}{\left[1 - \left(\frac{f^2}{f_r}\right)^2\right]^2}$$

where, for copper,
R_o is the low-frequency resistance given by

$$R_o = \frac{0.831}{d}\left[1 + 25.67\left(\frac{d}{D/\sqrt{\epsilon_r}}\right)^2\right]\sqrt{f}\ \ell_t \times 10^{-7} \text{ ohms}$$

$\ell_t = n\,\ell$ in inches

The NIA product for matched conditions into 50 ohms is given by

$$NIA = NA\, I_o \sqrt{\frac{50}{R}}$$

where, I_0 is the input current into 50 ohms
(exp. 0.632 amps for 20 watts)

The antenna resistance is that for solid or stranded copper wire. The use of Litz wire has been considered during this program to reduce the wire resistance component of the total antenna series resistance including losses external to the winding.

Litz wire consists of a number of separately insulated strands woven or bunched together so that each strand tends to take all possible positions in the crossection of the entire conductor. The purpose of Litz wire is to reduce skin-effect losses by distributing the flow of radio frequency current more uniformly over the wire crossection.

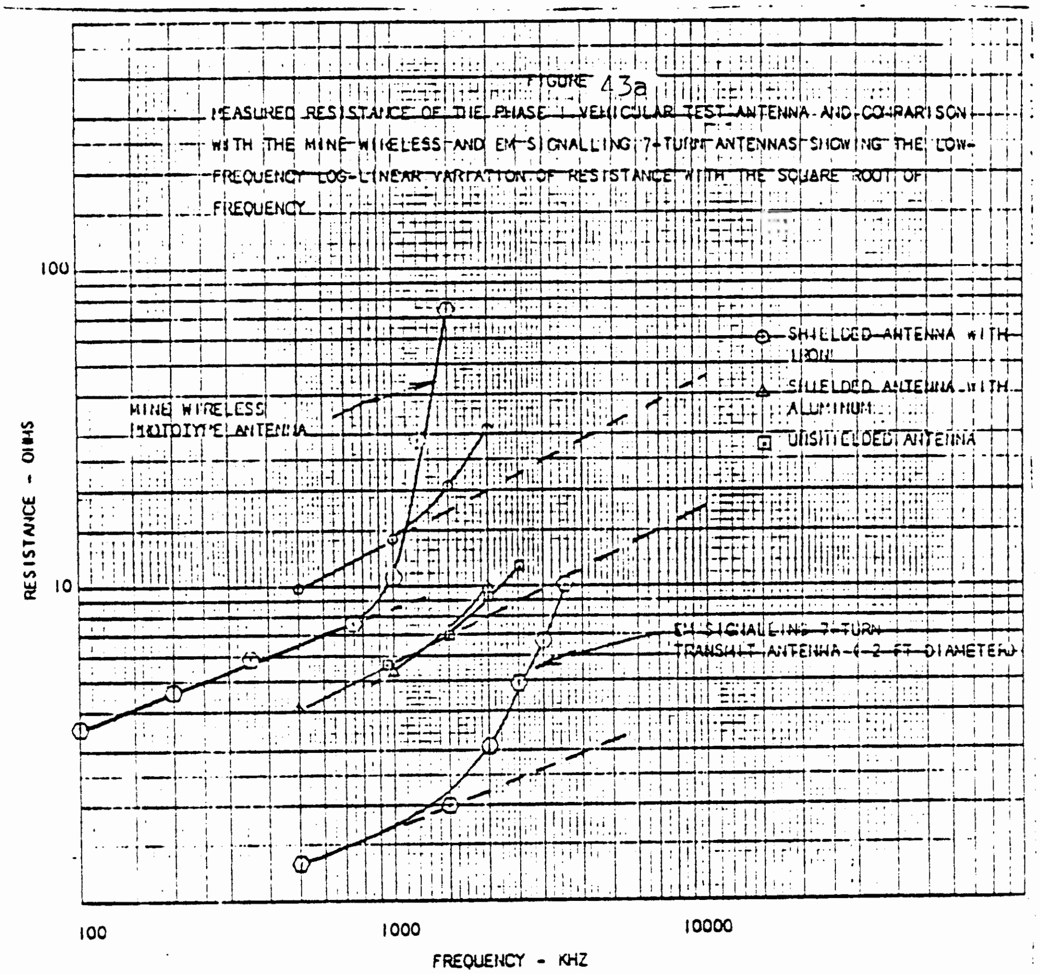


FIGURE 43a

MEASURED RESISTANCE OF THE PHASE I VEHICULAR TEST ANTENNA AND COMPARISON WITH THE MINE WIRELESS AND EM SIGNALLING 7-TURN ANTENNAS SHOWING THE LOW-FREQUENCY LOG-LINEAR VARIATION OF RESISTANCE WITH THE SQUARE ROOT OF FREQUENCY

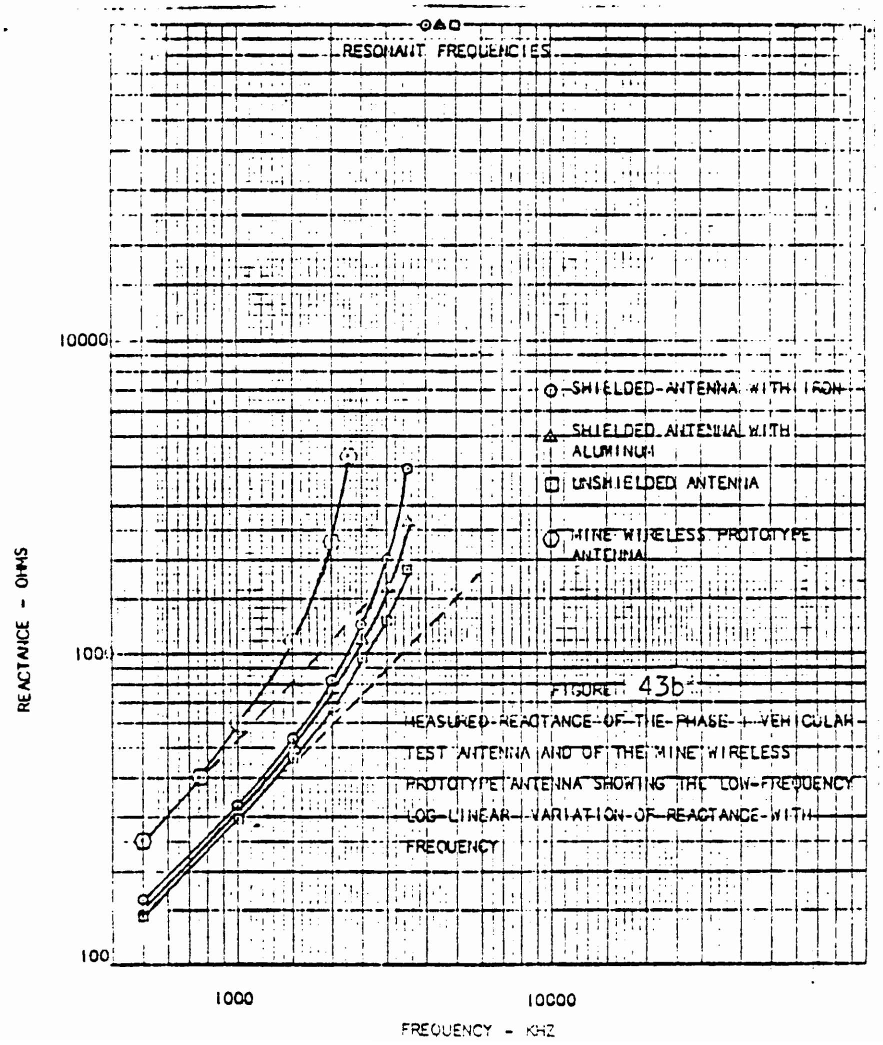


FIGURE 43b

MEASURED REACTANCE OF THE PHASE I VEHICULAR TEST ANTENNA AND OF THE MINE WIRELESS PROTOTYPE ANTENNA SHOWING THE LOW-FREQUENCY LOG-LINEAR VARIATION OF REACTANCE WITH FREQUENCY

The resistance of Litz wire is frequency dependent with the resistance being a function of the overall wire diameter, d, the strand diameter, d_s, and the wire-wire spacing, D. A low frequencies, the use of Litz wire results in a significant reduction in the low-frequency ac resistance, R_o. At higher frequencies, typically 1 - 3 MHz, the advantage disappears and Litz wire can actually have a greater resistance than solid wire. This latter effect is primarily a function of the strand diameter, d_s, and operation at higher frequencies requires a smaller strand diameter and, hence, more strands for a fixed desired wire diameter.

Terman   gives an expression for the ratio of R_o to R_{dc} for Litz wire. Fo antenna design, we are most interested in the ratio R_{oLITZ} / R_{oSOLID} so that the R_{oLITZ} can be used with the loop antenna design algorithm. The author has never seen curves of this ratio plotted in the literature, so these curves as applicable to antenna design were developed as part of this program and should serve as a standard reference for the future.

The appropriate formulations for R_{oLITZ} / R_{dc} and R_{oSOLID} / R_{dc} will be derived and then ratioed to obtain the above measure of Litz wire advantage for antenna design.

For a solid wire,

$$R_{oSOLID} / R_{dc} = H + A \left(\frac{d}{D}\right)^2 G$$

where A for multilayered coils = $\frac{1}{4}\left(\frac{Kbm}{D}\right)^2$

with Kb/D = 5 typically and with $m \equiv 3$ layers typically, so that $A = \frac{1}{4}(15)^2 = 56.25$

G is a proximity factor for multilayer coils varying nearly linearly with x ($x = 0.1087\ d \sqrt{f}$ for copper) for larger

values of x so that G is approximately equal to 0.0439 d f.

H is the ratio by which R_{dc} of an isolated wire is multiplied to give R_{ac} and = approximately $0.0962\ d \sqrt{f}$ for copper.

therefore,

$$R_{oSOLID} / R_{dc} = 0.092\ d \sqrt{f} + 2.469\ d \sqrt{f} \left(\frac{d}{D}\right)^2$$

For Litz wire,

$$R_{oLITZ} / R_{dc} = 1 + n^2\ G \left(\frac{d_s}{d}\right)^2 \left[2 + A \left(\frac{d}{D}\right)^2\right]$$

where, G = approx. $x^4/64 = 0.878 \times 10^{-4}\ d_s^4\ f^2$

$$R_{oLITZ} / R_{dc} = 1 + 0.878 \times 10^{-4} \left(\frac{d_s^3\ n\ f}{d}\right)^2 \left[2 + 56.25 \left(\frac{d}{D}\right)^2\right]$$

A summary of the performance achieved in the vehicular antenna design is given in Figure 44 illustrating NIA vs frequency and in Table 5 illustrating the partitioning of losses in the prototype hardware at a particular frequency.

Use of the design algorithm has revealed several important aspects of MF multi-turn loop antenna design, which include:

- There are two optimum approaches for the design of these antennas which depend upon power level and whether or not the antennas are matched to a coaxial line impedance before connecting to the radio.
- One approach entails a "high impedance", many turns design.
- The other approach entails a "low impedance", few turns design.
- The optimum high impedance design is also optimum for intrinsic safety and is also "inherently" intrinsically safe (for only a 5-watt radio, either design approach can easily be made intrinsically safe).

The "high impedance" approach is to operate the antenna at as high an impedance level as possible for as high a raw antenna Q as possible; then use fixed series resistance to de-Q the antenna to the propoer bandwidth (which also automatically provides DC current-limiting resistance. This means using as many spaced turns as possible before the NIA begins to drop (and also before the inductance enters the constant-energy portion of the intrinsic safety curve for the chosen DC supply voltage). This type design has been used for prototype vehicular antennas. Use of Litz wire should be made to provide as near constant a bandwidth as possible by maximizing the ratio of fixed added resistance to wire resistance.

The "low impedance" approach is to use only a few turns and keep the impedance level as low as possible. The number of turns is dictated by the number required to enter the near-constant NIA region of operation. and also to provide maximum drive current from a directly coupled PA.

The design characteristics achievable with a Portable antenna are illustrated in Table 6 .

The most critical aspect of Portable antenna design is the choice of operating bandwidth so that the potential detuning of an operationally required flexible antenna can be accomodated. For a narrowband FM radio with a modulation index = 1 and with ± 3 kHz deviation, the 10 dB bandwidth is expected to be about 8 kHz so that an antenna bandwidth of 12-15 kHz should be adequate. This means that the maximum allowable antenna Q will be less than 100 and probably of the order of 67.

FIGURE 44

NIA VS FREQUENCY FOR 6-INCH BY 3-FOOT VEHICULAR ANTENNA OF 12 TURNS IN A 1¼ INCH ELECTROSTATIC SHIELD WITH 1700/44 LITZ WIRE

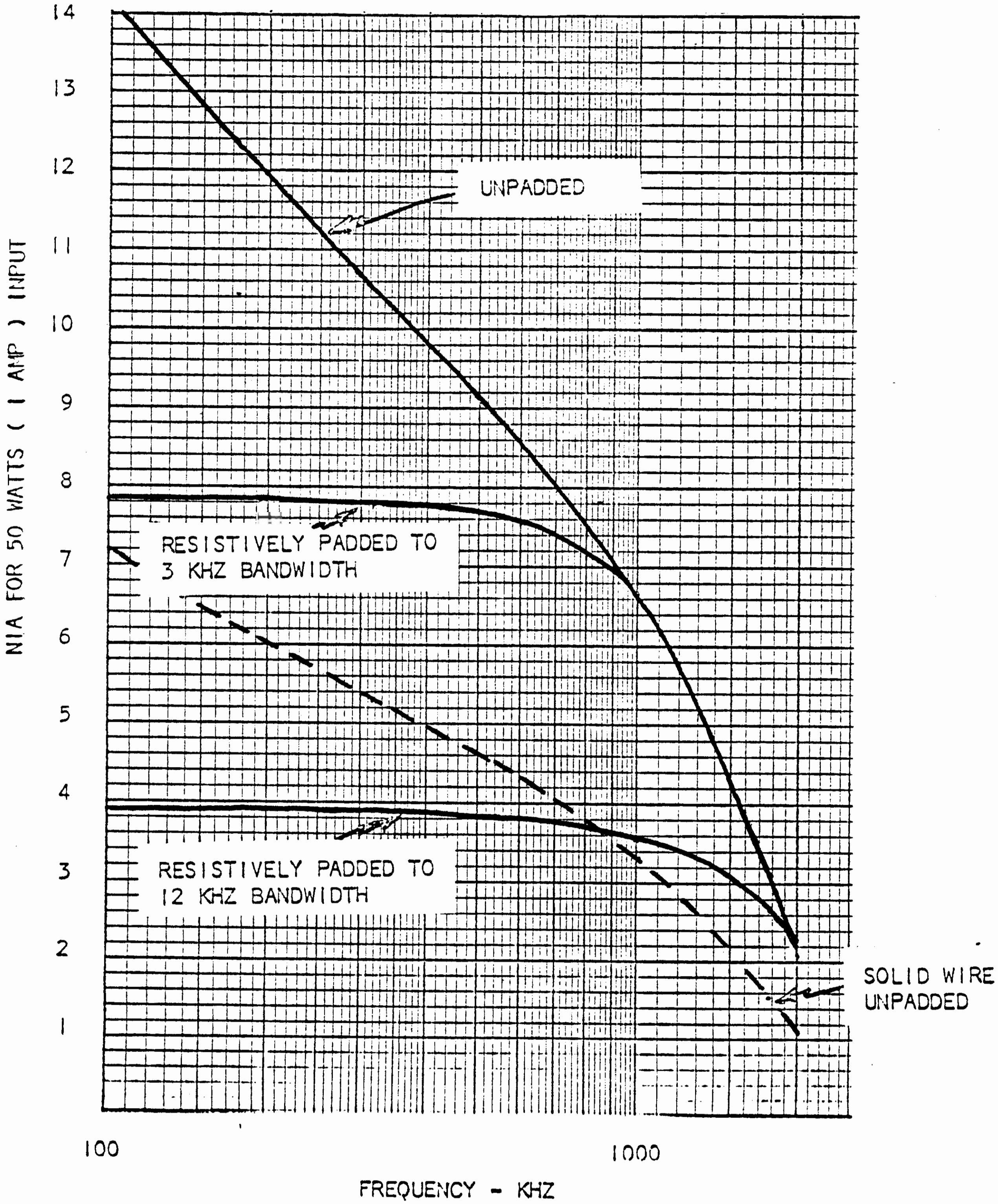


TABLE 5

PERFORMANCE DIAGNOSIS FOR VEHICULAR PROTOTYPE ANTENNA AS OBTAINED DURING PRELIMINARY TESTING @ 476 KHZ

	Q	R_L	BW
ANTENNA TUNED AND TRANSFORMED WITH TUNING CKRT IN ENCLOSURE	37.1	11.3	12,830
ANTENNA TUNED AND TRANSFORMED WITH TUNING CKRT NOT ENCLOSED	47.2	8.9	10,084
ANTENNA TUNED BUT NOT TRANSFORMED WITH TUNING CKRT NOT ENCLOSED	90	4.67	5,289
ANTENNA NOT TUNED(RAW ANTENNA)	404	1.04	1,166
TUNING CAPACITORS(100 VOLT SILVERED MICA)	110	3.63 OHMS OF LOSS	
TRANSFORMER		4.23 OHMS OF LOSS	
ENCLOSURE		2.42 OHMS OF LOSS	

TABLE 6

NIA, TOTAL SERIES RESISTANCE R_T, AND ANTENNA CURRENT FOR 5 WATTS INPUT VS NUMBER OF TURNS FOR PORTABLE ANTENNA RESISTIVELY PADDED TO 12 KHZ BANDWIDTH

	500 KHZ			1000 KHZ		
# OF TURNS	NIA	R_T (OHMS)	I (AMPS)	NIA	R_T (OHMS)	I (AMPS)
4	1.39	1.64	1.75	1.35	1.73	1.70
5	1.43	2.39	1.44	1.41	2.45	1.42
6	1.47	3.27	1.23	1.45	3.36	1.22
7	1.51	4.24	1.09	1.48	4.40	1.06
8	1.54	5.32	0.97	1.51	5.57	0.95
10	1.60	7.68	0.81	1.55	8.23	0.78
12	1.65	10.40	0.69	1.58	11.40	0.66

#16 WIRE ($d = 0.0508$ INCHES)

ANTENNA CIRCUMFERENCE = 69 INCHES

CENTER-CENTER SPACING BETWEEN TURNS = 0.25 INCHES

5.4 CONDUCTOR COUPLING

Generally speaking, the conductor "close coupling" coefficients can be expected to vary between

C_T -60 dB to -28 dB

C_R -50 dB to - 6 dB

over the typical transverse crossection of an entry containing conductors; depending on the conductor configuration and the separation distance between the radio antenna center and the conductor(s) center.

Considering the most likely operating positions of Portables and Vehiculars in the entry crossection, the Portable coupling coefficients are expected to be

C_T -45 dB to -55 dB

C_R -15 dB to -25 dB

and for Vehiculars

C_T -40 dB to -50 dB

C_R -27 dB to -37 dB.

The presence of a vehicle in the entry crossection is expected to enhance the vehicular coupling approximately 3 dB from that at the same location using the same antenna (but with the vehicle absent) if the antenna is mounted on the side of the vehicle closest to the conductor(s) (assumed near a rib). If the antenna is mounted on the other side of the vehicle, no coupling enhancement is expected.

The maximum transmit coupling is bounded and is expected to be about -28 dB (-30 dB is obtained using the simple C_T formula previously presented for NA = 1.4, Z_o = 50 ohms, r = 0.3 meter. That this is true can be visualized from the following argument:

> The surge impedance of the transmission line formed by the AC power cable in close proximity to the roof and rib has to be in the vicinity of 50 ohms. Because the "line"/cable goes in two directions, and assuming match, the series impedance level of this line is about 100 ohms. The total series path resistance of a typical transmit loop antenna of near-optimum design is about 4 ohms.
>
> Now, coupling from a transmit loop to the AC cable is equivalent to using a transformer whose secondary is constrained to always be 1 turn. As the transmit loop tuned impedance is always less than the surge impedance(x2), the ideal coupling for maximum power transfer would be from a transformer with a fractional turn on the primary. This cannot be in the physical world and, thus, the "available"

> transformer is always "reversed" from that which we would like. Thus, for very close coupling, one could argue that the best transformer has just I turn on the primary. If we had an ideal transformer and the coupling were perfectly tight, then a resistance level of 100 ohms would be "reflected" into the primary instead of the typically 4 ohms when loosely coupled. Thus, for a fixed power input properly matched, the available current drops by a factor of 25 in going from the loosely coupled to the tightly coupled case, which is - 28 dB.

This transmit coupling bound was measured experimentally via transmitting from a Base Station antenna to a section of monofilar line placed over ground (the experiment was conducted on the surface). The results of this testing are shown in Table 7 . Note that the coupling is quasi-independent of the transverse spacing of the antenna from the line. This is due to "overkill" in antenna size as the antenna links essentially all the magnetic flux surrounding the line conductor at all ranges. This same effect can be expected in a mine and, thus, a large Base Station antenna located antwhere in the conductor entry and oriented for maximum coupling can be expected to couple as well as a very close spaced (to the conductor) current transformer.

Perhaps the most accurate coupling levels for more complex geometries can best be determined using the graphical field mapping technique (quasi-static limit for the monofilar mode transverse fields). Coupling estimates have been made and the results as shown in Figure 45 for fQ_A/X_L of the antenna equal to 55,000 which is appropriate for the vehicular antenna. The coupling coefficient, C_R , is given by:

$$C_R = \frac{w\mu\ NA}{2n\Delta R\ R_L}$$

Where, n = the number of flux lines per 360 degrees of rotation around the conductor (64 for the charts shown)
R_L is the loop antenna series resistance (18 ohms used)
ΔR is the curvilinear square dimension in meters

For use in two-frequency systems, all Portable & Vehicular and selected Base Station antennas and current transformers will have to be tuned or tunable to both frequencies. This can be accomplished passively (no tuning control required) or actively via a switch line from the radio. The actively tuned antenna is envisioned as having two separate matching circuits which are switched into place on command. The control is envisioned functionally as follows. Normally (without a control signal), the antenna is tuned to the receive frequency. If the radio controls are set to transmit the second frequency, a key line is energized so that when the radio is keyed, the antenna tuning circuitry is switched.

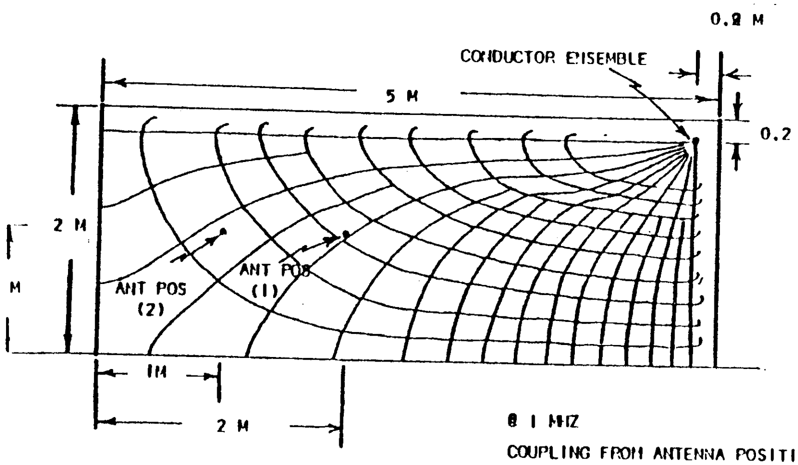
TABLE 7

MEASURED CURRENT COUPLING COEFFICIENT VS TRANSVERSE SPACING OF A BASE STATION LOOP ANTENNA FROM A MONOFILAR LINE SECTION OVER A CONDUCTING INTERFACE (GROUND)

COUPLING COEFFICIENT

CONDUCTOR END	TERMINATION IMPEDANCE	LOOP/CONDUCTOR SEPARATION - FEET 3	6	12	24	48
A	25 ohm		-27.6			
	50	-21.6	-27.0	-29.6	-26.6	-27.6
	100	-21.9	-29.0	-28.4	-26.2	-27.2
	infinite.			-30.9		
B	50	-30.4	-31.1	-28.7	-26.6	-27.4
	100	-30.2	-33.8	-28.8	-26.7	-27.6
	infinite			-31.9		

GRAPHICAL FIELD MAPPING FROM CONDUCTOR NEAR ROOF & RIB CORNER WITHOUT A VEHICLE PRESENT

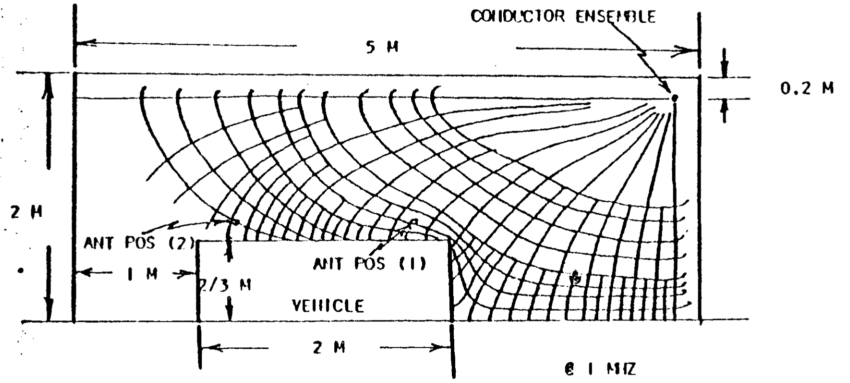


@ 1 MHZ

COUPLING FROM ANTENNA POSITION (1) -36.1 DB

COUPLING FROM ANTENNA POSITION (2) -40.6 DB

GRAPHICAL FIELD MAPPING FROM CONDUCTOR NEAR ROOF & RIB CORNER WITH A VEHICLE PRESENT



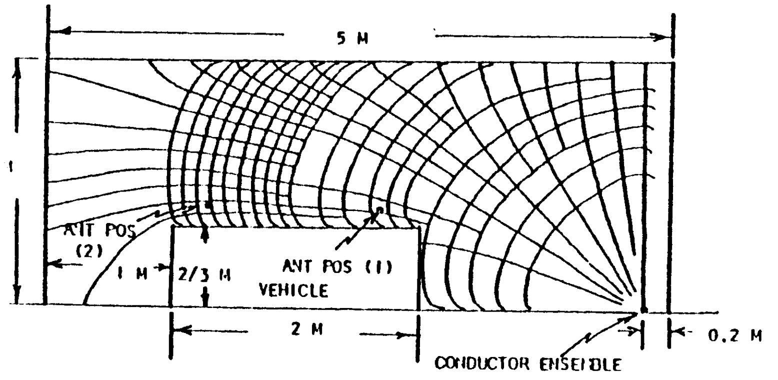
@ 1 MHZ

COUPLING FROM ANTENNA POSITION (1) -32.6 DB

COUPLING FROM ANTENNA POSITION (2) -40.8 DB

FOR ANTENNA POSITION (1) W & W/O
VEHICLE PRESENT, RATIO W TO W/O + 2.0 DB

GRAPHICAL FIELD MAPPING FROM CONDUCTOR NEAR FLOOR & RIB CORNER WITH A VEHICLE PRESENT



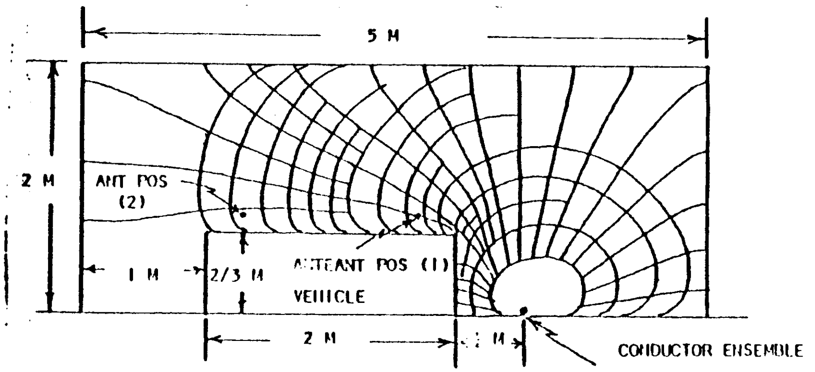
@ 1 MHZ

COUPLING FROM ANTENNA POSITION (1) -35.9 DB

COUPLING FROM ANTENNA POSITION (2) -39.1 DB

FOR ANTENNA POSITION (1) W & W/O
VEHICLE PRESENT, RATIO W TO W/O - 2.1 DB

GRAPHICAL FIELD MAPPING FROM CONDUCTOR ON FLOOR CLOSE TO VEHICLE



@ 1 MHZ

COUPLING FROM ANTENNA POSITION (1) -35.4 DB

COUPLING FROM ANTENNA POSITION (2) -46.2 DB

FIGURE 45

QUASI-STATIC GRAPHICAL FIELD MAPPING OF
ENTRY CROSSECTIONS AND COUPLING ESTIMATES
MADE FROM THESE MAPPINGS

5.5 PROTOTYPE EQUIPMENTS

The purpose of this subsection is not to present an exhaustive description of equipment available to-date; but, is to briefly review the operating parameters of these equipment, to discuss receive system sensitivity, and to present additional detail on the prototype vehicular antenna design.

To date, only four prototype radios have been built and evaluated on a limited basis in coal mines. Traditional trolleyphone manufacturers such as Femco and Comptrol are adapting their equipment for use in trackless haulage applications. The MF prototype radios to-date include:

- South African (ECAM)
- Collins (built for USBM)
- Lee Engineering (Ferry Telemetry)
- South African (RACAL)

The ECAM and Collins radio packages for Portables were very similar; being roughly 10" x 10" x 4" with self-contained batteries, top-mounted controls, voice and tone signalling, and a nominal 20 watts of power. These radios, furthermore, shared a nearly identical antenna design consisting of about 7 conductors housed inside an oval-shaped rigid tube roughly 1-inch in diameter, 0.2 m^2 area, and separately tuned to 50 ohms at single frequencies (520 kHz for Collins, 335 kHz for ECAM) for connection to the radios via a short length of coaxial cable. The major differences consist of modulation type and operating frequency.

The Collins radio used narrowband FM. The ECAM radio used SSB. The ECAM radio used a small handset whereas the Collins radio used a speaker mike. The ECAM radio was housed in a canvas carrying case with a shoulder strap whereas, the Collins radio was intended to be belt-mountable. Collins provided a table-mountable Base Station version of their radio with internal tuning for the large antenna. The Collins radio employed a 2 dB noise figure receiver. Comparative testing of these two radio types in quiet mine areas produced nearly identical communication ranges.

The Lee Engineering radio is a small unit of approximate dimensions 2½" x 7" x 7" powerable from an external 4.5 volt battery, expected to be the cap lamp battery. This SSB radio was factory tunable to a variety of single frequencies over the MF range with a power output of 6-7 watts. The radio is intended for belt mounting and uses top-mounted controls. This radio radio has been manufactured for Lee Engineering/CONSOL by Ferry Telemetry of Hiawatha, Iowa.in Portable versions only. The antenna is flexible, single-frequency matched, and connects to the radio package via a short length of coaxial cable. Limited testing by BuMines of this radio in a DC mine resulted in limited range which, presumably, was due to the inherent impulse noise susceptability of SSB radios. The ECAM radio was never carefully tested in a heavily impulse noise environment.

The most recent prototype radio available is the South African RCAL unit operating at a 1-watt level using SSB modulation and with provisions for tone signalling. This single-frequency radio is factory tunable via a programmable divider to a variety of frequencies in the MF range. The radio operated from a self-contained battery and is intended to be carried on a persons chest. The radio package itself is approximately 3" x2½" x 14" . The antenna is a flat canvas/wire strap of the bandoller type and the radio attaches directly to the antenna via a special quick disconnect arrangement. The radio has been found to be susceptable to impulse noise due to the automatic non-adjustable AGC type squelch. A 100 usecond impulse of sufficient amplitude will shut the radio down for approximately two seconds. The RACAL radio is also packaged in a table-mountable Base Station version.

A prototype vehicular antenna has been built and bench evaluated; the antenna employing a single-frequency integral matching circuit to 50 ohms. The design employs a rigid rugged electrostatic shield with a single circumferential slot to enable radiation. When balanced-fed with the shield at ground potential, the shield has no effect on the basic winding electrical characteristics. The antenna, depicted in Figures 46&47is attached to a frame which provides for magnetic mounting to a flat metallic (ferrous) surface on the vehicle. The rigid loop radiator is positionable for vertical, 45-degree, and horizontal loop plane orientations to accomodate low vehicle head clearance when necessary. The antenna winding characteristics are depicted in Figure The radiator consists of 12 circumferentially spaced turns of Litz wire in a rectangular 6-inch by 36-inch shape. The tuning characteristics of the prototype antenna(s) as built are given in Figure 48 .

The receive system sensitivity is largely determined by the antenna size. A simple formula for computing the sensitivity is given by:

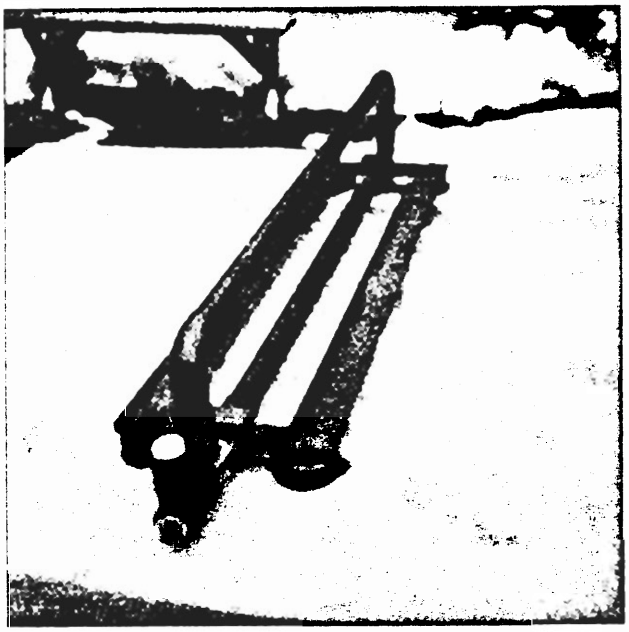
$$H_{SN} = \frac{86.9}{120\pi}\sqrt{\frac{\Delta f}{f}\left(\frac{1}{Q}\right)\frac{1}{A^{3/2}}} \times 10^{N/20} \quad \text{in uamps/meter}$$

Where, Δf is the noise bandwidth , Hz
Q is the antenna quality factor
A is the antenna area, m^2
N is the receiver noise figure

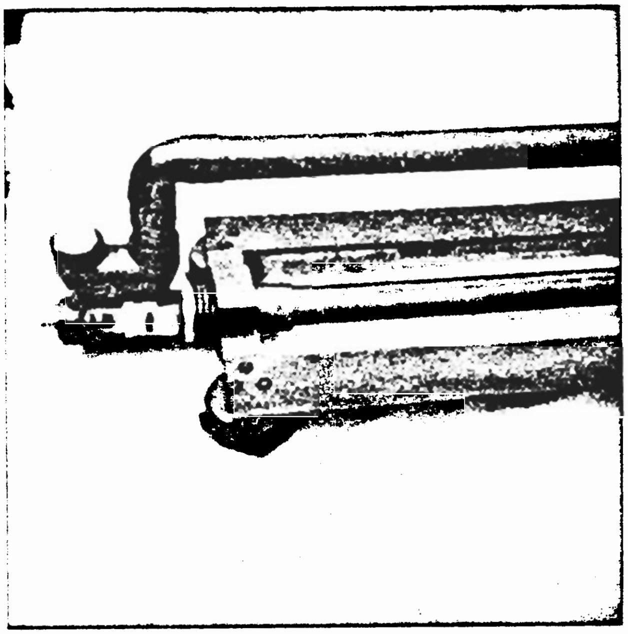
The proportionality constant has been adjusted to define the minimum incident magnetic field strength to achieve 12 dB SINAD for narrowband FM modulation (13.5 dB signal-to-noise ratio per Hamshur).

A potentially more accurate sensitivity expression is that after the method of Shimbo, and is given by:

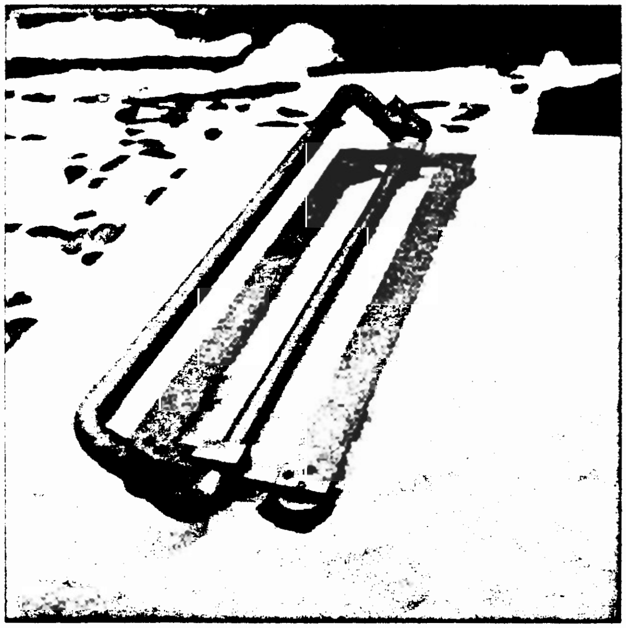
$$H_{SN} = 3686.8\sqrt{\frac{R_L\left(\frac{\gamma^2 H_n^2 + F_r}{4R_L\ k\ T_o} + F_r\right)}{fNA}}$$



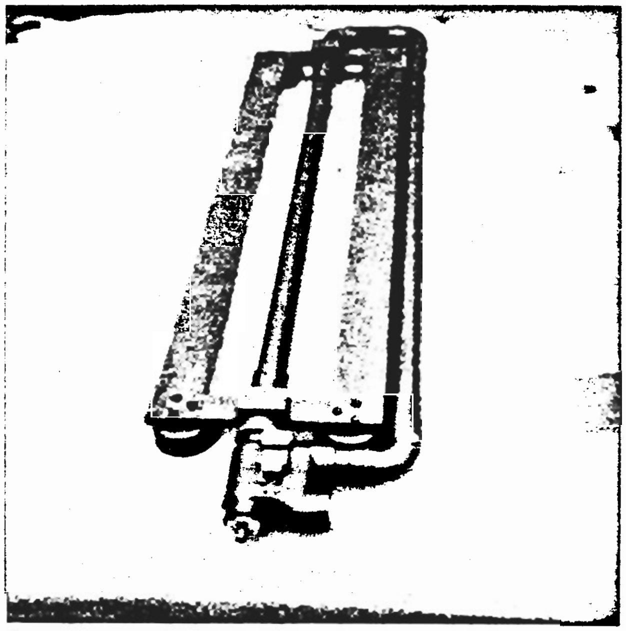
VEHICULAR ANTENNA PROTOTYPE
SHOWN WITH LOOP IN THE VERTICAL
ORIENTATION



VEHICULAR ANTENNA PROTOTYPE
SHOWING DETAILS OF THE LOOP/FRAME
MOUNTING AND OF THE CIRCUITRY ENCLOSURE



VEHICULAR ANTENNA PROTOTYPE
SHOWN WITH LOOP IN THE 45 DEGREE
ORIENTATION



VEHICULAR ANTENNA PROTOTYPE
SHOWN WITH LOOP IN THE HORIZONTAL
ORIENTATION

FIGURE 46

VEHICULAR ANTENNA PROTOTYPE

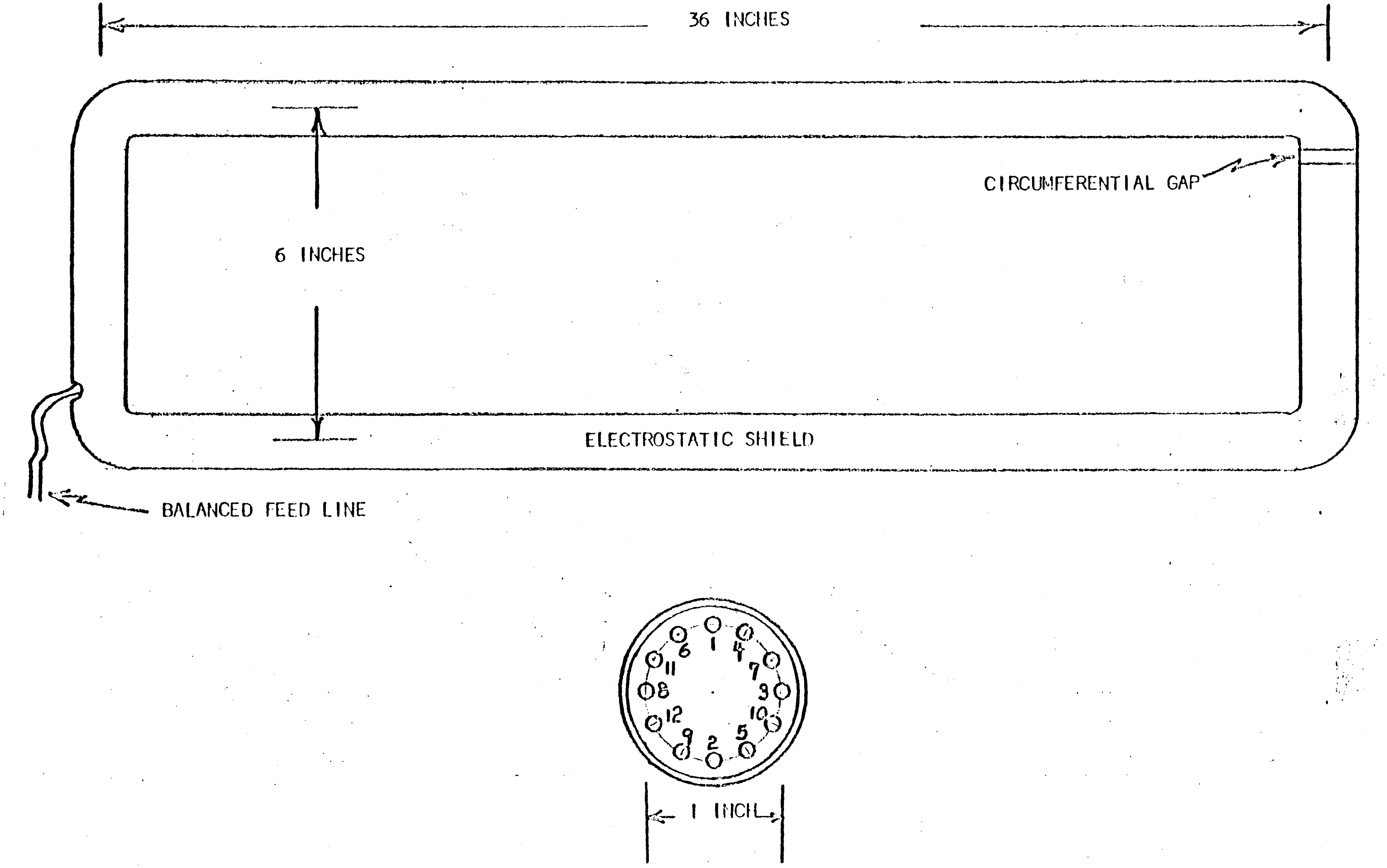
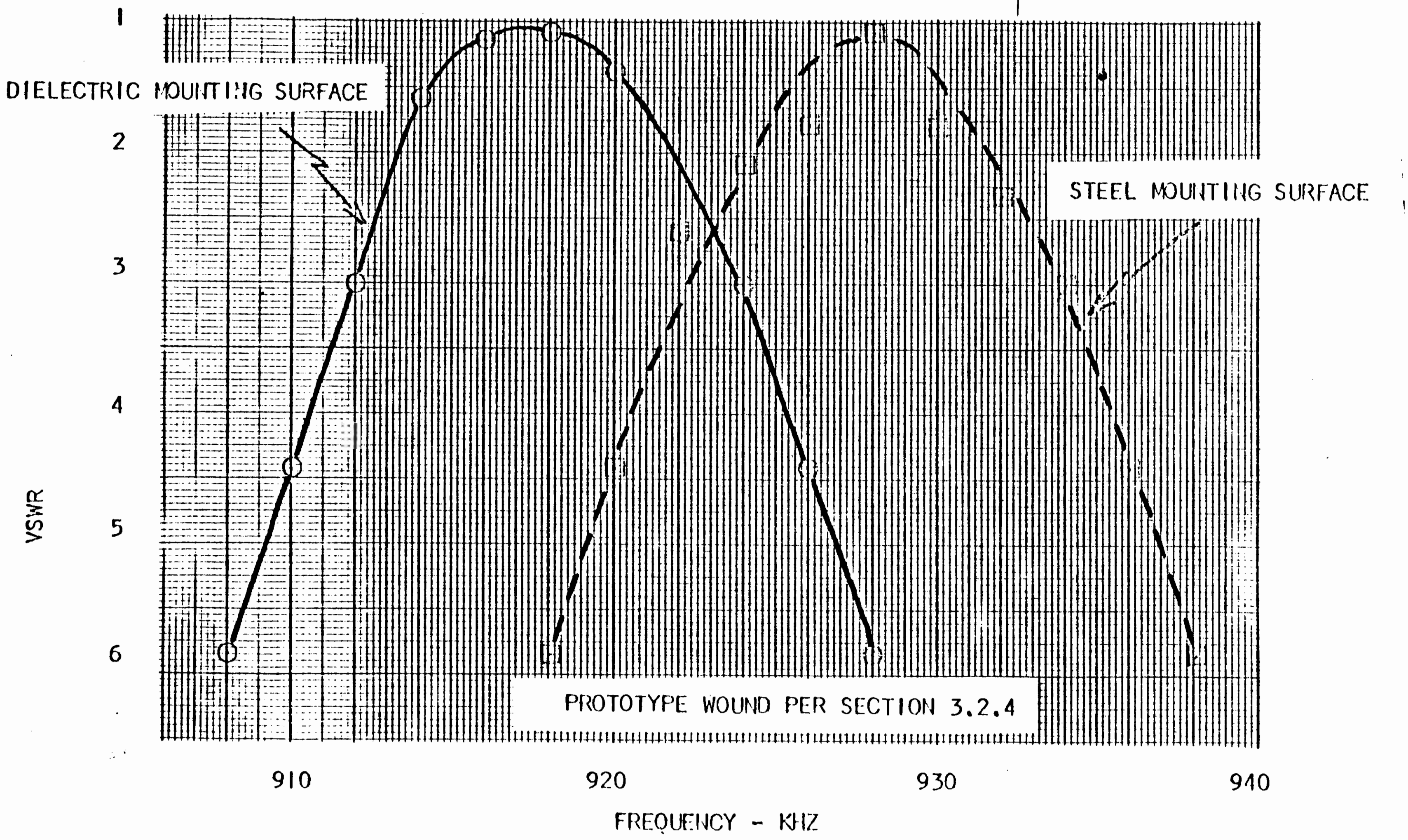


FIGURE 47

WINDING AND WIRING CONFIGURATION FOR THE VEHICULAR ANTENNA PROTOTYPE SHOWING THE CONNECTION ARRANGEMENT OF TURNS TO MINIMIZE DISTRIBUTED CAPACITANCE

FIGURE 48

TUNING CURVE FOR PROTOTYPE VEHICULAR ANTENNA TUNED TO NOMINALLY 920 KHZ SHOWING FREQUENCY SHIFT DUE TO MEASUREMENT OVER DIELECTRIC AND STEEL MOUNTING SURFACES



Where, $\gamma = 4\pi NA \times 10^{-7}$

F_r is the receiver noise figure
k is Boltzman's constant
T_o is the ambient temperature
R_L is the antenna series resistance
A is the antenna area, m^2
N is the number of turns
H_n is the external noise field strength

Comparisons of sensitivities for the Collins FM prototype radio as calculated by the simple formula(Hamshur), by the method of Shimbo, and as measured; and, as calculated by the simple formula for the RACAL radio are given in Table 8 .

5.6 APPLICATION OF OTHER TECHNOLOGIES

The system design put forth in Section 3 is capable of providing a compatible interface with either an existing pager phone system; or else, with a new select channel FDM type multiplex phone system (should one be developed). Additionally, if MF is used for long distance local area-to-local area transmission, a means to provide either direct radiation from the bifilar mode phone line, carrying the MF signal, at discrete locations or else to convert the bifilar mode to the monofilar mode transmission is needed.

Baseband audio signalling and control links from Base Station to Remote Base repeater elements could provide the interface to existing pager phone systems. Similarly, an above-base-band translation frequency on the same links could be made compatible with an FDM channel frequency on a select channel phone system. Alternatively, although not included as a link signalling option in Section 3, TDM signalling could be employed on the same links; however, the MF system element designs would become more complex.

MF energy can be extracted from a bifilar mode phone line at discrete locations or in desired localized areas by two means; placing balanced loop antennas in shunt across the line or by purposely unbalancing the line and favoring the excitation of common (monofilar) mode currents. The excitation of a single antenna can, at best, extract only a portion of the available energy from the line. Also, the antenna then radiates directly over a limited area and/or excites monofilar current in the phone line with substantial "conversion loss". More efficient energy extraction can be accomplished by either using a sequence of spaced antennas or else, a sequence of spaced "unbalancers" on the line acting as a leaky feeder and converting the energy from bifilar to monofilar.

For most efficient mode conversion, the distributed loading must slow the transmission signal wave down so that the phase velocity matches the phase velocity of the monofilar mode. An aid in visualizing this concept is afforded by considering spaced antennas as an array. The phase of the antenna currents must match the phase of an assumed monofilar mode traveling wave at the discrete locations of the element antennas. Also, as with leaky feeder structures from the bifilar exciting wave point of view, the periodically loaded modal eigenvalues must be between -1 (backward wave) and +1 (forward wave) placing the "mode" in the "visible" region.

TABLE 8

COMPUTED AND MEASURED SENSITIVITIES OF RACAL AND COLLINS PROTOTYPE PORTABLE RADIOS

	Sensitivity, dB above 1 ua/m	
(1) Collins fm radio for 12 dB SINAD & 2 dB noise figure @ 520 KHz, 12 KHz BW	(a) Hamshur	-34.0
	(b) Shimbo	-37.6
	(c) measured	-35.5
(2) RACAL SSB radio 0.2 uv for 15 dB S/N	For 10 dB S/N	-34.9

Spaced antennas can accomplish this slow wave loading with shunt capacitance, meaning that the antennas must be tuned with their input impedance being capacitive. Alternatively, the use of unbalanced devices on the line must effectively use series inductance to slow the wave down. The efficient extraction on energy from the bifilar line does involve some impedance matching for antennas and/or minimizing the reflection of incident energy when using line "unbalancers". This may require both shunt C and series L so as to be able to vary the characteristic impedance of the line. It should be possible to build "clip-on" devices to be periodically spaced on the phone line for mode conversion.

5.7 MODULATION

This section deals with the qualitative comparison of narrowband FM vs single side band (SSB) modulation and, given FM as the choice for mine wireless radio systems, the factors governing the frequency separation required for operation of the Repeater Elements.

The early South African (ECAM) as well as the more recent RACAL and Lee Engineering radios have employed SSB modulation. The Collins prototype radios employed narrowband FM (m = 1, ± 3 kHz deviation). Unfortunately, all early comparisons of ECAM and Collins radios were performed in quiet areas of mines; the two being very nearly equal in performance in this type of environment. Only recently (within the past year) have SSB radios been tested in potentially noisy areas of mines. The results of recent tests have suggested that the SSB radios are inherently susceptable to mine noise; particularly impulsive noise.

The hypothesis for the impulse noise susceptability of SSB radios resides in the inherent linearity over a large signal and noise dynamic range requirements imposed on SSB radios for use in mines. The linearity,of course, is inherent to SSB modulation. To provide good dynamic range for steady state signals, SSB radios employ a fast-attack/slow-release AGC. The hypothesis contends that the occurance of noise impulses is such that the fast AGC attack "shuts the radio down" and another impulse occurs before the AGC can release so that the radio stays "shut down". The alternative of "opening up" the AGC circuitry would cause excessive distortion when the impulses are of much higher amplitude than the signal. A detailed statistical analysis of impulse noise characteristics in DC mines has not been performed, but the data taken in the Harewood mine suggests that

- The average impulse amplitude is about 18 dB above the average "broadband noise level
- The average noise impulse basewidth varies between 333 and 1000 microseconds
- The average occurrance rate of impulses is between 2-6 milliseconds

This hypothesis is based on operation inclose proximity to mine wiring conductors and, in particular, in DC mines. In quiet areas of mines, which probably comprise all areas removed at least 1-2 entries from conductors, the classic advantage of SSB in providing better intelligibility than FM for signals near threshold holds. The choice of modulation type is then dependent on the expected locations within mines where the radios will be operated. In DC mines, the choice is clear; FM will be necessary to effect operation near conductors at all. For trackless haulage operation in AC mines, the choice based on the above arguments may not be so clear; not only in that impulses of high amplitude will be less likely to occur, but also in that the expected signal-to-noise dynamic ranges are smaller and rather well ordered. Perhaps the possible eventual usage of MF radios in metal/non-metal mines provides the "push" for FM where, again, the noise environment near conductors is expected to be impulsive.

Other arguments can be made for the use of FM over SSB. The author's contention for the selection of FM over SSB is built on three factors:

- The potential advantage of SSB over FM in threshold sensitivity (intelligibility) is of marginal significance in the first place and represents about a maximum of 7 dB improvement assuming that narrower bandwidth antennas can be used for receiving SSB signals (a questionable assumption at best if flexible Portable antennas are envisioned).
- Although the SSB system is perhaps more conservative of transmitter RF power than is FM, the number of low level class A stages required equalize this potential advantage in terms of battery drain. The FM system is expected overall to operate longer from a given battery than is an SSB system
- Use of narrowband FM is compatible with FSK data transmission (equipment design wise via circuit commonality) so that common radio design techniques apply for both FSK and FM voice systems

The comparison of intelligibility of FM vs SSB is summarized in Table 9 . The maximum potential advantage of SSB, which occurs for a low articulation index of 0.2, presumes a 3 dB narrower bandwidth antenna. On this basis, SSB is potentially better than FM in quiet areas by 7 dB on an average power basis with SSB and FM being about equal on a peak power basis.

The frequency separation required at MF for repeater operation to essentially provide the full receiver sensitivity is governed primarily by modulation spectrum fall-off as opposed to broadband noise. This is because the spectral width of FM voice signals is a greater percentage of the operating frequency at MF than it is, for example, in the VHF land mobile bands (where broadband noise predominates). The broadband noise of a well designed phase-locked-loop exciter in a 12 kHz band is expected to be 80-85 dB down 20 kHz away and 110-115 dB down a MHz away from the center frequency.

TABLE 9

SUMMARY COMPARISONS OF FM VS SSB MODULATION BASED ON INTELLIGIBILITY

NON-IMPULSIVE NOISE

ARTICULATION INDEX	AVERAGE POWER BASIS COMPARISON
0.2	SSB BY 4.0 DB
0.3	SSB BY 0.5 DB
0.4	FM BY 2.2 DB

IF IT WERE POSSIBLE TO DESIGN TO A STABLE 3 KHZ BANDWIDTH, THE MAXIMUM SSB ADVANTAGE (ARTICULATION INDEX = 0.2) WOULD BE 7 DB

SSB, OPTIMALLY CLIPPED, HAS ABOUT A 7 DB PEAK-TO-AVERAGE POWER RATIO; THUS ASSUMING THE MAXIMUM ADVANTAGE, SSB & FM IN BROADBAND NOISE ARE ABOUT EQUAL ON A PEAK POWER BASIS

The spectral roll-off of a narrowband FM signal of m=1 is illustrated in Figure 49 which shows a 12 dB/octave roll-off. To achieve full receiver sensitivity, the received signal should be about 160 dB below the output of a 5-watt transmitter. A graph showing the composite fall-off of a 4-pole filter plus normal spectral roll-off is given in Figure 50. The composite roll-off is expected to be 36 dB/octave so that a level of -160 dB is achieved about 65 kHz away. This represents roughly a 10% frequency separation. Note that at 65 kHz, the spectral portion of the roll-off of about -71 dB is roughly 20 dB higher than the expected boradband noise level of -92 dB. The minimum frequency separation is, thus, expected to be 10%.

5.8 INTRINSIC SAFETY CONSIDERATIONS

This section assumes that the MSHA requirements for obtaining intrinsically safe circuit design have been updated from Schedule 2G to those of UL-913.

The design of antennas and transmitter RF circuitry for MF systems can easily be made intrinsically safe for a nominal 5-watt power level for battery voltages between 4.5(cap lamp) and 24 volts. The antenna circuits operate in the constant power (voltage-current curve) rather than the constant energy region of the curves. The antenna design parameters are such that the use of blocking capacitors to isolate the antenna circuit are not required. High impedance antenna designs (such as are required for optimum vehicular antenna operation) can be shown to be inherently intrinsically safe. Low impedance Portable antenna designs can be made intrinsically safe with the addition of small current limiting resistors which will not degrade the RF efficiency of the antenna.

This section presents an "appeal" to provide a consistant and systematic means for the intrinsic safety evaluation of MF antennas. Additionally, the subject of "AC intrinsic safety" is important for ensuring that all transient current levels are accounted for.

Intrinsic safety requirements are geared toward preventing potentially dangerous dc sources from producing arcs which might explode a methane-air mixture under fault conditions in coal mines. The curves for minimum voltage-current combinations, minimum ignition current in inductive circuits, and minimum ignition voltage in capacitive circuits apply strictly to dc excitation of circuits. The ac excitation of antenna circuits at radio frequencies are not explicitly covered by the curves. The proceedure for inductive circuit protection now being applied involves isolating the antenna circuit from potential dc sources through the use of blocking capacitors. The requirements for these blocking capacitors come from UL-913 whereby two capacitors are placed in series and then tested for voltage breakdown with an ac voltage level equal to twice the working (potential fault) voltage + 1000 volts rms.

It is reasonable to expect that arcs from ac sources at radio frequencies under fault conditions could explode a methane-air mixture in a circuit not intrinsicly safe at dc. It is also reasonable to assert that dc circuit performance represents the worst case; thus, a circuit which is "dc intrinsically safe" will also be "ac intrinsically safe".

FIGURE 49

FM VOICE MODULATION SPECTRUM, M = 1

DEVIATION = ± 3 KHZ

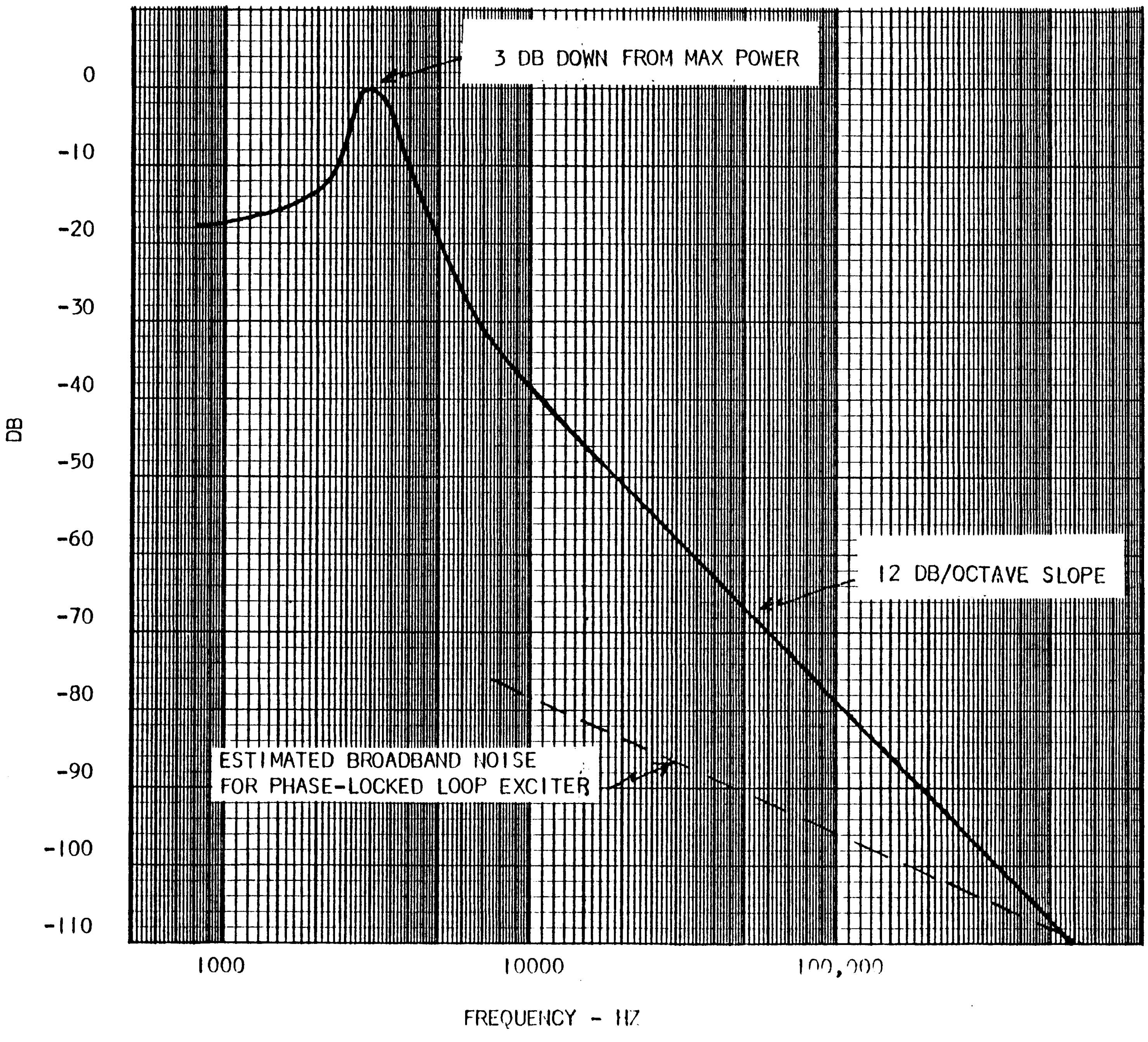
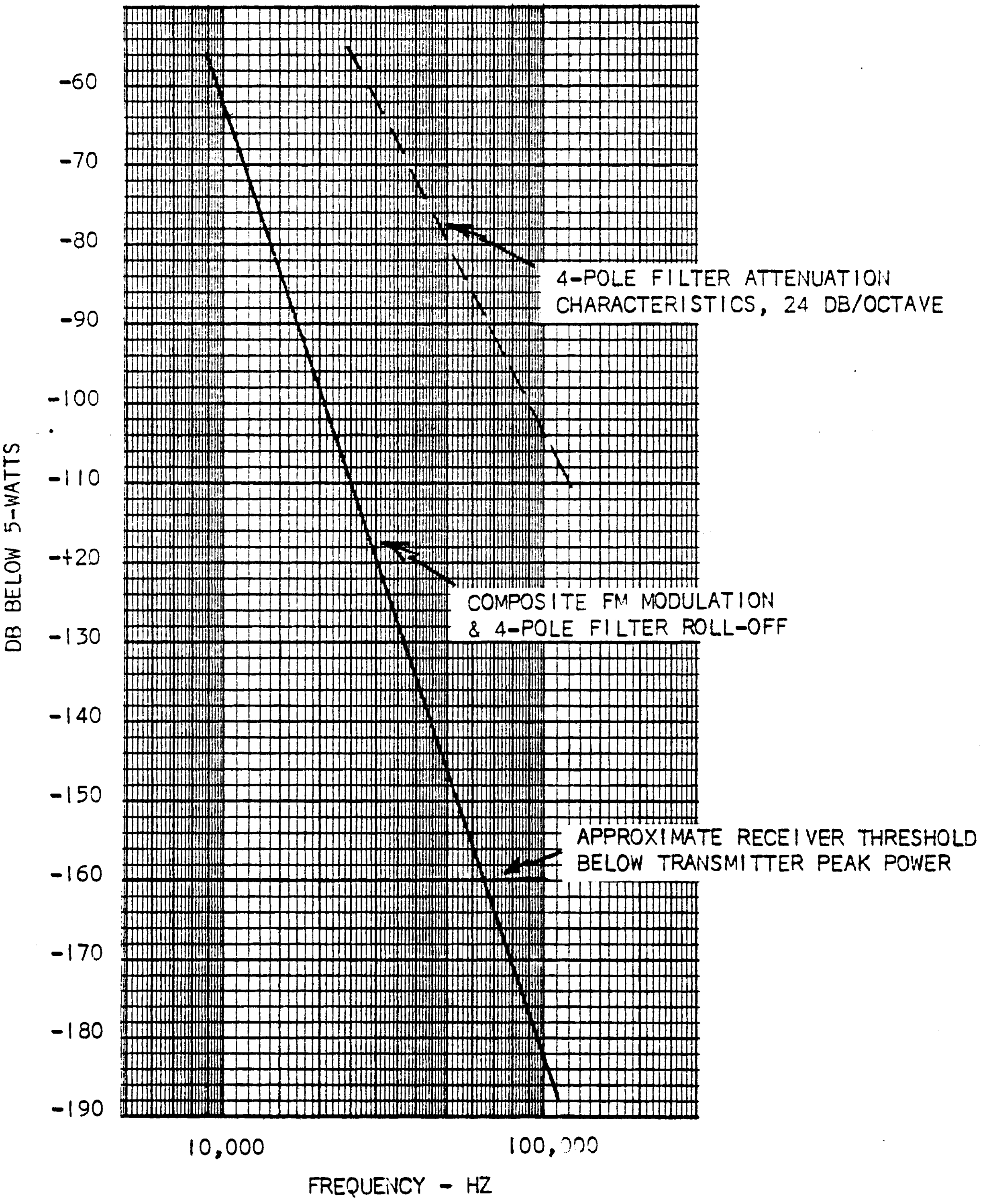


FIGURE 50

MINIMUM FREQUENCY SEPARATION FOR ACHIEVING FULL RECEIVER SENSITIVITY FOR REPEATERS



It is probably to the designer's advantage to take any steps toward making an antenna "dc intrinsically safe", over and above any blocking isolation, if this can be accomplished without serious performance loss. This could be termed the "inherent safety factor" of the antenna.

Toward evaluating ac intrinsic safety, it may be worthwhile to define operating power levels for which the antenna would be intrinsicly safe if the dc and ac aparameters were the same and the dc curves could be applied.

It is possible to at least partially protect a loop antenna without loss of performance so as to achieve some inherent safety. This is possible because the NIA of a loop antenna of restricted dimensions is relatively constant over a range of numbers of turns and because there are ac losses in the antenna other than those encountered in the wire resistance. Specifically:

(1) impedance level; the antenna low-frequency wire resistance should be as high as is practical without reducing NIA in order to minimize the peak current which could flow in the circuit. This is accomplished by using as many turns as possible.

(2) added series loss; the antenna matching circuitry losses will produce an equivalent series antenna loss resistance in addition to the wire resistance. A lumped current-limiting resistor of value comparable to the above loss resistance can be added without reducing the NIA significantly. The lumped resistance will retain its value at dc whereas the wire resistance will not.

It is better, in designing to a fixed allowable wire resistance, to use Litz wire and then add a lumped current-limiting resistor than to use solid wire or stranded wire having the same resistance as the Litz plus the lumped resistor.

Assuming the dc curves apply, the current in the loop as a function of input power is given by

$$I^2 = \frac{P}{2\pi L(BW)} .$$

In terms of stored energy,

$$\tfrac{1}{2}LI^2 = \frac{P}{4\pi(BW)}$$

where, P is the input power
L is the inductance
(BW) is the 3 dB bandwidth

so that for a fixed maximum energy level, the allowable bandwidth is a function only of the input power. If for a fixed input power and bandwidth the current is to be minimized, then the current is inversely proportional to inductance, so the inductance should be as large as possible while still maintaining the bandwidth.

The minimum ignition current curve is given for 24 volts and essentially plots a constant energy level, which determines the bandwidth power relationship for that voltage level. For other voltage levels (as defined on the voltage-current curve), the constant energy level varies. If the antenna parameters are fixed, as in any particular design, then the power cannot be independent of energy level and must follow the voltage-current curve.

The inductance of the vehicular antenna @ 1 MHz will be shown in the next section to be approximately 190 uh . To illustrate possible power-bandwidth limits for "ac intrinsic safetyy", calculations were made assuming

(1) a constant energy of 0.5 millijoule
(2) energy-power as defined from voltage-current curve and antenna parameters
(3) Inherent intrinsic safety provided by 5 and 10 ohm current-limiting resistors

The results of these calculations are given in Figure 51. This figure shows the voltage-current derived condition to be the most stringent in restricting the minimum bandwidth for higher power levels for a 50 ohm matched antenna. Using this condition as the basis, a 10-ohm current limiting resistor (for example) provides inherent protection up to a power level of about 11 watts.

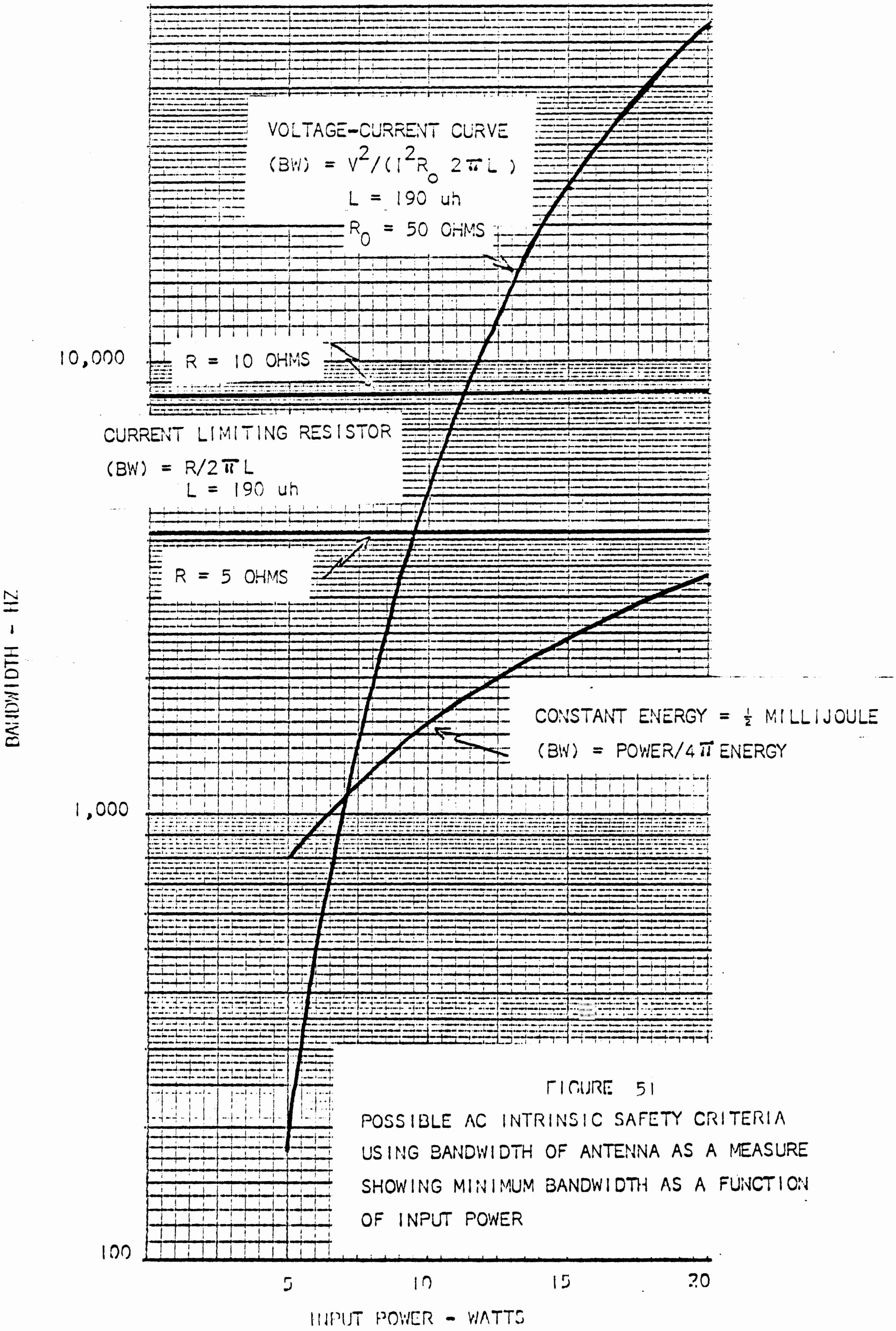


FIGURE 51

POSSIBLE AC INTRINSIC SAFETY CRITERIA USING BANDWIDTH OF ANTENNA AS A MEASURE SHOWING MINIMUM BANDWIDTH AS A FUNCTION OF INPUT POWER

6.0 SYSTEM CAPABILITY DEMONSTRATION PLAN

This section contains the elements of an MF system demonstration plan based on the predicted results and configuration alternatives for the Lucerne #8 mine from Section 3.5.

6.1 OBJECTIVES OF DEMONSTRATION/TESTING

The purpose of the demonstration/testing is to:

- Demonstrate the communicating capability of a mine-wide MF system design; get mine personnel reactions
- Test particular generic radio links and combinations of Radio Terminal Element types independent of the particular overall system configuration
- Confirm and/or improve upon the MF system performance predictive model capability
- Identify any particular factors or features associated with an MF system and/or the particular designs of prototype Radio Terminal Elements which will either constrain or enhance mining operations

The overall demonstration plan should include a period of operational usage by mine personnel so as to provide subjective information such as reliability, maintainability, user acceptance or rejection, logistics, and traffic density/channel (which may influence the spacing, location, and type of Repeater Elements chosen).

To serve these ends, the demonstration/testing plan provides for definite phases which include:

Phase I Installation & Scientific Data Gathering

performed by USBM and/or communication system Contractor personnel

Phase II Capability Demonstration & Mine Personnel Training

involving technology transfer between USBM/Contractor and mine personnel

Phase III Operational Evaluation & Support

performed by mine personnel using the system with USBM/Contractor furnished logistical support

At an appropriate time in either Phase II or Phase III, the plan should provide for demonstrating the capability to operations personnel of other mines/mining companies and to communication system manufacturing representatives.

6.2 PROPOSED SYSTEM CONFIGURATION

The system configuration for demonstration/testing is proposed to embrace the use of Portable, Vehicular, and Base Station Radio Terminal Elements and of Line Amplifier and Remote Base Repeater Elements. Use of a Line Coupler Repeater Element may be included in a section, although its use is not further addressed in the technical details of the plan in this section.

Prior to obtaining field strength measurements in the Upper Freeport seam, the Lucerne #8 mine was considered by the author to be too small in extent to adequately demonstrate system capability. This was based on assuming that the seam characteristics would be similar to those experienced in the Pittsburgh seam.

Now, the Lucerne #8 mine appears to be ideal for system demonstration/testing at MF. This is because:

- The North and South Main areas can be adequately partitioned with little interference from one area to another expected
- Each North and South Mains area can be adequately served using a single haulageway repeater (extended quasi-conductor-free range in rooms without conductors may be improved by using an additional repeater there)
- Measurements supporting the use of either a Line Amplifier or a Remote Base type repeater, including interference fringing, can conveniently be made in the general location of the portal.

The particular repeater locations, of Section 3.5, have been chosen based on the assumption of using Line Amplifiers. These locations can be adjusted somewhat using Remote Base Repeaters; however, the selected locations are approximately correct for both types.

The plan calls for testing both types of repeaters in these locations and, during Phase I (or perhaps early in Phase II) selecting the best performing type for continuation into Phases II and III.

The complement of system equipments expected to be required for the demonstration/testing includes:

2 ea	Base Stations (one unit underground near the portal and one on the surface)
2 ea	Remote Base Repeaters
2 ea	Line Amplifier Repeaters
1 ea	Line Coupler Repeater

The Vehicular and Portable radio complements consider outfitting two sections (onein each of the North and South Mains) plus maintainance and supervisorypersonnel. These complements are inclusive of:

- 18 ea Vehiculars-
  - 2 ea electrical maintainance jeeps
  - 2 ea mechanical maintainance jeeps
  - 4 ea mantrips
  - 2 ea shop vehicles
  - 2 ea miscellaneous supply vehicles
  - 4 ea section (2 ea extra for testing in each of 2 section vehicles)

- 18 ea Portables-
  - 8 ea(4 ea/section)
  - 2 ea mechanical maintainance foremen
  - 2 ea electrical maintainance foremen
  - 2 ea supervisory or inspectors
  - 2 ea spares
  - 2ea shop/portal area personnel

6.3 DEMONSTRATION/TESTING TECHNICAL APPROACH

Phase I-

The first step in testing is to install the Base Station plus one or two Vehicular radios and to determine the ranges V-V, V-P, P-P, V-B, P-B in operationally significant areas of the mine without repeaters and for both close coupling and remote coupling I-entry away. This testing will include determining the effect of line characteristics; namely, taps/branches and SWR (identifying any "dead" zones).

The second step is to install the haulageway repeaters (one type at a time) and to determine V-B, P-B coverage for an assumed single user in all operationally significant areas of the mine. Next, the multiple user and interferance related characteristics will be determined. These include:

- The interferance fringing produced,due to simulcast transmissions, in the portal area; defining the effect on Base Station reception, if any
- The threshold "capture" levels for simultaneous multiple users desiring repeater access
- The distortion caused by multiple "unhearing" Vehiculars or Portables accessing the repeater(s) at approximately the same amplitude level
- Deducing the ground rules for operation when a Vehicular or a Portable radio is close to a repeater

From these studies, the locations chosen for the repeaters will be evaluated and the locations will be modified as required.Depending on the detailed operations in sections, the Line Coupler Repeater may be installed, evaluating the range extensions away from conductors achievable for Portable or Vehicular operation in a quasi-conductor-free environment.

The above scientific studies will be used in conjunction with the system performance predictive model, modifying the model (if required) toward obtaining compatible theoretical and experimental results.

The operational significance of particular communication links will be determined from mine supervisory personnel during Phase I and will impact the details of the testing.

Phase II-

The first step is to conduct orientation sessions for potential user personnel on the capability of and the mainatainance of the radio system. Specific emphasis will be placed on acquainting dispatcher or communication center personnel on the capabilities.

Some of the Vehicular and Portable radios will be disseminated selectively to mine supervisory and maintainance personnel for a "preliminary evaluation" of capability and user acceptance. The results of this evaluation will govern the detailed plans for incorporating additional radios into the system large enough for a demonstration.

The next step will involve a brief familiarization and training program (if required) and then the demonstration of the system capability to all mine personnel. Some mine personnel will only be convinced of the utility of the system once they are actively using it; others will require only a comprehensive demonstration of capability.

Phase II is expected to result in some modificationsof the overall configuration to accomodate particular requirements. These modifications will be accomplished prior to a longer term evaluation program which is the objective of Phase III.

Phase III-

Phase III embodies a relatively long term evaluation of the fully operational system including logistical support to be furnished by USBM/Contractor.

The first step in Phase III is the "hand-off" of the system to the mine for normal maintainance and support. During the first part of this, USBM/Contractor personnel will periodically evaluate the condition and operability of the System Elements, systematically recording the reliability/maintainability experiences. This step will establish the true cost basis of such a system to the mine.

The second step in Phase III involves a combined mine/USBM analysis of the system benefits, system features, and identification of additional features which, if available, would enhance the value of the system.

Throughout Phase III, control of spare/repair parts inventory will be the responsibility of USBM/Contractor to ensure proper service and the establishment of records.

Also during Phase III will be an organized "public relations" effort toward technology transfer to the industry based on the "test-bed" system under evaluation.

6.4 DEMONSTRATION/TEST TASK SCHEDULE

6.4.1 TASK & SCHEDULE DESCRIPTIONS

Considering the MF System Elements to be on-hand at the start of this activity, a program involving approximately 23 months is envisioned.

Phase I is estimated to require 3 months for completion; allowing,

(1) 1-month for initial installation of the Base Station and selected Vehicular radios

(2) 1-month for gathering scientific data and for the installation of repeaters

(3) 1-month for data evaluation and for Phase II planning,

these steps to be roughly sequential.

Phase II is estimated to require 8 months for completion; allowing,

(1) 1-month for user orientation

(2) 1-month for preliminary system evaluation by supervisory personnel and for planning the overal mine demonstration activity

(3) 2-months for installation of the remaining Vehicular radios

(4) 1-month for personnel training and familiarization with the system operation

(5) 2-months of capability demonstration via trial operation of the entire demonstration system

(6) 2-months for assessment of results and mine system reconfiguration, if necessary

Steps (1) & (2) performed concurrently, 2-months elapsed time

Steps (3) & (4) performed concurrently, 2-months elapsed time

Steps (4) & (5) performed concurrently, 2-months elapsed time

Step (6) performed sequentially following Steps (4) & (5)

Phase III is estimated to require 12 months, minimum, for completion; allowing,

(1) 2-months for "hand-off" of responsibility for normal maintainance and support; USBM/Contractor furnishing very close support

(2) USBM/Contractor visits every 30-60 days to examine equipment, and to review the system operational experience for the remaining 10 months

(3) USBM/Contractor providing "on-call" support and high-level repair and maintainance of the system

(4) USBM/Contractor meetings periodically with mine personnel for overall reviews; also providing during pre-planned demonstration activities to the mining industry

6.4.2 ESTIMATED LEVEL OF EFFORT

Phase I is estimated to require the equivalent of 2 men full time for 3 months; or approximately 126 man days of effort.

Phase II is estimated to require the equivalent of 1 man full time for 8 months; or approximately 168 man days of effort.

Phase III is estimated to require the equivalent of ½ man full time for 10 months and 1 man for 2 months; or approximately 147 man days of effort.

7.0 REFERENCE INDEX OF MF TECHNOLOGY RESOURCES

This section is intended as a resource guide to available literature on MF technology pertaining to underground coal mines. Many of the documents listed in this section are not in the open literature, including NTIS. Access to these documents may be obtained through consultation with U.S. Bureau of Mines PMSRC technical personnel at the Bruceton Research Center or via contact with the author(s). General release of information may be subject to governmental approval.

The documents are herein divided according to subject matter; the major topical areas being subsections of this section.

7.1 MEASURED PROPAGATION DATA

The following two reports were prepared under USBM Contract H0346067, Phase I, Rockwell/Collins Subcontract C-651171 by Spectra Associates, Inc. entitled "Mine Wireless Propagation Test Program".

(1) Cory, T.S., "Summary Data Report-1, Rose Valley Mine Measurements", 7 January, 1975

This composes the first documented set of MF field strength measurements ever made. This report is contained as Appendix III to the Mine Wireless Phase I Final Report. Rose Valley is an AC mine.

Measurements were performed in the I-Left, Main East working section of this mine in the Pittsburgh seam. Data includes quasi-conductor-free field strength, field strength near conductors (4160 VAC cable and phone line) and conductor current distributions. Test transmit antennas included the coal pillar VMD. Field polarization of the receive antenna was varied. South African (ECAM) and Motorola UHF portables were range tested.

HMD polarization was observed for the first time to provide the strongest coupling, but close proximity to conductors precluded positive identification of it as the exciter of the primary conductor-free coal seam propagation mode.

(2) Cory, T.S., "Summary Data Report-2, Ireland Mine Measurements", 12 March, 1975

This comprised the first documented results in a conductor-free area in a coal mine. HMD polarization was confirmed as providing the strongest coupling in the coal seam. Ireland is a DC mine.

Measurements were performed in the 8-North Escapeway area of the mine. Magnetic field strength vs range and frequency was obtained; also, the maximum range limit of the ECAM radios was determined. The August 1974 observations of BuMines personnel in this same mine were confirmed with range; with a range of 1200 feet in the Pittsburgh seam being verified.

The first maximum communication range vs frequency curve used as the basis for the Collins FM Mine Wireless radio development was derived.

The following six reports were prepared under USBM Contract H0366028, Rockwell/Collins Subcontract C-651333 by Spectra Associates, Inc. entitled "Propagation of EM Signals in Underground Mines".

(3) Cory, T.S., "Summary Data Report-1, Ireland Mine Test Data at Medium Frequency," 1 October 1976.

Measurements were performed in the 8-North Submain,close to the 8-North Escapeway of Reference (2), one entry removed from the AC power cable. The presence of the cable was observed not to cause a decrease in field strength (null regions). Both principal HMD polarizations of magnetic field were taken. 1000 kHz was observed to produce the greatest field strength excitation.

The first measurement of a field strength "shelf" due to conductor scattering was made and observed. Quasi-conductor-free ranges in excess of 1000 feet were again observed.

Data was gathered comprising the first "area coverage" field strength contour mapping in the 8-North 3-Right working section. This data showed for the first time that complete area coverage of a working section panel could be obtained from a single transmitter location near the section belt headpiece.

(4) Cory, T.S., "Summary Data Report-2, Sesser Mine Tests at Medium Frequency and UHF," November 1976.

Measurements were performed in the Esat Mains and in the East 5-Left, 6-Left, and 9-Right working sections. Comparative testing of the Collins FM Mine Wireless prototype and the ECAM SSB radios were made in a quasi-conductor-free area. The measurements included quasi-conductor-free magnetic field strength tests and extensive magnetic field strength mappings. The maximum range of the UHF portable radios was also observed. Sesser is an AC mine.

These measurements,in the Herrin #6 seam, were the first to be made out of the Pittsburgh seam. The results exhibited a greatly decreased quasi-conductor-free maximum range of about 400-500 feet.

Comparable ranges were observed with the FM and SSB radios; the Collins FM radio having a slight edge over the ECAM SSB radio.

The first confirmation of carrier current conducted in mine wiring producing in excess of one mile of communication range was obtained.

The Herrin #6 seam exhibited the highest field strength attenuation properties with range of any coal seam measured to date.

(5) Cory, T.S., "Summary Data Report-3, Consolidation Coal Mine No. 95 (Robinson Run Portal)," December 1976.

Measurements were made in the Main North 2-West area of this mine; consisting of both quasi-conductor-free and conductor-proximity data. This mine was the third to be used for tesing in the Pittsburgh seam. Robinson Run is a DC mine.

The results in this mine confirmed the results from the Rose Valley and Ireland mines. Testing was limited, for the first time, to the principal HMD polarization except near conductors.

(6) Cory, T.S., "Summary Data Report-4, Eastern Associated Coal Federal No. I Mine (Eddy Portal)," December 1976.

Testing was conducted in two areas of this DC mine in the Pittsburgh seam; the 8-Main-North and 3-Main-Left working sections 10 and 22. Both quasi-conductor-free and conductor-proximity magnetic field strength data were gathered.

The results in this mine again confirmed previous measured results in the Pittsburgh seam. The resulting data curves were so well ordered that they have been used by the author as being typical of the Pittsburgh seam for system calculations.

(7) Cory, T.S., "Summary Data Report-5, Island Creek Coal Co. Virginia Pocahontas No. I Mine," February 1977.

Testing was conducted in two areas of this DC mine in the Pocahontas #3 seam; the 2-North #I Plow and 3-South areas. This was the first mine in low-medium coal in which measurements were made. Both quasi-conductor-free and conductor-proximity magnetic field strength data were gathered. Also, the Collins FMprototype radios were range tested both in a room-and-pillar area and through a solid block of coal.

The concept of scatter gain was first applied to measured results to predict the field strength in proximity to conductors.

This is the first mine in which the in-seam field strength was observed to be significantly topology dependent.The apparent maximum communication range between portables was 140-150 meters through the coal block compared with up to 280 meters in the room-and-pillar area.

Quasi-conductor-free ranges were intermediate to those typifying the Pittsburgh and Herrin #6 seams.

(8) Cory, T.S., "Summary Data Report-6, Peabody Coal Co. Mine No. 10," March 1977.

Testing was conducted in two areas of this DC mine in the Herrin #6 seam; the 1-South 1st West and $5\frac{1}{2}$-East/1-South & 1-South Main junction areas. Both quasi-conductor-free and conductor-proximity magnetic field strength data were gathered.

The results confirmed the previous Sesser results in the Herrin #6 seam.

Further evidence of the topological dependence of field strength data was obtained for frequencies above-1000 kHz.

A particular trolleyphone branch signal "suck-out" problem was analyzed and reported.

(9) Cory, T.S., "Propagation of EM Signals in Underground Mines," Spectra Associates, Inc. on Subcontract C-651333 for Rockwell/Collins under BuMines Contract H0366028, September 1977.

This final report summarizes the results of references (3) - (8). Computation of maximum communication range in quasi-conductor-free areas were made using Collins FM prototype equipment parameters and set-noise/median-mine-noise.

The details of the measuring equipment arrangement and calibration are described including the development and packaging of the test transmitting equipment.

The Following five reports were prepared under USBM Contract H0377053, Rockwell/Collins Subcontract C-651672 by Terry S. Cory, P.E. entitled "Electromagnetic Propagation in Low Coal Mines at Medium Frequencies."

(10) Cory, T.S.,"Summary Data Report-1, Helvetia Coal Co. Margaret #11 Mine", January 1978.

Testing was conducted in two areas of this AC mine in the Upper Freeport ("E") seam; quasi-conductor-free magnetic field strength measurements were performed in the 1-Butt section and conductor-proximity measurements were performed in the 2-Butt section.

The quasi-conductor-free field strength attenuation rate in this mine was exceeded only by that experienced in the Herrin #6 seam.

This mine is in the same seam as Lucerne #8 which employs roughly comparable mining techniques. The data from this mine has been used to estimate MF system performance in Lucerne #8.

(11) Cory, T.S., "Summary Data Report-2, Upshur Coals Corporation Adrian Mine," February 1978.

Testing was conducted in the area parallel to Road 83C between 1st Right and 2nd Right in this DC mine in the Upper Freeport ("E") seam. This mine is in high coal near where the Upper Freeport seam outcrops.

Magnetic field strength data was obtained for the quasi-conductor-free case only at 90 & 220 kHz due to equipment malfunction.

(12) Cory, T.S., "Summary Data Report-2, Bethlehem Steel Coal Mine #31 Nanty Glo," March 1978.

Testing was conducted in two widely separated areas in this large old DC mine in the Lower Kittanning ("B") seam; the Main N and 5-Cross areas. Both quasi-conductor-free and conductor-proximity data were gathered.

Conductor-proximity data was gathered for the first time in a form to enable the direct determination of scatter gain from the measured data.

Data was gathered for the first time in a particularly low head clearance area where gob largely filled the entry crossection in which measurements of magnetic field strength were being made.

The maximum communication range for this seam was intermediate to the Upper/Lower Freeport and Pittsburgh/Elkhorn #3 seams.

(13) Cory, T.S., "Summary Data Report-4, Bethlehem Steel Coal Mine 38D Ehrenfeld," March 1978.

Testing was conducted in the 1-Right Main B area of this DC mine in the Lower Freeport("D") seam. Both quasi-conductor-free and conductor-proximity magnetic field strength data were gathered.

Again, conductor-proximity data was gathered in a form comprising the direct measurement of scatter gain.

Maximum communication ranges for the Upper and Lower Freeport seams were observed to be comparable.

(14) Cory, T.S., "Summary Data Report-5, National Mine Corp. Stinson #3 Mine," May 1978.

Testing was conducted in the C-Section area of this AC punch mine in the Elkhorn #3 seam. Both quasi-conductor-free and conductor-proximity magnetic field strength data were gathered.

Conductor-proximity data was gathered with primary emphasis on the partitioning of field strength polarization. VMD polarization was determined to be predominant at low frequencies; HMD polarization was determined to be predominant at higher frequencies.

Quasi-conductor-free maximum communication range was observed to be second only to the Pittsburgh seam.

(15) Cory, T.S., "Electromagnetic Propagation in Low Coal Mines at Medium Frequencies," Terry S. Cory, P.E. on Subcontract C-651672 for Rockwell/Collins under BuMines Contract H0377053, June 1978.

This final report summarizes the results of References (10) - (14). Computation of maximum communication range in quasi-conductor-free areas was made using the Collins FM prototype equipment parameters & set-noise/median-mine-noise.

The composite maximum range results of Reference (9) and the low coal measurements is given.

(16) Cory, T.S., "Magnetic Field Strength Mapping of the Helvetia Coal Co. Lucerne #8 Mine at Medium Frequency," Terry S. Cory, P.E. under BuMines Purchase Order P0372716, September 1977.

The results of MF magnetic field strength mapping are presented for this mine in the Upper Freeport ("E") seam.

This measured data provides a basis for area coverage and conductor carrier current standing wave ratio estimation for this mine.

(17) Cory, T.S., "In-Situ Measurement of Coal Seam Conductivity using a Parallel Wire Transmission Line Method," Special Technical Report on Terry S. Cory, P.E. Subcontract C-651672 for Rockwell/Collins under BuMines Contract H0377053.

This report presents a unique technique for determining the coal seam conductivity via measurement of the propagation phase constant on a spaced open two-wire transmission line and curve fitting with computed data. Derivation of the theoretical model is given; conductivities are determined using the technique for two mines.

(18) Cory, T.S., "Wireless Radio Transmission at Medium Frequency in Underground Coal Mines - Summary of Measurements and Expected System Propagational Effects," 1978 USBM Guided Wave Electromagnetic Workshop under BuMines Purchase Order P0381076, March 1978.

This paper summarizes MF propagation field strength measured results to data and the maximum range computations which can be made from them (including those using scatter gain). The paper draws from References (9) and (15).

(19) Balanis, G.A., et. al., "Electrical Properties of Eastern Bituminous Coal as a Function of Frequency, Polarization, and Direction of the Electromagnetic Wave, and Temperature of the Sample," West Virginia University, 1978 USBM Guided Wave Electromagnetics Workshop, March 1978

This paper reports on a series of systematic laboratory measurements on coal samples toward determining the constituitive properties (dielectric constant and conductivity).

The dielectric constant is essentially independent of wave polarization, direction of travel, and decreases slightly with increase in temperature.

The conductivity is less by a factor of 3-6 for a vertically polarized wave than for a horizontally polarized wave and decreases slightly with increase in temperature.

The conductivity increases and the dielectric constant decreases with increase in frequency.

(20) Chang, D.C. & Kuester, E.F., "In-Situ Determination of Bulk Electrical Properties of Coal," Final Report, USBM Contract P0172080, April 1977.

This fine survey work reviews the techniques of conductivity determination appropriate for various frequency ranges of interest. The techniques are described in detail together with the necessary information/data to implement them.

(21) Lytle, R.J., "Measurement of Earth Medium Electrical Characteristics Techniques, Results, and Applications," Lawrence Livermore Laboratory, IEEE Trans. Geoscience Electronics, July 1974.

This survey paper is similar in structure and content to Reference (20) but is more generally oriented toward earth materials.

(22) Parkhomenko, E.I., "Electrical Properties of Rocks," Institute of Physics of the Earth, Acadamy of Science of the USSR, Translated and Edited by G.V. Keller, Plenum Press, New York 1967.

This book is a foundation resource for the electrical properties of earth and rocks; also including some data on coal.

7.2 CONDUCTOR-FREE PROPAGATION ANALYSIS

(23) Cory, T.S., "Research Report - Mine Wireless Communication Models at Medium Frequency," Spectra Associates under Subcontract C-651171 for Rockwell Collins, 7 March 1975.

This report was prepared for Rockwell/Collins following completion of the measurements of References (1) and (2) and was probably not furnished to the Bureau. This report is available from the author.

The report works toward validation of the Ireland mine measured data by:

(a) Employing the method of images and modified geometrical optics to predict the coal seam mode excitation levels.

(b) Exploring the close-in transition of the optimum field polarization from VMD to HMD

(c) Fitting the far range field strength data to an exponential decaying model

This report developed an analytical model for the first prediction of conductor scattering effects. This analysis included a model for the monofilar mode propagation constant on a quasi-static basis.

(24) Lagace, R.L., et. al. , "Propagation of Radio Waves in Coal Mines," Arthur D. Little, Inc., Contract Report, Task F, Task Order #1, USBM Contract H0346045, October 1975

This report presents the first theoretical quasi-TEM mode analysis for the MF coal seam waveguide mode propagation and the model is validated via comparison of measured results and theoretical analyses.

The theory, subsequently refined, has provided the basis for not only validating measured results in all ensuing measurement programs, but also for deriving constituitive properties for the coal seam and for the rock overburden/underburden. This is a 3-layer model assuming equal overburden/underburden constituitive parameters.

The theory and analysis technique are particularly useful for engineering R & D purposes as they can be implemented on an HP-67/97 calculator.

(25) Decker, R.P., "Notes on Comparison of Measured Mines Magnetic Field Strength Data by Multi-layer Theory," Spectra Associates, Unpublished monograph, 13 Decmber 1976.

This paper is available only from the author. It employs the general multi-layer theory of Wait to coal seam waveguide propagation using a five-layer model permitting differing constituitive parameters for the overburden and the underburden. The paper contains comparisons of both the 5-layer and ADL 3-layer models with the measured data.

This analysis is particularly useful in making propagation predictions at the lower LF/MF frequencies of nominally 200 kHz and below.

(26) Wait, J.R. & Spies, K.P., "On Calculation of the Modal Parameters of an Idealized Earth-Crust Waveguide," ONR Report #1, March 1971.

This report provides the foundation theory on which Decker's analysis (Reference 25) was based.

(27) Wait, J.R., "Note on the Theory of Transmission of Electromagnetic Waves in a Coal Seam," Radio Science, Vol. 11, No.4 pp.263-265, April 1976.

This paper constitutes Waits identification of MF coal seam waveguide propagation to his earlier work, putting the theory in the open literature.

(28) Lagace, R.L. & Emslie, A.G., "Theory of the Propagation of Low and Medium Frequency Radio Waves in a Coal Seam," Radio Science, Vol. 11, No.4, pp. 253-262, April 1976.

This paper constitutes a refinement of the Reference (24) material and presents the first exposure of the 3-layer quasi-TEM mode theory in the open literature.

(29) Lagace, R.L., et. al., "Modelling and Data Analysis of In-Mine Electromagnetic Wave Propagation," Arthur D. Little, Inc., Interim Report, Task Order #4, USBM Contract H0346045, May 1978.

This report presents validation of the measured data of References (2) - (8) with a companion analysis based on the 3-layer model. From the analysis, constituitive parameters of the coal seam and of the rock are derived for each mine/seam evaluated via measurements.

(30) Lagace, R.L. & Emslie, A.G., "Analysis of MF Propagation Data from Margaret #11, Nanty Glo, Ehrenfeld, and Adrian Coal Mines," Arthur D. Little, Inc., Working Memorandum, Task Order #4, USBM Contract H0346045, May 1978.

This report provides the companion analysis, similar to that of Reference (29), for the low coal mines for which measured data is given in References (10) - (14).

(31) Emslie, A.G. & Lagace, R.L., "Medium Frequency Radio Propagation and Coupling in Coal Mines," Arthur D. Little, Inc., 1978 USBM Guided Wave Electromagnetic Workshop, March 1978.

This paper reviews some of the Reference (29) results and presents a refinement to the theory, using Bannister's quasi-static image technique, to improve on the modal excitation level and the close-in predicted field strengths. Good agreement with measured data is obtained between nominally 100 and 1000 kHz.

7.3 COUPLED CONDUCTOR PROPAGATION ANALYSIS

(32) Ibid. Ref. (23) Section 4.0 "Models for Fields in an Area With Conductors".

A simple theory is presented based on coupling from a matched, terminated single line source to multi-turn transmit and receive loop antennas is presented; including definition of the monofilar mode propagation constant. The range decay of field strength perpendicularly away from the line source is modified to be $1/r^{1.58}$ based on measurements taken in the Rose Valley mine.

(33) Ibid.Ref. (9), Section 4.2 " Analysis and Development of System Application of Data"

The theory of scatter gain is put forth for the prediction of conductor-proximity field strengths from a remote transmitter. Calculations of conductor-proximity maximum communication range are given for the Pittsburgh, Herrin #6, and Pocahontas #3 seams vs range of the transmitter away from the conductor ensemble using Collins FM prototype radio parameters and set-noise/median-mine-noise. At the time of the writing, correlation of scatter gain from theoretical and measured data was available only in two isolated cases. Formulas for scatter gain were developed for each of the three seams.

(34) Ibid. Ref. (15), Section 2.2.1 "Computation Criteria & Techniques"; Section 3.3 "Scatter Gain Comparisons"

Scatter gain formulas are presented for the Lower and Upper Freeport, and Lower Kittanning seams.

Extensive comparisons of computed scatter gain and scatter gain determined directly from measurements are given; validating the use of the theory.

(35) Emslie, A.G., et.al., "Theory of the Dedicated Wire as a Means of Aiding Propagation on a Trolley Wire," Arthur D. Little, Inc., Working Memorandum 1-8, USBM Contract H0346045, September 1976.

A theoretical analysis is given which puts forth the value of a dedicated wire placed parallel to and in close proximity to a trolley wire conductor to "stabilize" the transmission of carrier current past branch/junction points and along multi-conductor emsembles to minimize junction signal "suck-out" problems and which precludes severe losses due to unwanted mode conversion.

(36) Emslie, A.G., et. al., "Use of Auxilliary Dedicated Wires as a Means of Aiding Carrier Current Propagation on a Trolley Wire/Rail Transmission Line," Arthur D. Little, Inc., 1978 USBM Guided Wave Electromagnetic Workshop, March 1978.

Extending Refernce (35), an application of the dedicated wire theory to the coupling between a dedicated wire and the DC trolley wire/rail transmission line is given. Results show the advantages of a loosely coupled dedicated wire toward precluding null zones in trolley wire carrier current operation.

(37) Lagace, R.L. & Emslie, A.G., "Coupling of the Coal Seam Mode to a Cable in a Tunnel at Medium Radio Frequencies," Arthur D. Little, Inc., 1978 USBM Guided Wave Electromagnetic Workshop, March 1978.

A theory is put forth, based on the use of multiple "Bannister images", to predict the coupling into existing mine wiring cabling as an extension of the 3-layer model. Sufficient data is not available to validate the use of the theory.

(38) Wait, J.R., "Quasi-Static Limit for the Propagation Mode Along a Thin Wire in a Circular Tunnel," IEEE Trans. PGAP, Vol. AP-25, No.3 pp.441-443, May 1977.

This note develops essentially the same quasi-static limit for estimating the monofilar mode propagation constant along an idealized coaxial lossy line as has been used by Cory for monofilar mode loss computations. This technique requires refinement, however, to handle the complete MF frequency range in coal mines. This refinement for the phase constant only has been put forth by Cory in Reference (17).

(39) Wait, J.R. & Hill, D.A., "Guided Electromagnetic Waves Along an Axial Conductor in a Circular Tunnel," IEEE Trans. PGAP, Vo. AP-22, pp. 627-630, July 1974.

This paper gives the foundation theory for monofilar mode propagation along a symmetrically spaced axial conductor in a lossy coaxial transmission line.

(40) Reid, D.G.,"Wireless Communications for Trackless Haulage Vehicles," Section 7 "Antennas" by T.S. Cory under Subcontract C-651196 to Rockwell/Collins, Phase I Report on USBM Contract H0377013, August 1977.

Section 7.4 "Coupled-Repeater Antennas" gives results of the coupling coefficient between a large base station loop antenna and a conductor over a lossy interface.

The coupling is quasi-independent of range (for short ranges up to 48 feet at least) because of the concentration of magnetic flux near the interface such that the flux threads the loop for essentially all spacings for which measurements were made.

(41) Cory, T.S., "MF System Calculations for Lucerne #8 and Sesser Mines," unpublished monograph prepared for Rockwell/Collins on Subcontract C-651196 under USBM Contract H0377013, July 1977.

This monograph presents the first system performance predictions merging the close coupling theory with scatter gain computations from a remote transmitter.

(42) Cory, T.S., "Antenna Design and Coupling Studies at Medium Frequency for Improved Coal Mine Communications," Terry S. Cory, P.E. under BuMines Purchase Order P0382223, December 1978.

This report presents coupling coefficients for antennas to an assumed AC power cable,including the effects of vehicular mountbng, derived from quasi-static graphical field mapping.

7.4 MEASURED NOISE DATA AND ANALYSIS

The following five reports were prepared under USBM Contract H0133005 by the Electromagnetic Division, Institute for Basic Standards, Notional Bureau of Standards.

(43) Bensema, W.D., et. al., "Electromagnetic Noise in Robena No.4 Coal Mine," NBS Tech Note 654, April 1974.

(44) Adams, J.W., et. al., "Electromagnetic Noise in Grace Mine," NBSIR 74-388, June 1974.

(45) Kandu, M., et. al., "Electromagnetic Noise in McElroy Mine," NBSIR 74-389, June 1974.

(46) Bensema, W.D., et. al., "Electromagnetic Noise in Itmann Mine," NBSIR 74-390, June 1974.

(47) Scott, W.W., et. al., #Electromagnetic Noise in Lucky Friday Mine," NBSIR 74-391, October 1974.

These reports, on a per-mine basis, describe extensive measurements ofelectromagnetic noise in underground mines. These measurements were performed at 200 kHz and below. Until recently, extrapolation of these data into the MF region provided the only estimates of MF noise. Care must be taken in using some of the data as it was set-noise-limited.

This fine work, unfortunately, did not consider partitioning of noise according to type of mining operations (for example, AC, DC, belt or tracked haulage, close to or away from conductors, presence of trolley phone interferance, etc.).

(48) Decker, R.P., "Research and Development Contract for Coal Mine Communication System - Vol. 3 Theoretical Data Base," Collins Radio Co. Final Report, USBM Contract H0232056, November 1974.

This report summarizes the NBS noise measurements and put forth an empirical formula for the computation of median-mine-noise (a value which, since, has been determined to have limited operational significance).

(49) Cory, T.S., "Evaluation of Electromagnetic Noise in Coal Mines at VLF and MF Frequencies Based on Noise Measurements on Mine Telephone Lines," Working Memorandum #8, Terry S. Cory, P.E. under BuMines Purchase Order P0382497, March 1979.

This report describes differential mode and common mode noise measurements made on telephone lines in underground mines. The common mode data has been interpreted at MF frequencies in terms of a radiated noise field strength close to existing mine wiring. Use of this data in conjunction with extrapolations of the NBS data has been made to establish operationally significant noise curves from which MF system performance can be estimated.

7.5 PROTOTYPE SYSTEM ELEMENT DEVELOPMENTS

(50) Anderson, D.T., et. al., "Phase-I Mine Wireless Final Report," Rockwell/Collins under USBM Contract H0346067, 1975.

This report describes the design parameters chosen for the ensuing Phase II development of MF wireless radio prototype equipments; to consist of portables (plus antennas) and base stations (plus antennas).

(51) Wilson, L.R., et. al., "Phase-II Mine Wireless Final Report," Rockwell/Collins under USBM Contract H0346067, 1977.

This report provides the complete developmental description of the two-frequency FM prototype equipments developed and furnished to the Bureau for evaluation.

(52) Ibid. Ref. (42)

This report describes the design and build of two prototype vehicular MF antennas for use in coal mines. Included is the theoretical description of a multi-turn antenna design algorithm from which the developed antenna design performance was optimized.

(53) Cory, T.S., "Methane Telemetry System for Continuous Miners," Final Report of Contract J0166094 with Rockwell/Collins prepared on USBM Contract J0199026, April 1979.

This report describes a wireless MF radio remote monitoring system for the simultaneous and continuous unattended monitoring of up to 8 methane sensors installed on a continuous miner. Complete descriptions of the digital modulation, control (microprocessor), and RF transmitter/receiver designs are given.

(54) Ibid. Ref. (40)

This report provides a first order functional description of a possible MF system configuration for use in trackless haulage applications.

(55) Austin, B.A., "Underground Radio Communication Techniques and Systems in South African Mines," Electronics Division, Chamber of Mines of South Africa, Research Organization, 1978 USBM Guided Wave Electromagnetic Workshop, March 1978.

This report describes the development of radio components and the implementation of communication techniques (based on the RACAL SSB radio equipment parameters) in use in South African mines.

(56) Lagace,R.L., et. al., "Transmit Antennas for Portable VLF to MF Wireless Mine Communications," Arthur D. Little, Inc., Final Report Task C, Task Order #1, USBM Contract H0346045, May 1977.

With regard to MF antennas, this report provides a cursory overview of the thinking which has taken place prior to 1977 regarding wireless radio antennas.

(57) Lagace, R.L. & Emslie, A.G., "Antenna Technology for Medium Frequency Portable Radio Communications in Coal Mines," Arthur D. Little, Inc., 1978 USBM Guided Wave Electromagnetic Workshop, March 1978.

This paper discusses considerations related to the design and selection of MF portable radio antennas for use in coal mines; including the recommendation of R & D on ferrite-loaded antennas. Detailed design analyses and/or results are not given.

(58) Chufo, R.L., et. al.,"Medium-Frequency Mine Wireless Radio", Bureau of Mines Information Circular/1977 IC 8745, pp.63 - 72

This report describes the Rockwell/Collins narrowband FM prototype radios and the general potential for MF wireless systems based on the results experienced during the first major field strength measurement program (Reference 9). The paper describes the communications requirements which lead PMSRC to inititate R & D efforts in this technology area.