

ELECTROMAGNETIC PROPAGATION IN LOW COAL MINES AT MEDIUM FREQUENCIES

Prepared for

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BUREAU OF MINES**

by

**Collins Communications Switching Systems Division
Commercial Telecommunications Group
Cedar Rapids, Iowa 52406**



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16. Abstract This report covers magnetic field strength measurements vs range and frequency in low-medium coal mines. Both quasi-conductor-free and conductor-proximity areas were investigated. The program covered 5 mines, 4 seams, 6 measurement sets, and 3 geographic areas. The results have been summarized in terms of maximum communication range expected per seam and noise condition. Scatter gain is further explored as a simple measure of energy coupled to conductors.			
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FOREWORD

This report was prepared by Terry S. Cory, P.E., for Collins Communications Switching Systems Division, Commercial Telecommunications Group, Rockwell International, Cedar Rapids, Iowa, under USBM Contract H0377053 and Terry S. Cory, P.E., Subcontract C-651672. The contract was initiated under the Coal Mine Health and Safety Program. It was administered under the technical direction of Bruceton Research Center with Mr. Harry Dobroski acting as the Technical Project Officer. The Bu Mines Contracting Officer was Alan G. Bolton, Jr.

This report is a summary of the work recently completed as part of this contract during the period October 19, 1977 to May 31, 1978. This report was submitted by the author on June 12, 1978.

For clarity, this report contains equipment brand names as being generically representative of equipments which may be available to implement medium frequency systems in coal mines. Reference to specific brands, equipment, or trade names in this report is made to facilitate understanding and does not imply endorsement by the Bureau of Mines. No patentable techniques or items of equipment have been developed or otherwise used during the course of this program.

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1.0 INTRODUCTION

This is the Final Report covering work performed by Collins Divisions, Rockwell International Corporation under Bureau of Mines Contract H0377053 entitled Electromagnetic Propagation in Low Coal Mines at Medium Frequencies.

The technical work was performed by Terry S. Cory, P.E. under Subcontract C-651672 with administrative direction and technical support provided by Collins and using Collins' facilities.

The primary work consisted of performing measurements of magnetic field strength in five (5) mines and four (4) coal seams coordinated with a concurrent theoretical study performed by Arthur D. Little, Inc. (ADL) under separate contract* to the Bureau. The measurements were taken in such a manner as to enable the reduced results to characterize the wireless radio transmission properties of each mine/coal seam; both in areas without conductors and with conductors.

This program was a technological extension of a previous program entitled Propagation of EM Signals in Underground Mines (performed under Bureau of Mines Contract H0366028) herein referred to as the "EM Signalling Program". This current program has applied an established technique for transmission characterization to selected highly productive low-coal areas. The test equipment, furnished GFE, was developed and/or configured under this previous program and the reader is referred to the final report for that program for a detailed description of the technique and the measurement system.

The magnetic field strength measurement data sets from each mine were separately reported in each of five (5) Interim Summary Data Reports. The data summaries in the form of families of curves of magnetic field strength vs range and frequency and the mine map topological description of the measurement traverses have been compiled and are given in the Appendix to this report. The further summarizing of this data in terms of maximum communication range with a technique which can be used to apply the results to system designs for particular mines is the subject of this report.

Secondarily, a technique was developed under the contract funding for the independent in-situ measurement of coal seam conductivity and preliminary measurements using this technique were performed in two mines. This work was beyond the original scope of this program and has been reported separately in a Special Technical Report (2) which is not a part of this Final Report. For convenience, this Special Technical Report is submitted concurrently as an Attachment to this Final Report.

All program measurements were performed by a team consisting of the Subcontractor and Principal Investigator Terry S. Cory, a Bureau of Mines furnished technician, and a Collins furnished technician.

*Task Order #4, Basic Ordering Agreement H0346045.

1.1 PROGRAM BACKGROUND

The viability of wireless radio transmission in coal mines has been established; largely as a result of the Bu Mines sponsored EM Signalling Program, the companion ADL program, and prior Bu Mines sponsored research in this area dating back to 1973. The baseline studies and measurements were performed largely in high-coal in West Virginia and Illinois and in DC mines. Renewed national emphasis on coal production, largely underground, has spurred the here-to-fore embryonic and somewhat antiquated mine electronics technology into a major arena offering substantially increased capabilities for production efficiency, control, and for enhanced mine safety. A large portion of the U.S. coal reserves reside in low-coal (seams nominally 36 - 48 inches thick). Newer AC mines do not provide the trolley wire transport mechanism for implementation of the carrier phone communication systems prevalent in older mines for handling vehicle traffic. Pager phone systems alone, especially in low-coal where physical mobility is difficult, are not sufficient to regulate vehicle traffic, personnel movement, and to efficiently supervise production related activities in large working section panels.

Within the last year, sources of medium frequency portable radios have been identified and within the next one to two years, these radios are expected to have been certified and to become available in the marketplace. (RACAL Model TR58 from South Africa and a U.S. manufactured radio now in the production prototype stage sponsored by CONSOL via Lee Engineering).

The Bureau of Mines currently has an R&D program underway to define mine wireless system configurations adaptable to trackless haulage mines (H0366056) and planned research relating to portable and vehicular antenna development and coupling to existing mine wiring conductor configurations.

This program accomplishes the wireless transmission characterization of low-coal mines and provides a data base which may be used for preliminary estimates of wireless transmission system requirements.

1.2 PROGRAM OVERVIEW

Measurements were performed in five (5) mines in chronological order as follows:

- (1) December 1977, Helvetia Coal Co. Margaret #11 Mine in Armstrong Co., Pennsylvania - Upper Freeport seam
 - (a) Field strength vs range and frequency in 1-Butt Section - quasi-conductor-free
 - (b) Field strength vs range at 900 KHz in 2-Butt Section - conductor-proximity
- (2) January 1978, Upshur Coal Corp. Adrian Mine in Upshur Co., West Virginia - Upper Freeport seam

- (a) Field strength vs range and frequency in area parallel to Road 83C between 1st Right and 2nd Right - quasi-conductor-free
- (3) February 1978, Bethlehem Steel Coal Mine #31 (Nanty Glo) in Cambria Co., Pennsylvania - Lower Kittanning seam
 - (a) Field strength vs range and frequency in Main-N area - quasi-conductor-free conductor-proximity
 - (b) Field strength vs range and frequency in 5-Cross area - quasi-conductor-free conductor-proximity
- (4) February 1978, Bethlehem Steel Coal Mine #38D (Ehrenfeld) in Cambria Co., Pennsylvania - Lower Freeport seam
 - (a) Field strength vs range and frequency in 1-Right Main-B area - quasi-conductor-free conductor-proximity
- (5) May 1978, National Mine Corp. Stinson #3 Mine in Knott Co., Kentucky - Elkhorn #3 seam
 - (a) Field strength vs range and frequency in C-Section area - quasi-conductor-free conductor-proximity

1.3 REPORT CONTENTS

Section 2.0 presents an Executive Summary consisting of an overview of the results in terms of maximum communication range vs frequency plus specific observations, conclusions, and recommendations.

Section 3.0 presents the Technical Approach consisting of a description of the new two-turn receive antenna used, details of the data reduction process including calibration, and details concerning the comparison of measured and computed scatter gains and derivation of the simple scatter gain formulas.

Section 4.0 presents Individual Mine Test Descriptions including a summary of results for each of the five (5) mines visited.

Appendix presents the compended field strength curves and mine map traverses for each set of measurement results obtained. These have been extracted from the individual Summary Data Reports.

2.0 EXECUTIVE SUMMARY

The primary goal for this program has been to expand the mine/seam wireless radio transmission data base into additional low-coal mines/seams, while comparing the results for consistency with the previous EM Signalling program results. The program work exceeded the original expectation of four mines, four seams, and one measurement sample per mine by providing data from five mines, four seams, and six measurement samples. Qualitative observations of noise were made along the way during the program, searching for noise conditions which had not previously been experienced in high-coal. Quantitative noise measures in operating mines were not possible during the program time frame as most measurements were made during the mine strike. This shift of emphasis away from quantitative noise tests made it possible to gather additional field strength data, especially in close proximity to conductors, as well as expanding on the mine/seam/measurement set format.

A secondary goal for this program has been to define simple-to-implement measures for characterizing particular mines and to expand on the technique(s) for using the data base results, confidently, to obtain system performance estimates based on the mine/seam characterizations. An important part of obtaining this goal has been to validate the concept of scatter gain and to establish a simple means for measuring it. Once validated, scatter gain provides an easy-to-use empirically based way to estimate conductor coupling to radio fields. Also an important part of obtaining this goal has been to obtain conductor proximity data useful to ADL in their more rigorous analysis of conductor coupling and of the transmission modes associated with current traveling along multi-conductor ensembles.

To provide the most complete "total summary" of transmission effects, this report includes the use of data from the previous EM Signalling Program and conductivity data derived from ADL's ^{(3), (4)} modeling evaluation of the measured field strengths.

2.1 RESULTS SUMMARY

From the measured magnetic field strength vs range and frequency data, maximum communication ranges were computed both in quasi-conductor-free mine areas and in conductor-proximity situations for each seam under assumptions of both set-limited noise and median mine noise. Specific criteria upon which these computations were based are summarized in the next subsection.

As was characteristic of all seams except, perhaps, the Pittsburgh seam, all measurements (and, thus, the expected performance of actual radios) were set-noise-limited when the receiver was removed one or more entries away from an entry containing conductors. Conversely, the received noise levels in conductor entries are expected to conform approximately to median mine noise. The very few estimates of noise made close to energized conductors verified this; however, due to the strike, determination of typical operational noise levels was not possible.

The maximum communication range in quasi-conductor-free environments for the total data base of seven seams for set-limited noise and for median mine noise are given respectively in Figures 1 and 2. The communication ranges obtained were fairly tightly grouped; being greater in value than those for the Herrin #6 seam and less in value than those for the Pocahontas #3 seam.

In set-limited noise, the low-coal mines exhibited maximum ranges of 180-260 meters at frequencies lying between 200 and 300 KHz.

In median mine noise, the low-coal mines exhibited maximum ranges of 115-140 meters at frequencies lying between 400 and 800 KHz with the optimum frequency/range conditions being quite broad.

These range curves clearly show the Pittsburgh seam to be the exception rather than the rule for range performance with the range being approximately twice that for the other seams in the data base.

The maximum communication range in proximity to conductors for six of the seven seams (ADL data for the Elkhorn #3 seam was not available at the time of this writing) for median mine noise is given in Figure 3. The transmitter is assumed to be located one entry away from conductors and the receiver is assumed to be located in the conductor entry. Here, there is considerable difference between the values of range for the three displayed low-coal seams. The Upper Freeport seam gives the best range of 890 meters at 900 KHz and the Lower Kittanning gives the poorest range of 570 meters at 1150 KHz. With the exception of the Pittsburgh seam, the Upper Freeport seam gives the best performance of the total seam set; all other seams are fairly tightly grouped at between 570-670 meters at from 900-1150 KHz. The range shown is ostensibly the range along the conductor string with the conductor attenuation assuming a single transmission line mode (or single dominant mode).

FIGURE 1
 MAXIMUM COMMUNICATION RANGE VS OPERATING FREQUENCY IN
 CONDUCTOR-FREE AREAS OF COAL MINES - SET NOISE LIMIT

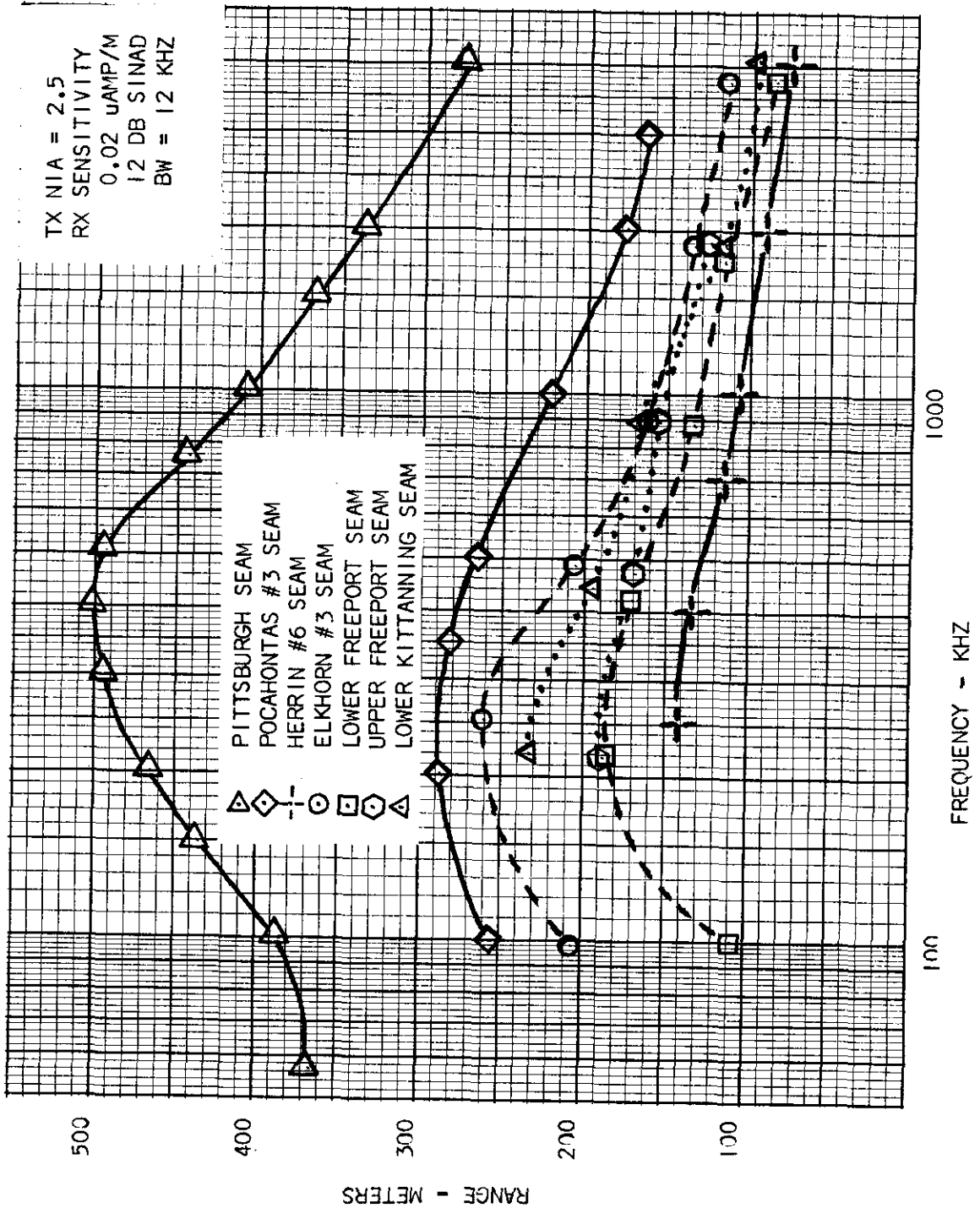


FIGURE 2
 MAXIMUM COMMUNICATION RANGE VS OPERATING FREQUENCY IN
 CONDUCTOR-FREE AREAS OF COAL MINES - MEDIAN MINE NOISE

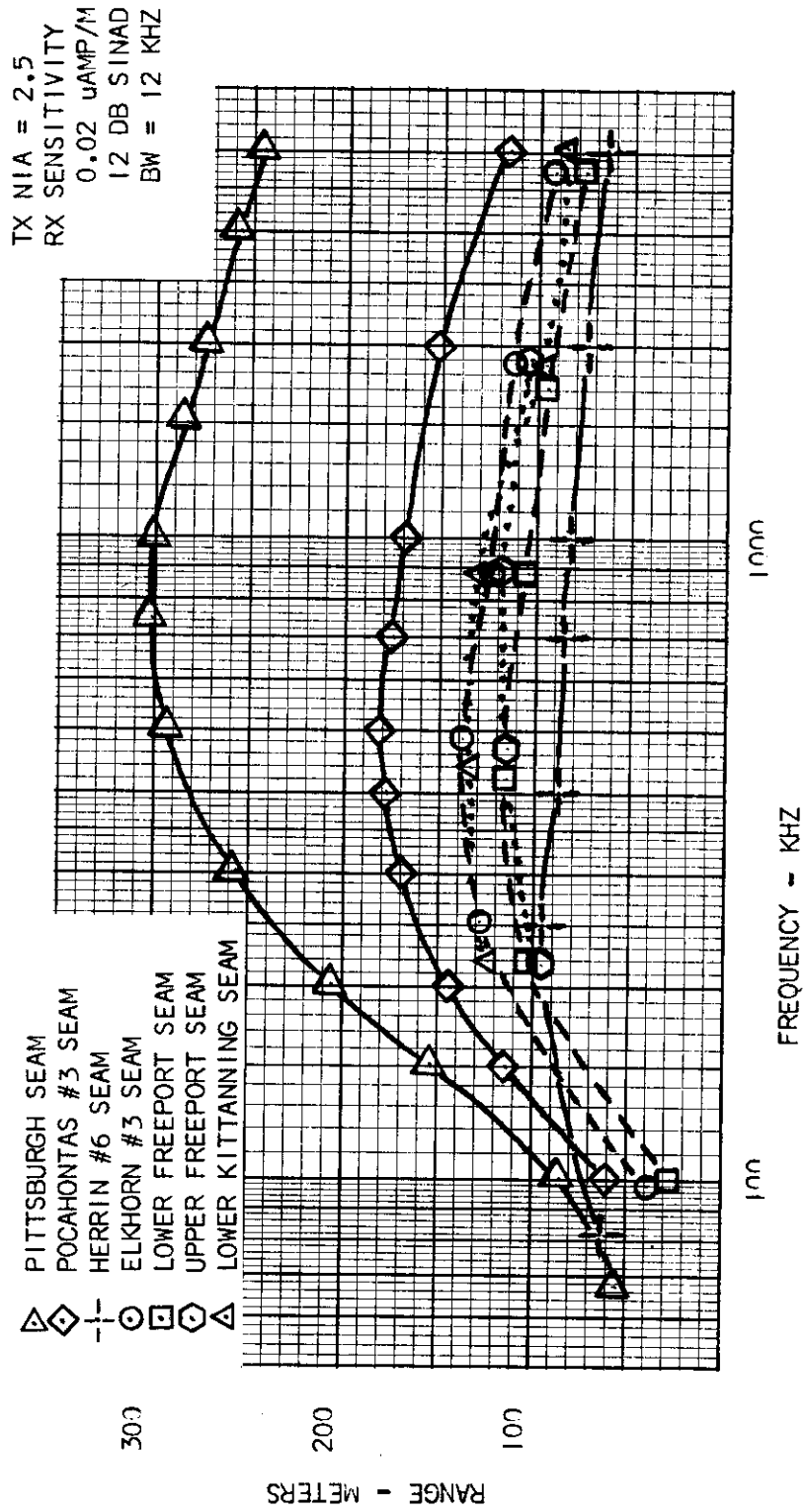
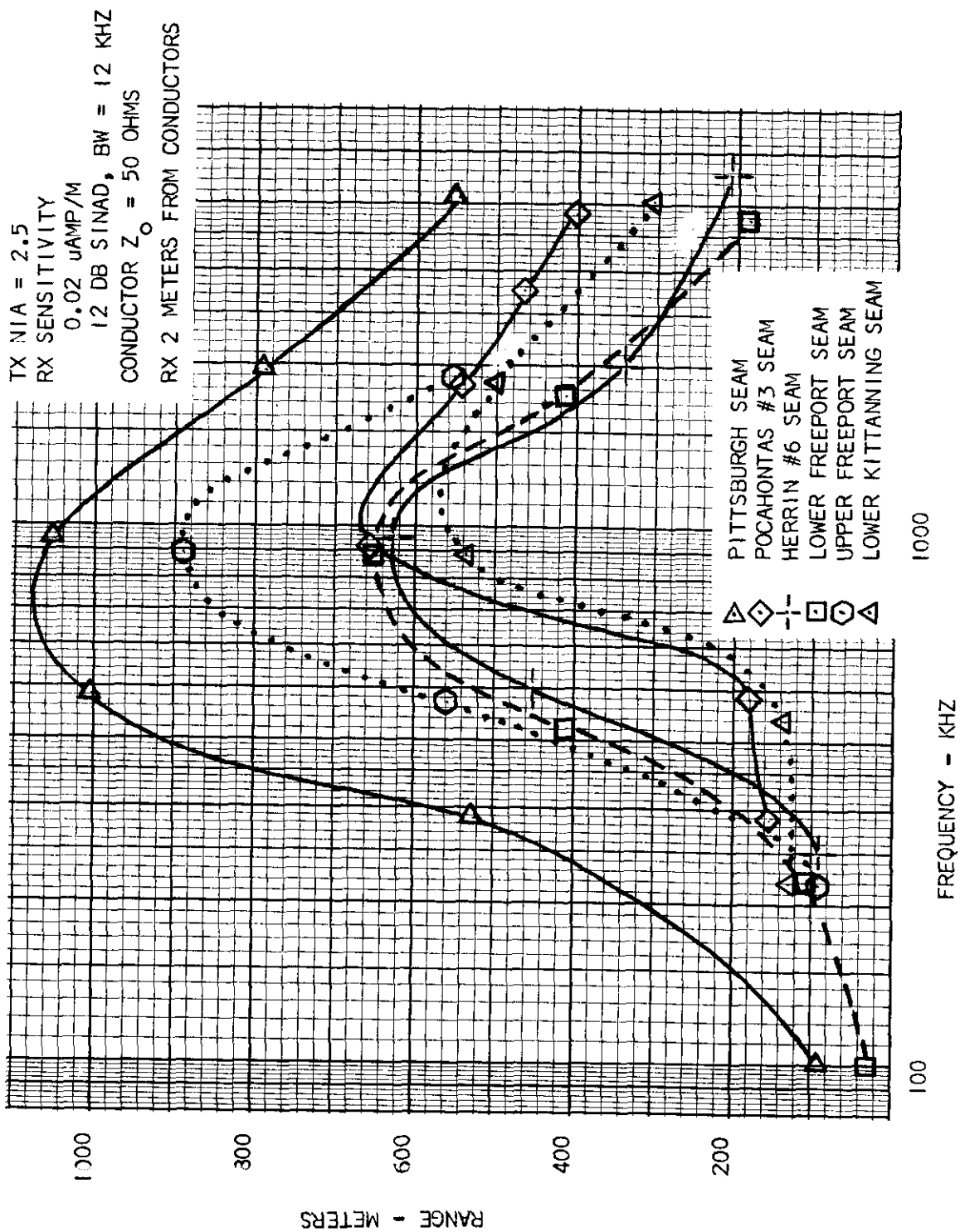


FIGURE 3
 MAXIMUM COMMUNICATION RANGE VS OPERATING FREQUENCY IN COAL MINES
 IN PROXIMITY TO CONDUCTOR(S) - TX LOCATED REMOTELY - MEDIAN MINE NOISE



The maximum communication ranges in proximity to conductors for the three low-coal seams for which data was available are given in Figure 4 for set-limited noise. These ranges were not previously computed in high-coal as the utility of this situation was at the time questionable. Recently, the possibility of an entry carrying only an AC power cable or the cable plus a phone line with low noise in newer AC mines has arisen so as to make this a reasonable limiting case. The data is shown assuming the transmitter located both one entry and two entries removed from the entry carrying the conductor(s). Just as the optimum frequency for coupling when both the transmitter and receiver are close to the conductors is known to be lower; so the optimum frequency for lower noise (ie greater margin to accomodate conductor attenuation) is also lower. For one-entry remoting of the transmitter, the maximum communication ranges are between 2400-5000 meters at optimum frequencies ranging between 220 and 350 KHz. For two-entry remoting of the transmitter, the maximum communication range lies between 470-1050 meters at optimum frequencies ranging between 220 and 700 KHz. In each case, the Lower Freeport seam provides the best range performance.

2.2 TRANSMISSION CHARACTERIZATION

2.2.1 COMPUTATION CRITERIA & TECHNIQUES

The summaries of maximum communication range presuppose values of receiver sensitivity and transmit NIA. The following criteria have been assumed for these summaries based on the Collins mine wireless (5) prototype fm radios developed for the Bureau and the NBS noise study (Bu Mines Contract H0133005):

NIA = 2.5, the transmit magnetic current moment of the radio using a loop antenna

Receive sensitivity of 0.02 microamps/meter for 12 dB SINAD for 12 KHz noise bandwidth

Set-noise-limited magnetic field strength level for 12 dB SINAD given by

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

where, Δf is the 12 KHz bandwidth

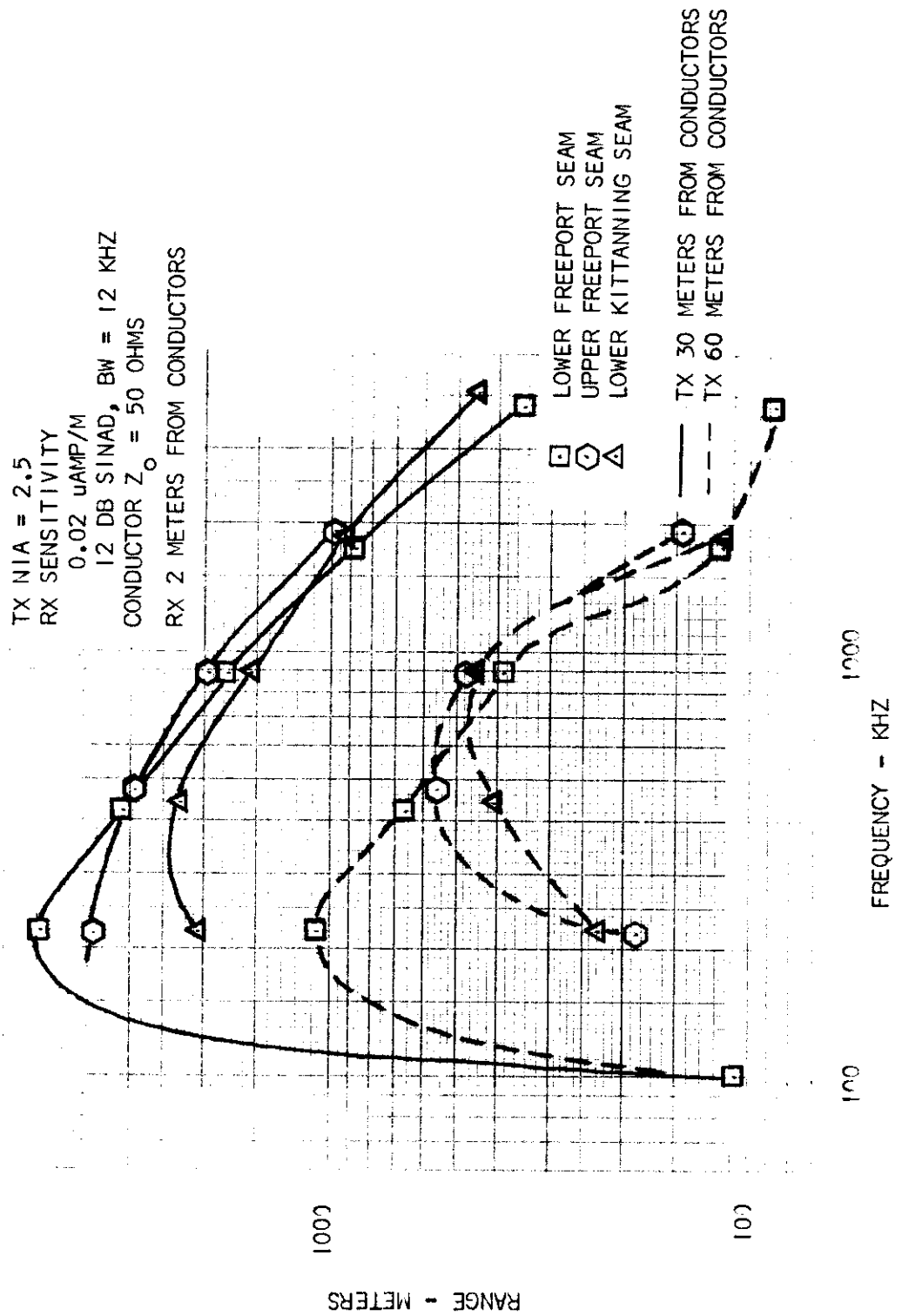
Q is the antenna "Q" made as narrow as possible to be consistent with transmission; Q = 44 for the Collins prototype fm radio

A is the antenna area = 0.217 m²

N is the noise figure of the receiver = 2 dB for the Collins Prototype fm radio

Median mine noise magnetic field strength level for 12 dB SINAD (13.51 dB signal-noise-ratio, Hamshur) is given by

FIGURE 4
 MAXIMUM COMMUNICATION RANGE VS OPERATING FREQUENCY IN COAL MINES
 IN PROXIMITY TO CONDUCTOR(S) - TX LOCATED REMOTELY - SET NOISE LIMIT



$$H_{SN} = 175.8 - 32.5 \log_{10} f(\text{hz})$$

dB above one microamp/meter in a 12 KHz band

The ranges are then derived by picking off the ranges from the measured data corresponding to the receive noise criteria given above. The formula results shown above are given in convenient form in Figure 5.

The summaries of maximum communication range in proximity to conductors further presuppose a coupling to the conductors of the radio fields and an attenuation rate of the coupled carrier current along the conductor strings as well as specific distances of the transmit and receive antennas from the conductors. The attenuation constants used are those appropriate for a single line source in close proximity to the roof (or floor). Using the ADL derived conductivities of the overburden/underburden, the attenuation constants given in Table 1 were obtained. Other line parameters assumed were:

$$a/a_1 = 9$$

where, a is the spacing from the conductor center to the rock

a_1 is the conductor radius

$Z_0 = 50$ ohms, the surge impedance of the lossy transmission line

The estimate of conductor coupling is based on the scatter gain ratio, which is that of the field strength at the receiver with the conductor present to the field strength at the receiver in absence of the conductor. Scatter gain has been determined during this program to be a valid way of specifying the coupling. For each seam, the computation of scatter gain has been reduced to the simple formulas given in Table 2. These formulas give values within 3 dB on average of measured scatter gain samples.

To obtain the field strength at the receiver, the computation proceeds as follows;

- (1) Choose ranges of the transmit and receive antennas from the conductor(s)
- (2) Obtain the magnetic field strength at the closest range between the transmitter and the conductor assuming the conductor is absent from measured field strength curves (or from ADL model calculations) for a conductor-free environment

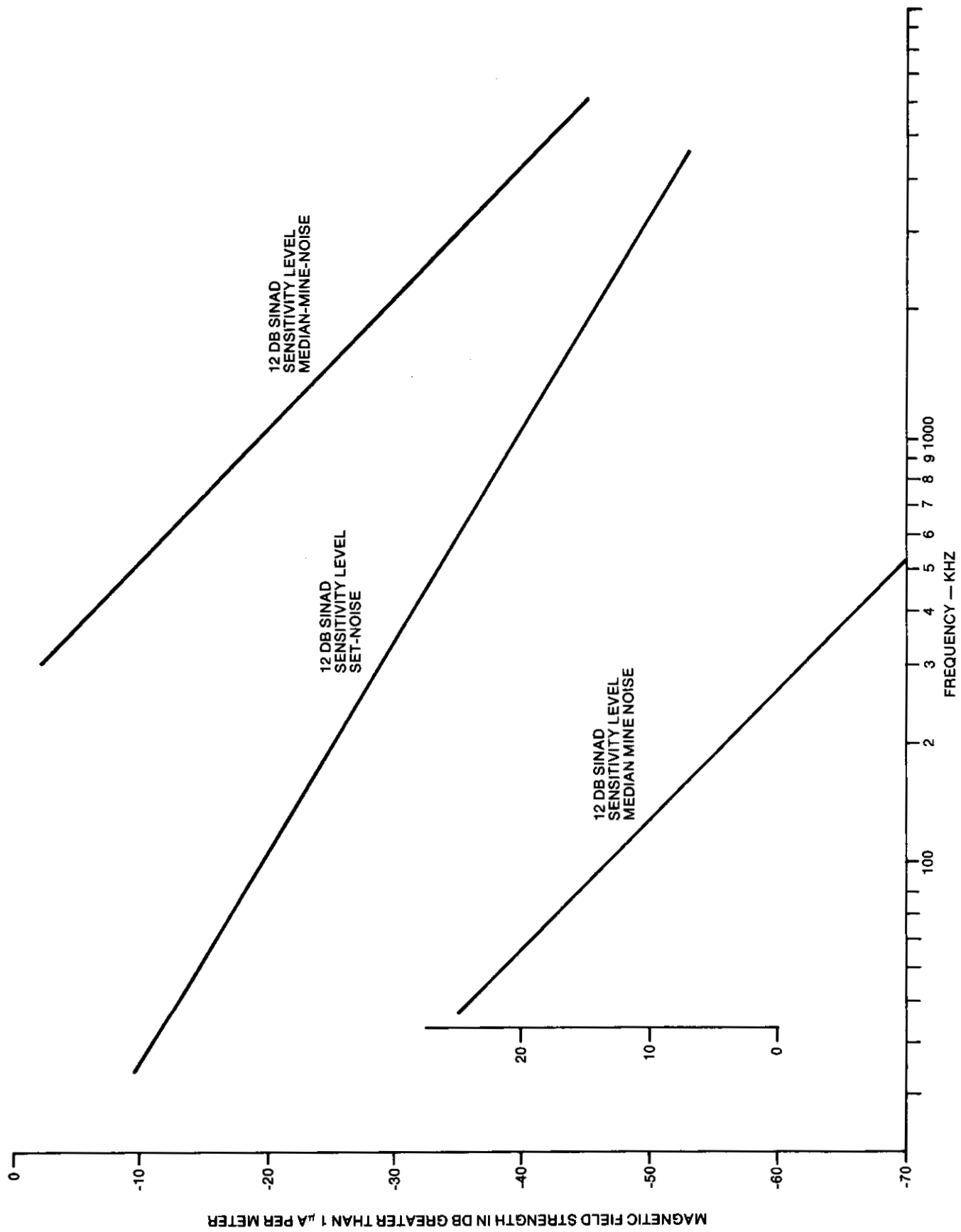


Figure 5 Required Field Strength Sensitivity Levels for Mine Wireless Radios Based on the Collins-Developed Mine Wireless Prototype Radios at 520 kHz.

TABLE I

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

<u>SEAM</u>	<u>FORMULA</u>
PITTSBURGH	$\alpha = 0.02665 \text{ DB/M @ 1 MHZ}$
POCAHONTAS #3	$\alpha = 0.02277 \text{ DB/M @ 1 MHZ}$
HERRIN #6	$\alpha = 0.02916 \text{ DB/M @ 1 MHZ}$
LOWER FREEPORT	$\alpha = 0.02130 \text{ DB/M @ 1 MHZ}$
UPPER FREEPORT	$\alpha = 0.02171 \text{ DB/M @ 1 MHZ}$
LOWER KITTANNING	$\alpha = 0.02171 \text{ DB/M @ 1 MHZ}$

NOTE: ASSUME α IS PROPORTIONAL TO FREQUENCY

TABLE 2

SUMMARY OF SHORT FORMULAS FOR SCATTER GAIN CALCULATION VS COAL SEAM

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

- (3) Multiply the field strength of (2) by the scatter gain (or add dB) as computed from Table 2
- (4) Subtract the result of (3) in dB from the sensitivity level obtained from Figure 5 for the appropriate type of noise
- (5) Divide the dB margin of (4) by the conductor attenuation as computed from Table 1. This gives the range along the conductor string.

2.2.2 UTILITY OF THE CHARACTERIZATION TECHNIQUE

The arrangements of conductors encountered in mine environments are highly variable. These impact both the coupling of transmitted radio fields into the conductors and the propagation of the induced carrier currents along the conductors. Usually, the coupling can be measured; ie measured scatter gain, by transmitting from a known useful location, measuring the field strength at a desired distance away from the conductor with a receive loop (but along the shortest distance between the transmitter and the conductors) and then measuring the received field strength again at the same spacing from the conductors but at a considerable distance "down" the conductor (ie, beyond the direct field range) where the current attenuation rate flattens out.

During the program, the strongest field strength was observed along the shortest path from the transmitter to the conductor even though the transmit loop was oriented parallel to the conductors. The coupling to the conductors was near optimum because of the relatively good agreement between measured and computed scatter gains. This does not infer that the optimum orientation of the transmit antenna for best coupling is known, however. To assure optimum coupling when measuring scatter gain one should begin with the "distant" measurement orienting the transmit antenna for optimum coupling; then, keeping this transmit antenna orientation constant, move in close and obtain the "in-line" measurement orienting the receive antenna again for optimum coupling. This simple technique for assessing coupling will work and provide meaningful results providing the mine wiring topology does not change between receive measurement locations.

Conductor attenuation may be difficult to determine if the configuration is complex. Measurement may be required of the attenuation in specific mines rather than computation to obtain accurate results. ADL⁽⁸⁾ has computed the complex propagation constant for typical multi-conductor configurations which lend insight to these particular situations. ADL is currently formulating a conductor coupling model from which to determine optimum antenna orientations for conductor coupling. A particular set of conductor-proximity measurements made in the Stinson #3 Mine showed that the VMD orientation produced the greatest coupling at low frequencies of 200-300 Khz or less, VMD and both principal HMD orientations produced nearly equal coupling at 400-500

KHz, and at 800-900 KHz the HMD orientation with the loop plane perpendicular to the conductors was predominant.

2.3 RECOMMENDATIONS

From the results of this program and the EM Signalling Program, the quasi-conductor-free transmission performance of wireless radio in most seams is fairly well bounded to a small region of optimum ranges and frequencies. While scatter gain seems to work in defining rough coupling estimates from a remotely located portable transmitter, more accurate coupling definition from practical mineworthy antenna mountings to a variety of useful mine wiring topologies should be made. This is particularly true for transmit locations in close proximity to the conductor ensembles. In addition, measurements of attenuation along a variety of useful mine wiring topologies should be made and correlated with ADL theory.

The transmission along mine wiring conductor strings has been shown by ADL⁽⁹⁾ to be aided by the presence of a dedicated wire. Alternatively, a mine wireless radio system could operate with the aid of a leaky feeder specially designed to provide optimal coupling from a transmitter in a particular working area, carry the current from this area a long distance and then "reradiate" most of the energy over another predetermined working area. The local coupling from a remote transmitter into this type of conductor should be investigated.

3.0 TECHNICAL APPROACH

3.1 EMPIRICAL TECHNIQUE

The measuring equipment arrangement was identical to that used during the EM Signalling program and described in Section 3.0 of that final report. Again, Singer NM-12 and NM-25 field strength meters were used for reception. The single-turn shielded coaxial 0.73 m² loop antenna was rewound into two-turns on easy-to-assemble wooden frames to facilitate physical maneuvering in low-coal. The new design preserved the antenna reactance so that the same coarse tuning networks could be used. The two-turn loop usage resulted in an approximate 6 dB decrease in system sensitivity. Calibration data comparisons between the one-turn and two-turn loops are given in Table 3. These comparison differentials were used to adjust the calibration data obtained during the EM Signalling Program to obtain new absolute calibrations. The two-turn loops were used to obtain most of the measurements during this program.

The NM-12 field strength meters were calibrated so that a known incident field strength will produce a reading of +25 dB on the instrument panel meter with the attenuator in the -20 dB position. The NM-25 field strength meters were calibrated so that a known incident field strength will produce a reading of +10 dB on the instrument panel meter with the attenuator in the -20 dB position. These known field strengths are in terms of microvolts/meter (the plane wave equivalent electric field strength). As the actual calibration was performed using loop antennas, the true H calibration field strength is obtained by dividing the equivalent electric field strength by 377 ohms.

In reducing the field strength data, the field strength at each location in dB greater than 1 microamp/meter was found as the sum of the meter reading as determined in dB minus the field strength calibration point in dB (+10 for the NM-25, +25 for the NM-12) plus the attenuator range setting in dB plus 20 dB plus the calibration field strength in dB greater than 1 microamp/meter plus the NIA normalization factor. In equation form, this is expressed as

$$\text{Field Strength} = \text{analog meter reading} - (10 \text{ or } 25) \\ + \text{attenuator range setting} + 20 + \\ \text{calibration field strength} +$$

$$20 \log_{10} \frac{2.5}{\text{Tx current} \times \text{NIA}}$$

$$\text{NIA} = 2.04 \text{ for 7-turn loop below } 1000\text{KHz} \\ 1.17 \text{ for 4-turn loop above } 1000 \text{ KHz}$$

This equation normalizes the NIA to a standard of 2.5 which is representative of the Collins fm prototype radio and the older ECAM am radio.

The absolute calibrations in terms of equivalent electric field strengths used to reduce the data taken during this program are given in Table 4.

TABLE 3

COMPARISON OF ONE-TURN AND TWO-TURN LOOP RX ANTENNAS

<u>FREQ(KHZ)</u>	<u>ANT TYPE(TURNS)</u>	<u>RX ANTENNA BAND SET #</u>	<u>RELATIVE FIELD STRENGTH(DB)</u>
100	1	1	18.6
100	2	1	11.8
250	1	1	11.2
250	2	1	5.2
500	1	1	9.0
500	2	1	2.7
500	1	2	12.6
500	2	2	6.2
1000	1	2	9.0
1000	2	2	2.8
1000	1	3	11.7
1000	2	3	5.8
1500	1	3	10.2
1500	2	3	4.0
2000	1	3	7.7
2000	2	3	1.6
2000	1	4	11.2
2000	2	4	4.3
3000	1	4	10.7
3000	2	4	3.3
3000	1	5	11.5
3000	2	5	5.6
4000	1	4	8.6
4000	2	4	1.6
4000	1	5	12.1
4000	2	5	6.1

TABLE 4
 CALIBRATION FIELD STRENGTHS USED DURING THE PROGRAM

<u>RX ANTENNA BAND SET #</u>	<u>FREQUENCY KHZ</u>	<u>FIELD STRENGTH MICROVOLTS/M</u>
1	98-100	549.6
1	218-220	144.0
1	252-258	139.0
1	420	128.0
1	440	123.9
1	470-486	115.7
2	470	88.8
2	440	82.8
2	880-900	73.3
3	1750	43.4
3	1850-1860	41.4
3	1890-1900	37.5
4	3620-3710	22.4
5	3620	13.3
5	3750	12.8
5	4050	11.8

3.2 SYSTEM CALCULATIONS

The criteria used to prepare the maximum communication range summaries are presented in Section 2.0 and will not be repeated here. The comparison of the criteria used with that expected for other radios is, however, of interest. The Collins fm radio criteria were used in this report for consistence with the EM Signalling Program results which, when prepared, were representative of the radio parameters expected to be available.

The transmit NIA has, in all cases, been assumed to be 2.5. This corresponds to 20 watts into a 0.22 m² antenna of 7 turns with an NA of 1.52 (typical for a portable man-carried antenna). Newer radios are expected to be in the 1-5 watt range for portables and probably SSB where the power rating is in PEP. Normally we think of SSB having an approximate 9 dB advantage over am and being approximately equal to fm on a PEP basis under low but intelligible signal-to-noise conditions. The receive system sensitivity of the Collins fm receiver and the new RACAL SSB unit are roughly equal using the Hamshur criteria of 12 dB SINAD which was the basis for the report summary calculations. This is shown as

	<u>Sensitivity, dB above 1 ua/m</u>	
(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

The conclusion is that the PEP SSB power rating ratioed to 20 watts gives the NIA reduction factor and, hence, the total system comparison of the Collins fm system as analysed herein and new SSB radio systems using the same antenna.

3.3 SCATTER GAIN COMPARISONS

Measured scatter gains for the Upper Freeport and Lower Kittingham seams have been given to the Bureau in monthly progress reports under this program. These were based on the field strength in absence of the conductor being that taken directly from the quasi-conductor-free curves in the same manner as if the scatter gains were being analytically calculated. Analysis has shown these previously reported values to be incorrect as the actual measured field strength at the receiver via the shortest path between the transmitter and the conductor should have been used. Using these actual measured values of the dominant direct field strength at the receiver on the "in-line" path, there is good agreement between measured and computed scatter gains. This also shows that the "in-line" measured values were near optimum for the orientation of the transmit antenna employed (loop plane parallel to the conductors). For actual system estimates, the field strength on the "in-line" path was assumed to be that between coplanar loop antennas. Based on the Stinson #3 results, this polarization will probably produce optimum

coupling from at least 500 KHz upward in frequency and this is in agreement with periodic observations made over the term of this program and the EM Signalling Program for either the transmitter or the receiver located at least one entry removed from the conductors.

The scatter gain computations in the data summaries used simple "short formula" expressions for scatter gain. These were derived via correcting the "full formula" scatter gain expression slightly to be consistent with the measured scatter gain frequency dependence.

The "full formula" scatter gain is given by

$$G_S = \frac{11.97}{Z_0 (h + \delta_r) \sqrt{R_T R_R} (\alpha^2 + \beta^2)^{\frac{1}{4}}}$$

The scatter gain was calculated using coal seam and rock conductivity values derived from ADL modeling and computing α and β from

$$\alpha + i\beta = \sqrt{\frac{2Z}{\left(\frac{s}{h} + i\omega u_0\right) (\delta_c + i K_c \epsilon_0)}}$$

$$Z_s = \frac{1+i}{\delta_r \delta_r} \quad , \quad \delta_r = \sqrt{\frac{2}{\omega u_0 \delta_r}}$$

where, K_c is the dielectric constant = 6

δ_r is the rock conductivity

δ_c is the coal seam conductivity

h is the seam height

The simple "short formula" scatter gains were derived using the form

$$G_S = \frac{F_1 F_2}{Z_0 \sqrt{R_T R_R}}$$

where F_1 expresses the frequency dependence of the "full formula" and F_2 expresses the frequency dependence correction to make the overall frequency dependence agree with the measured data.

Comparisons of the measured and computed scatter gains for the Upper Freeport, Lower Freeport, and Lower Kittanning seams are given respectively in Tables 5, 6, and 7. These comparisons show good agreement between measured and computed results except in the case of the AC power cable in the Upper Freeport seam (Margaret #11) case. Oddly enough, the complex phone line and belt support cabling configuration gave good results whereas the simple conductor did not. The only conclusion to be drawn is that the AC power cable must have been open circuited somewhere in the vicinity of the measurements so as to create a high surge impedance.

TABLE 5
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		
AC POWER "	14.0	0.25	-41.5	-20.7	20.8		
CABLE "	10.4	3.7	-57.5	-42.8	14.7		
ONLY "	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	9.8	0.25	-22.0	-19.1	2.9	-13.9	8.1
SUPPORT							

NOTE: AC POWER CABLE MUST HAVE
BEEN OPEN CIRCUITED NEAR
THE MEASUREMENT AREA

NOTE: CALCULATION ASSUMPTIONS

$$h = 1.30 \text{ M}$$

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

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

$$Z_0 = 50 \text{ OHMS, FULL FORMULA}$$

$$25 \text{ OHMS, SHORT FORMULA}$$

TABLE 6

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

$$\begin{aligned}
 h &= 1.12 \text{ M} \\
 \Delta_C &= 6.3 \times 10^{-5} \text{ MHO/M} \\
 \Delta_F &= 5.4 \times 10^{-3} \text{ MHO/M} \\
 Z_O &= 50 \text{ OHMS}
 \end{aligned}$$

TABLE 7
 COMPARISON OF MEASURED & COMPUTED SCATTER GAINS
 NANTY GLO #31 MINE - LOWER KITTANNING SEAM

<u>FREQ(KHZ)</u>	<u>R_T(M)</u>	<u>R_R(M)</u>	<u>MEASURED G_S(DB)</u>	<u>FULL FORM CALCULATED G_S(DB)</u>	<u>MEAS/CALC Δ (DB)</u>	<u>SHORT FORM CALCULATED G_S(DB)</u>	<u>MEAS/CALC Δ (DB)</u>
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

$$\begin{aligned}
 h &= 1.04 \text{ M} \\
 \Delta_C &= 6.2 \times 10^{-5} \text{ MHO/M} \\
 \Delta_r &= 7.2 \times 10^{-3} \text{ MHO/M} \\
 Z_0 &= 50 \text{ OHMS}
 \end{aligned}$$

4.0 INDIVIDUAL MINE TESTS DESCRIPTIONS

4.1 MARGARET #11 MINE

The Margaret #11 Mine is in low-medium coal in the Upper Freeport seam. In the area used for testing, the seam was approximately 48-54 inches thick. In haulage entries, the overburden and underburden have been trenched out to give entry heights of approximately 6 feet.

This mine is the most productive one Helvetia/R&P Coal Cos. has and is a "punch mine" with an expected lifetime of roughly 5-10 years. At this location, the Upper Freeport seam is about 100-120 feet beneath the surface. The mine employs only two working sections and three mining machines. The mine is AC with belt haulage using tracked support vehicles in the mains and rubber tired vehicles in the sections. In this mine, the AC power cable is run in the entry adjacent to the haulage entry. The AC power is 7200 VAC. Both the miner(s) and the shuttle cars operate from stepped-down 480 VAC.

The entries are nominally 18-20 feet wide and the coal pillars are nominally on 60 foot centers. There are pager phones only at the section head and tail pieces.

Most of the measurements were performed in the conductor-free 1-Butt and in the conductor-proximity 2-Butt sections with supplemental measurements being performed in the #1 mains. The mine traverse topology and the measured field strength data plotted vs range and frequency are given in Appendix A-1.

Selected observations based on the reduced data include:

- (1) The field variation near the phone line/beltway from a transmitter located 32 feet away due to interaction of the direct and scattered fields was about 5 dB and the ripple due to SWR was about ± 2.5 dB.
- (2) The coupled current in the phone line/belt support cabling from a transmitter located 32 feet away was about 15 dB greater in the direction toward the face than in the direction toward the mains.
- (3) In an entry containing the phone line and belt support cabling, the VMD and HMD field components in the opposite rib plane were of near-equal amplitude. The rib plane field strengths were about 15 dB less than those at close proximity to the conductors when the transmitter was 32 feet away and about 25 dB less when the transmitter was located 88 feet away.
- (4) In an entry containing only the AC power cable, the cable "carrier" current was about 12 dB greater when the transmitter was located 14 feet away than when it was located 46 feet away. The rib plane field strength was about 15 dB less than the close proximity field strength when the transmitter was located 46 feet away.

4.2 ADRIAN MINE

The Adrian Mine is in high coal in the Upper Freeport seam. In the area used for testing, the seam is approximately 72 inches thick.

This mine, established in 1965, is of small-to-moderate size, and is scheduled for another 18-20 years of life. This is one of the farthest south mines in the Upper Freeport seam. Although the overburden in the test area was approximately 300 feet, the seam outcrops in the nearby area. The mine employs continuous miners and belt haulage, working three sections with a production of approximately $9\frac{1}{2}$ tons per man shift.

The mine uses the room and pillar technique with the pillars being on 70 foot centers in length and on 50 foot centers in width. The entry crosssectional widths are nominally 17 feet. The overburden material is metamorphasized shale with no draw slate adjacent to the seam. No top coal is left in mining. The mine employs track and trolley for service vehicles. The continuous miners are AC operated at 2480 or 1575 volts stepped down from the 4160 VAC line. The shuttle cars are DC operated and the roofbolter is AC operated.

All measurements were performed in the area parallel to Road 83C between 1st-Right and 2nd-Right with the transmit antenna oriented HMD with the loop plane coplanar in the entry crosssection. The mine measurement traverse topology and the measured field strength data plotted vs range and frequency are given in Appendix A-2. Only frequencies of 90 and 220 KHz were used in this mine.

The data taken in the two entries compared within 2 dB at 90 KHz and within 5 dB at 220 KHz at the same range with the transmitter entry having the advantage over the entry two entries removed from the transmitter entry.

4.3 NANTY GLO MINE #31

The Nanty Glo #31 Mine is in low-medium coal in the Lower Kittanning ("B") seam. In the area used for testing, the seam was approximately 39-43 inches thick.

This is a large old mine (approximately 50 years); the Main-N and 5-Cross areas of the mine being approximately 16 miles apart underground. This shaft entry mine maintains 600-900 feet of overburden with a substantial variation in the seam elevation. The Leidy Portal, in a valley, marks the low point of the seam and the Main-N area is relatively near this portal. The 5-Cross area is approximately 900 feet higher in elevation than Main-N and is near where the seam outcrops on a mountain top.

The mine uses entries driven on 60-foot centers (crosscuts every 120 feet in the old area) in Main-N and on 70-foot centers (crosscuts every 100 feet) in 5-Cross. The entry widths are 18 feet. The roof is hard rock and is flat; the best roof the author has ever experienced. No top coal is left in mining.

This mine provided the equivalent of two mines worth of data due to the wide separation of measuring locations. Although both quasi-conductor-free and conductor-proximity data were taken in the Main-N area, only the quasi-conductor-free data was conclusive. This data was "dearly won" for the floor had heaved and the data was gathered with only 2-3 feet of head clearance. Both quasi-conductor-free and conductor-proximity data were gathered in the 5-Cross area. The test traverse and reduced data are given in Appendix A-3.

Selected observations based on the reduced data include:

- (1) The limited conductor proximity data taken in the Main-N area show comparable coupled field strength levels along entry centers at 218 KHz in both power cable and belt entries. In the power cable entry, the coupled field strength is about 5 dB more at 480 KHz than at 218 KHz and about 22 dB more than at 3620 KHz.
- (2) In the 5-Cross area very close to the power cable, the optimum coupled field strength appears to be in the 1860-4050 KHz range (approximately 10 dB greater than at 890 KHz) while in the rib plane, the field strengths seem to be much lower with the purely coupled field strength condition not being obtained.
- (3) Pursuant to (2), there appears to be an effect at higher frequencies which produces a periodic variation in field strength with distance along the power cable entry rib plane.

4.4 EHRENFELD #38D MINE

The Ehrenfeld #38D Mine is in low-medium coal in the Lower Freeport ("D") seam. In the area used for testing, the seam was approximately 42-46 inches thick.

This drift mine, established in the late 1950's, is of moderate size with several seams being mined. Currently, most of the production comes from the "D" seam; an operation to mine the Upper Freeport ("E") seam is just beginning. This mine employs conventional mining sections with belt haulage. In the test area, the overburden level was approximately 250 feet.

The mine uses the room and pillar technique with the pillars being on 100 foot centers in length and on 70 foot centers in width. The entry cross-sectional widths are nominally 18 feet. The power cable entry used for the conductor-proximity testing contained only the 4160 VAC cable suspended beneath a 3/8 " stranded steel messenger cable.

All measurements were performed in the I-Right Main-B area with the transmitter in a fixed location. Quasi-conductor-free measurements were made in the entry containing the transmitter. Conductor-proximity measurements were made in the adjacent power cable entry. The test traverse topology and the measured field strength data plotted vs range and frequency are given in Appendix A-4.

Selected observations based on the reduced data include:

- (1) The optimum coupling frequency observed in the rib plane was about 470 KHz.
- (2) Optimum coupling immediately adjacent to the AC power cable appears to be between 470 and 880 KHz.
- (3) At 200 KHz, the coupled field strength is 10-15 dB below the optimum coupled results.

4.5 STINSON #3 MINE

The Stinson #3 Mine is in low-medium coal in the Elkhorn #3 seam. In the area used for testing, the seam was approximately 50-56 inches thick.

This is a small drift mine and is one of a connected set of mines in the immediate area; serviced via separate power systems and separate portals to facilitate operation using battery operated service vehicles, accommodate the mountainous topography, and minimize belt-to-tipple runs. This seam is one of seven Elkhorn seams (numbered from the bottom up) and stacked approximately 60 feet apart. Existing leases in the area will permit National Mine Corp. to continue operation in the highly productive #3 seam alone for 20-30 years. This mine employs conventional mining sections with belt haulage. In the test area, the overburden was approximately 500 feet thick and about 100 feet thick at the C Section face (outcropped just before our trip).

The mine uses the room and pillar technique with the pillars being on 60 foot centers (nominally 38 foot pillar widths) and are roughly square. The mine is not pillared in retreat mining due to the intended mining of the other seams. The pillars in these future mines will be made to coincide vertically with the pillars in the currently mined areas.

The overburden/underburden consists of approximately 1½ feet of shale on the roof/floor followed by sandstone.

This mine runs all conductors in the belt entry; the 4160 VAC power cable lies on the floor. All service vehicles are battery operated and are of the articulated variety.

All measurements were performed in C-Section of this mine. The quasi-conductor-free measurements were made in an entry three entries removed from the conductor entry. Conductor-proximity measurements were made both from a remote transmitter (same location as for the quasi-conductor-free tests) and from a tightly coupled transmitter for the coupled field polarization measurements. The test traverse topology and the measured field strength data plotted against range and frequency are given in Appendix A-5.

Selected observations based on the reduced data include:

(1) Conductor-proximity measurements show:

VMD polarization to be predominant at low frequencies

HMD polarization with the loop plane perpendicular to the conductors to be predominant at higher frequencies

All polarizations produce nearly equal field strengths at 486 KHz

A pronounced null, just off the loop-plane-parallel direction in the HMD polarization

The best coupling frequency to be the highest used; 890 KHz.

APPENDIX

MINE TEST DATA

This Appendix gives the mine maps and summary field strength reduced data sets from each of the five Summary Data Reports prepared during this program. For additional information regarding a particular mine, the reader is referred to the particular Summary Data Report for that mine.

The information in this Appendix is organized as:

A-1	Margaret #11 Mine
A-2	Adrian Mine
A-3	Nanty Glo #31 Mine
A-4	Ehrenfeld #38D Mine
A-5	Stinson #3 Mine

The particular references for the five Summary Data Reports are given as References (10) through (14).

A-1

MARGARET #11 TEST DATA AT MEDIUM FREQUENCY

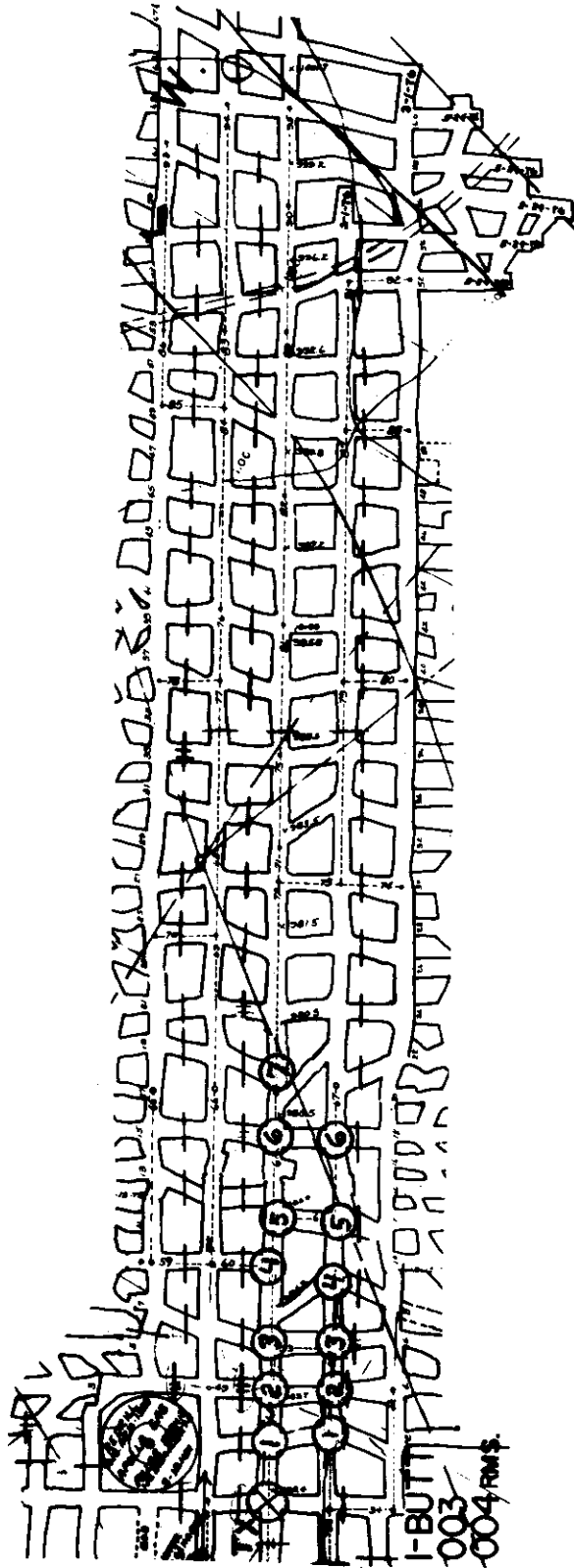


FIGURE A1

MINE MAP SHOWING TOPOLOGY, TRANSMITTER LOCATION, AND MEASUREMENT STATIONS FOR CONDUCTOR-FREE DATA IN I-BUTT SECTION

HELVETIA COAL CO. MARGARET #11 MINE

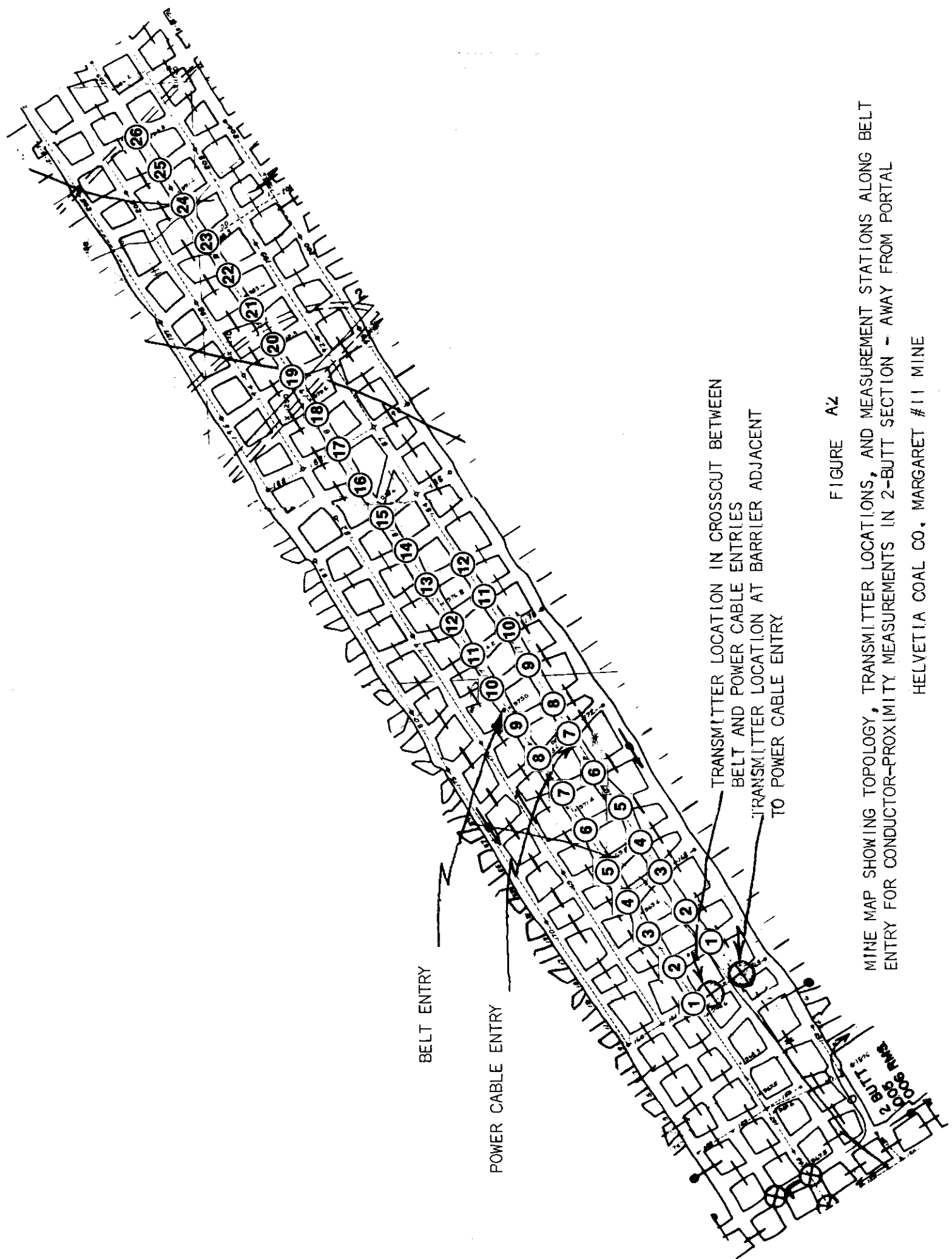


FIGURE A2

MINE MAP SHOWING TOPOLOGY, TRANSMITTER LOCATIONS, AND MEASUREMENT STATIONS ALONG BELT ENTRY FOR CONDUCTOR-PROXIMITY MEASUREMENTS IN 2-BUTT SECTION - AWAY FROM PORTAL
 HELVETIA COAL CO. MARGARET #11 MINE

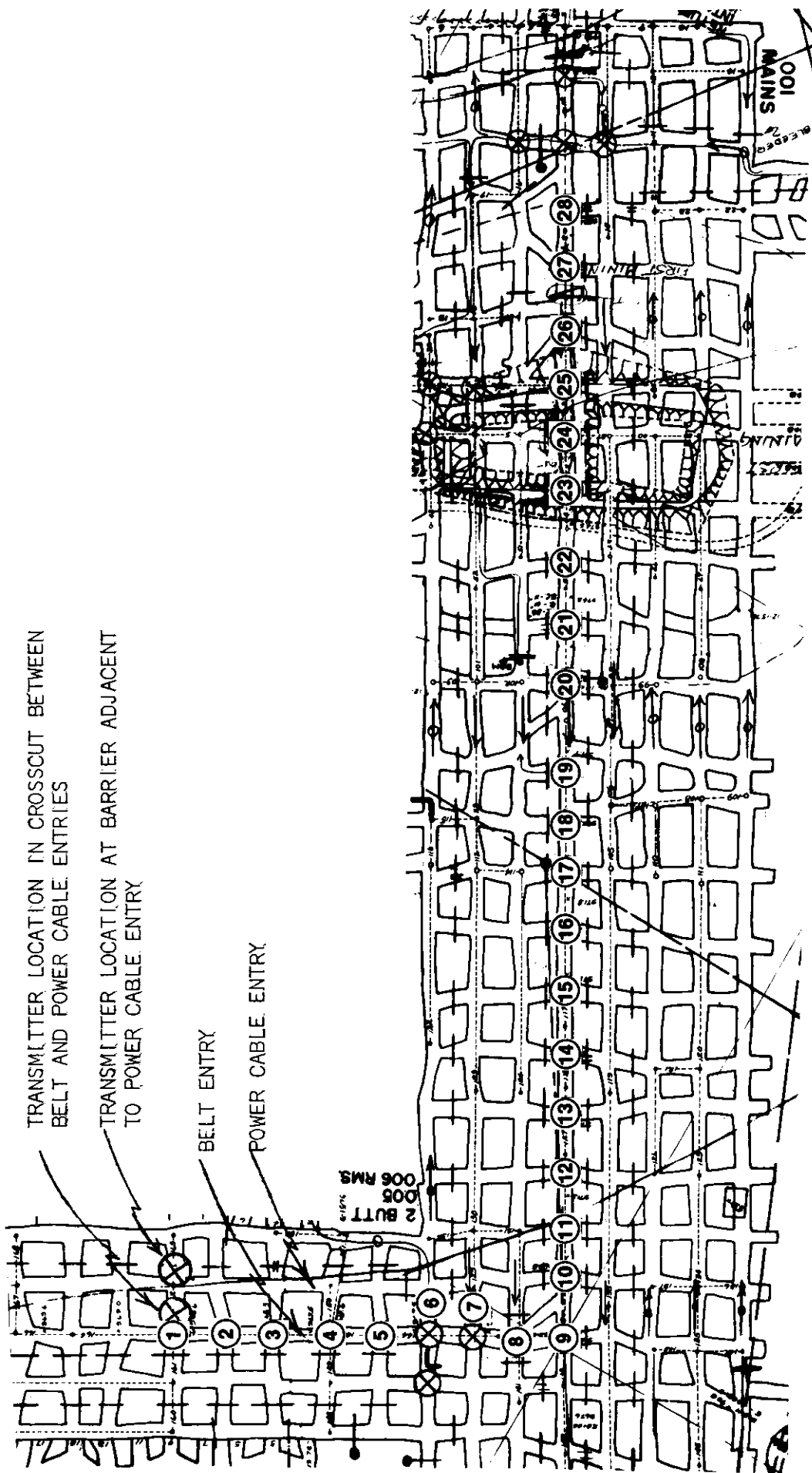


FIGURE A3

MINE MAP SHOWING TOPOLOGY, TRANSMITTER LOCATIONS, AND MEASUREMENT STATIONS ALONG BELT ENTRY FOR CONDUCTOR-PROXIMITY MEASUREMENTS IN 2-BUTT SECTION AND #1 MAINS - TOWARD PORTAL

HELVETIA COAL CO. MARGARET #11 MINE

FIGURE A4

MAGNETIC FIELD STRENGTH VS RANGE IN
CONDUCTOR-FREE I-BUTT SECTION OF
HELVETIA COAL CO. MARGARET #111 MINE

NIA = 2.5

DATA TAKEN IN ENTRY CONTAINING TRANSMITTER

COPLANAR HMD ORIENTATION OF ANTENNAS

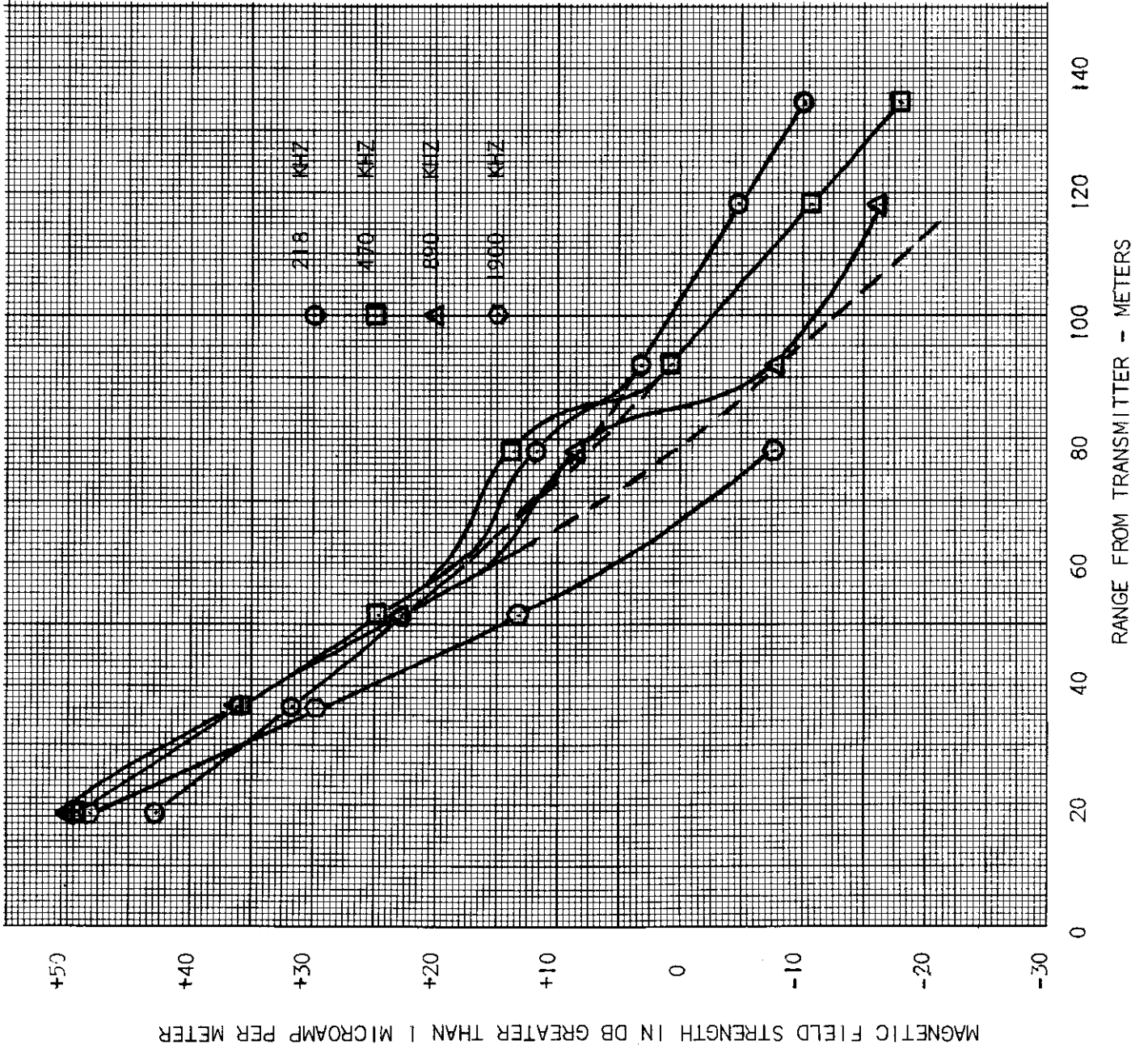
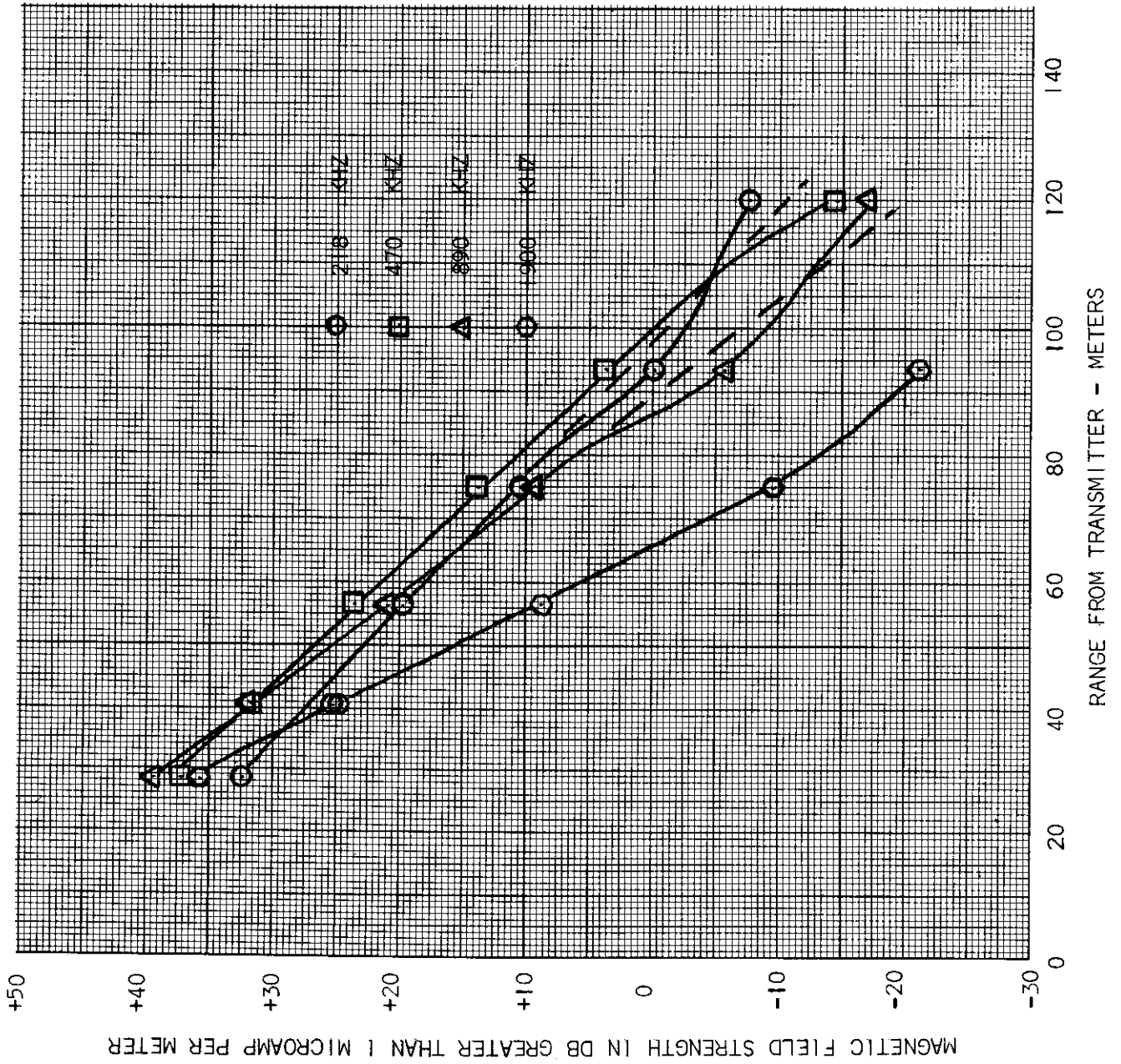


FIGURE A5

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



MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICROAMP PER METER

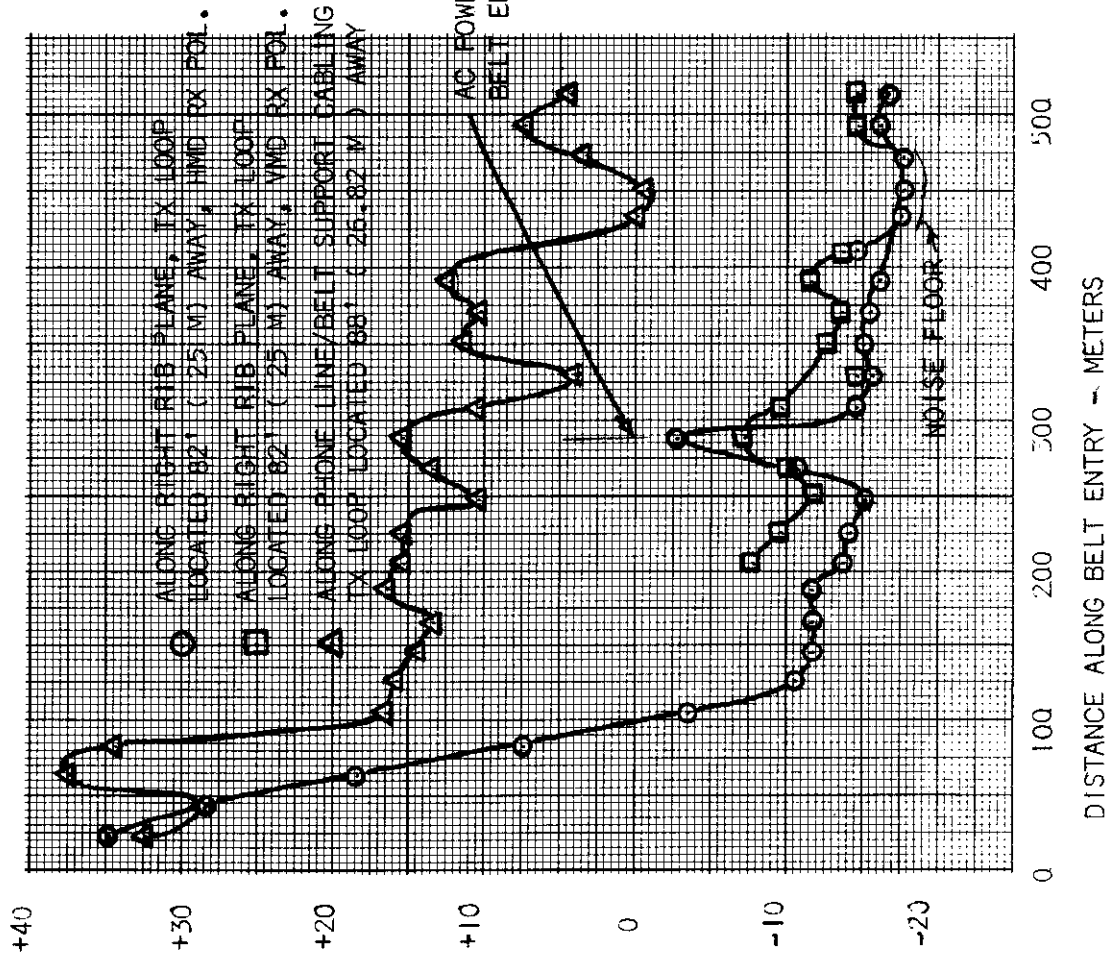
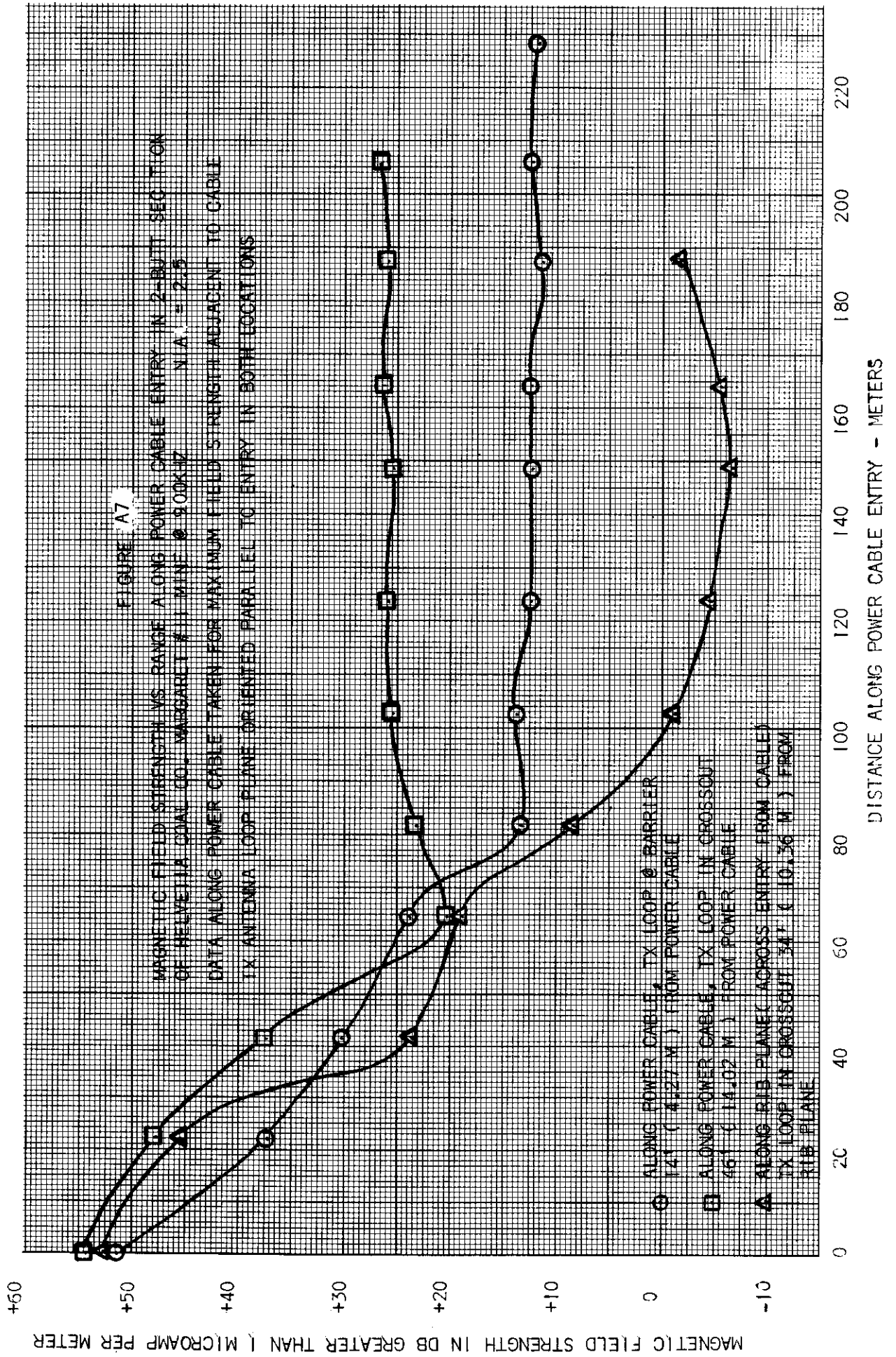
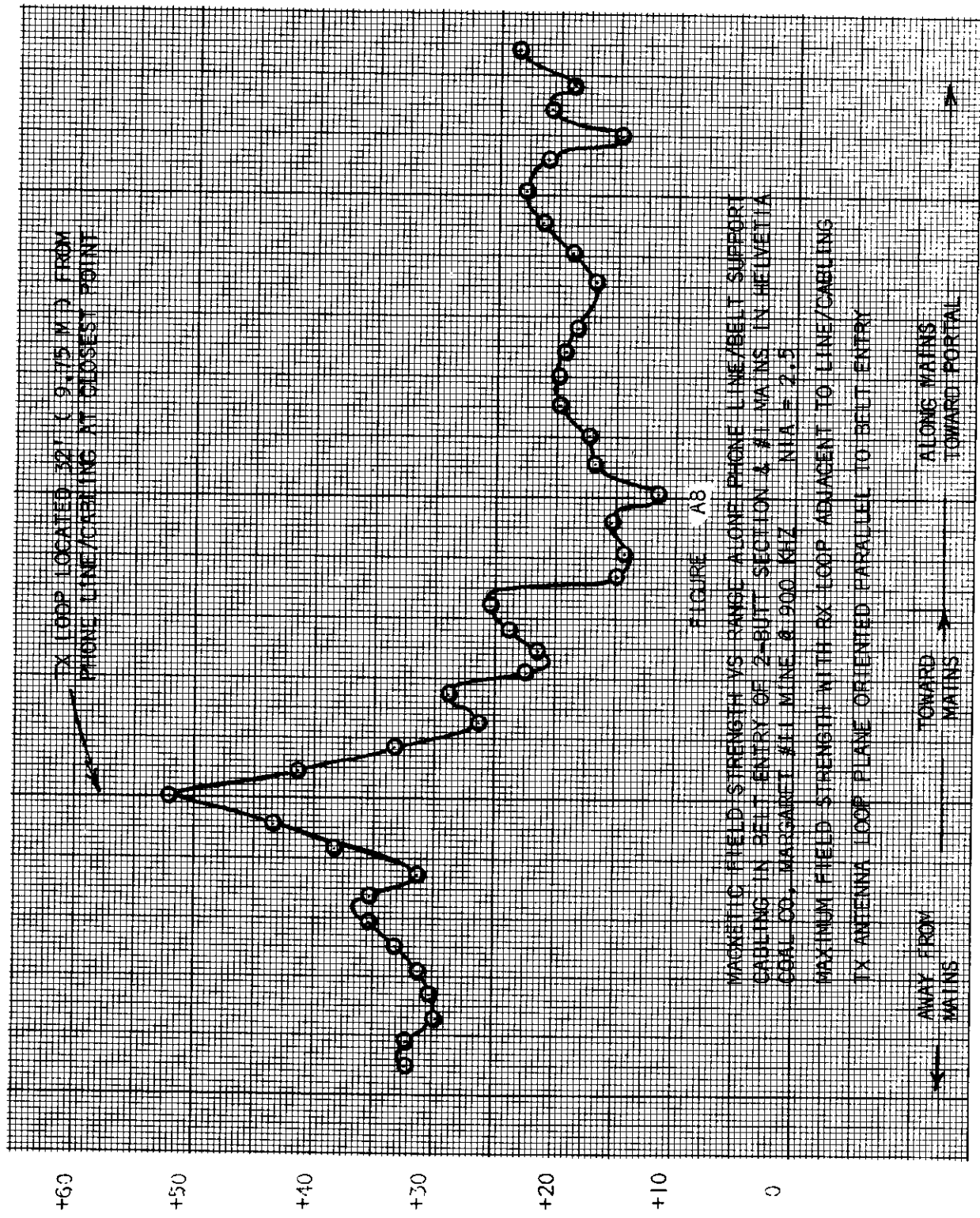


FIGURE A6

MAGNETIC FIELD STRENGTH VS RANGE ALONG BELT ENTRY
 IN 2-BUTT SECTION OF HELVETIA COAL CO. MARGARET #11
 MINE @ 900 KHZ WITH TRANSMIT LOOP LOCATED 1 1/2 ENTRIES
 AWAY NIA = 2.5
 DATA TAKEN ALONG PHONE LINE/BELT SUPPORT CABLING IS
 FOR MAXIMUM FIELD STRENGTH ADJACENT TO LINE/CABLING
 TX ANTENNA LOOP PLANE ORIENTED PARALLEL TO ENTRY





MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICRAMP PER METER

FIGURE A8

TX LOOP LOCATED 321' (97.75 M) FROM PHONE LINE/CABLING AT CLOSEST POINT

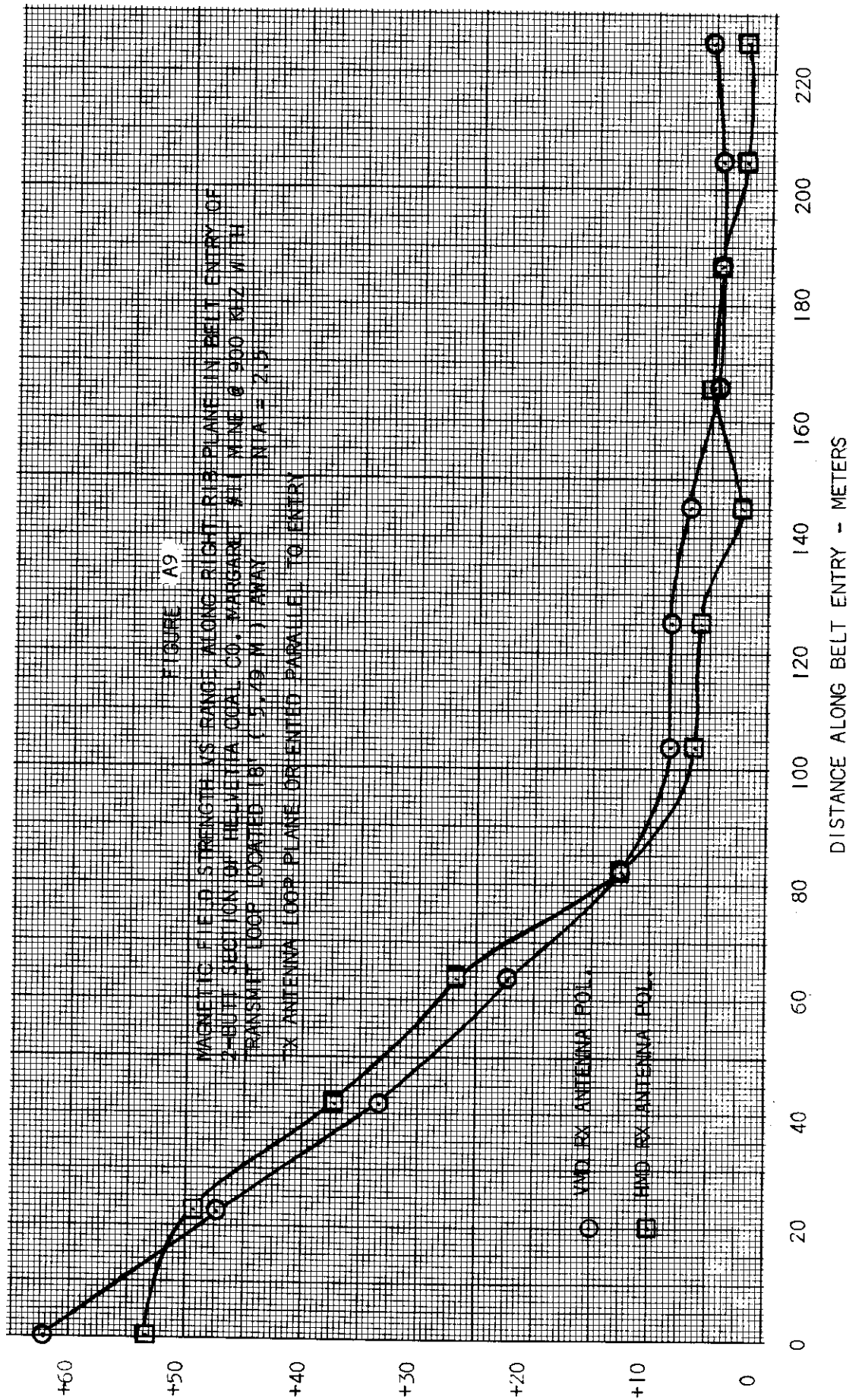
AWAY FROM MAINS
TOWARD MAINS
ALONG MAINS TOWARD PORTAL

MAGNETIC FIELD STRENGTH VS RANGE ALONG PHONE LINE/BELT SUPPORT CABLING IN BELT ENTRY OF 2-BUTT SECTION #1 MAINS IN HELVETIA COAL CO., MARGARET #11 MINE @ 900 KHZ NIA = 2.5

MAXIMUM FIELD STRENGTH WITH RX LOOP ADJACENT TO LINE/CABLING TX ANTENNA LOOP PLANE ORIENTED PARALLEL TO BELT ENTRY

RANGE ALONG BELT ENTRY - METERS

MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICROAMP PER METER



A-2

ADRIAN MINE TEST DATA AT MEDIUM FREQUENCY

FIGURE A11

MAGNETIC FIELD STRENGTH VS RANGE IN CONDUCTOR-FREE AREA PARALLEL TO ROAD 83C
BETWEEN 1ST-RIGHT AND 2ND-RIGHT @ 90 KHZ FOR NIA = 2.5

UPSHUR COALS CORP. ADRIAN MINE

RECEIVE ANTENNAS ORIENTED HMD WITH LOOP PLANE OF TRANSMIT & RECEIVE ANTENNAS PARALLEL

MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICROAMP PER METER

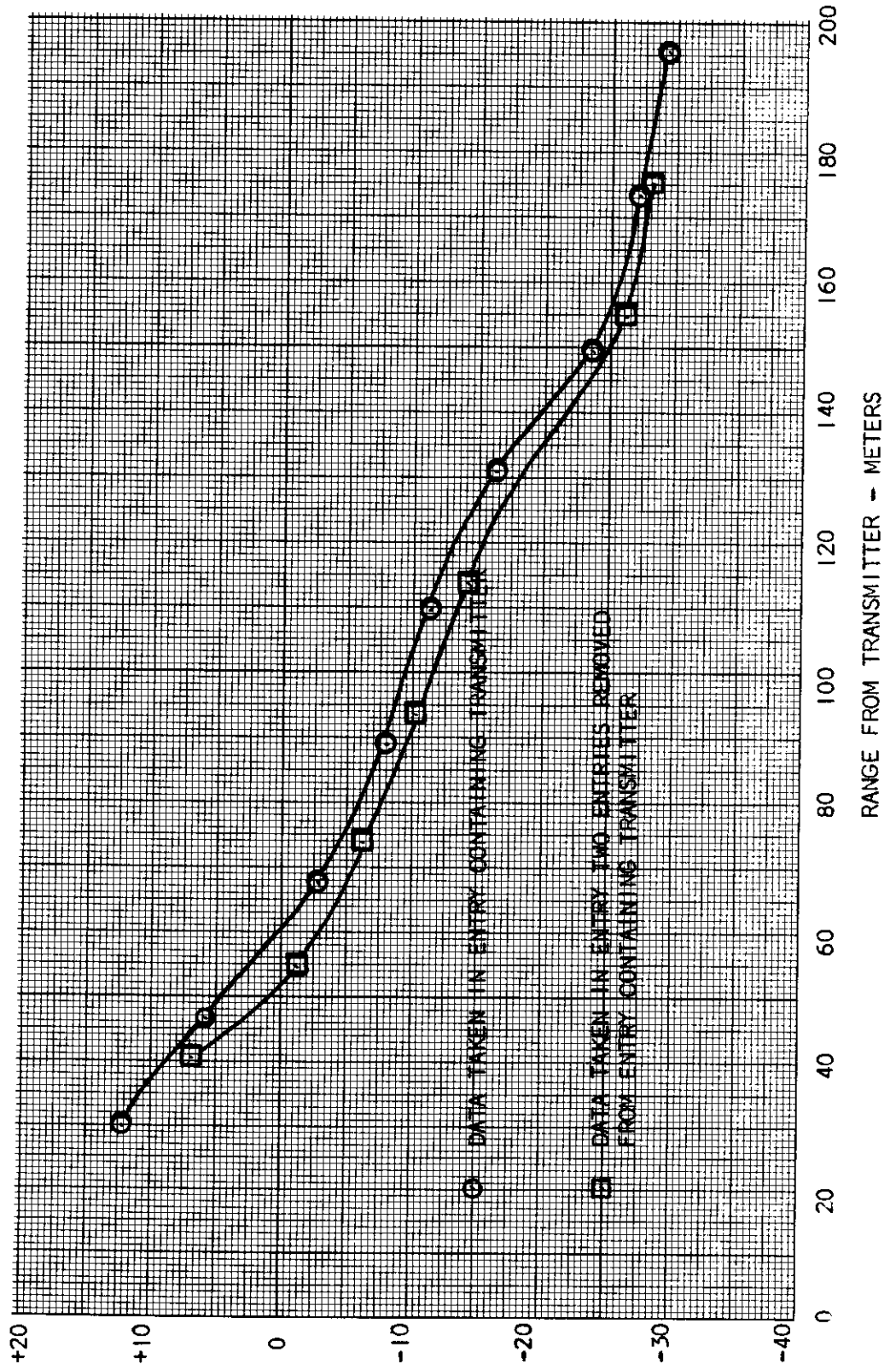
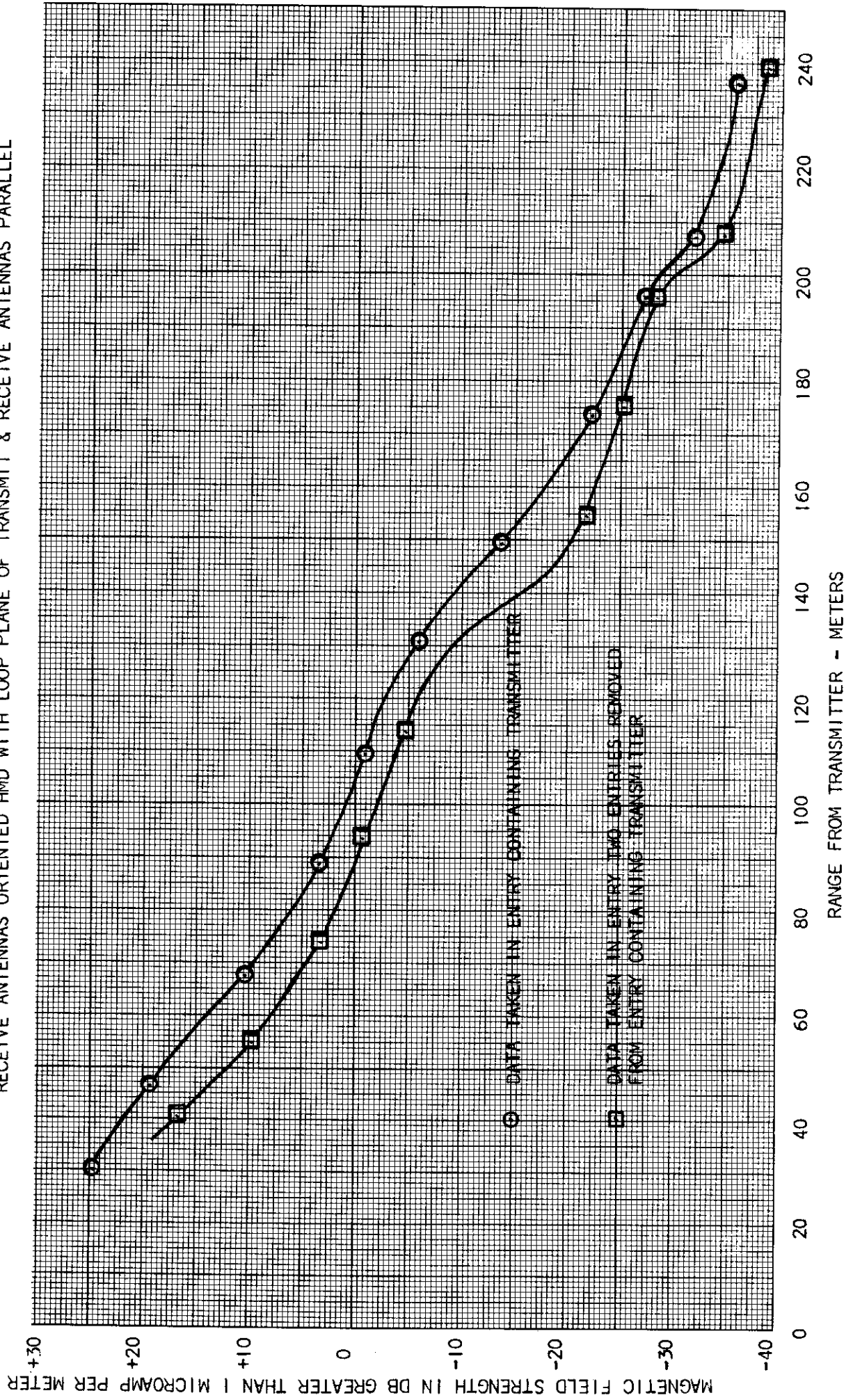


FIGURE A12

MAGNETIC FIELD STRENGTH VS RANGE IN CONDUCTOR-FREE AREA PARALLEL TO ROAD 83C
BETWEEN 1ST-RIGHT AND 2ND-RIGHT @ 220 KHZ FOR NIA = 2.5

UPSHUR COALS CORP. ADRIAN MINE

RECEIVE ANTENNAS ORIENTED HMD WITH LOOP PLANE OF TRANSMIT & RECEIVE ANTENNAS PARALLEL



A-3

NANTY GLO #31 MINE TEST DATA AT MEDIUM FREQUENCY

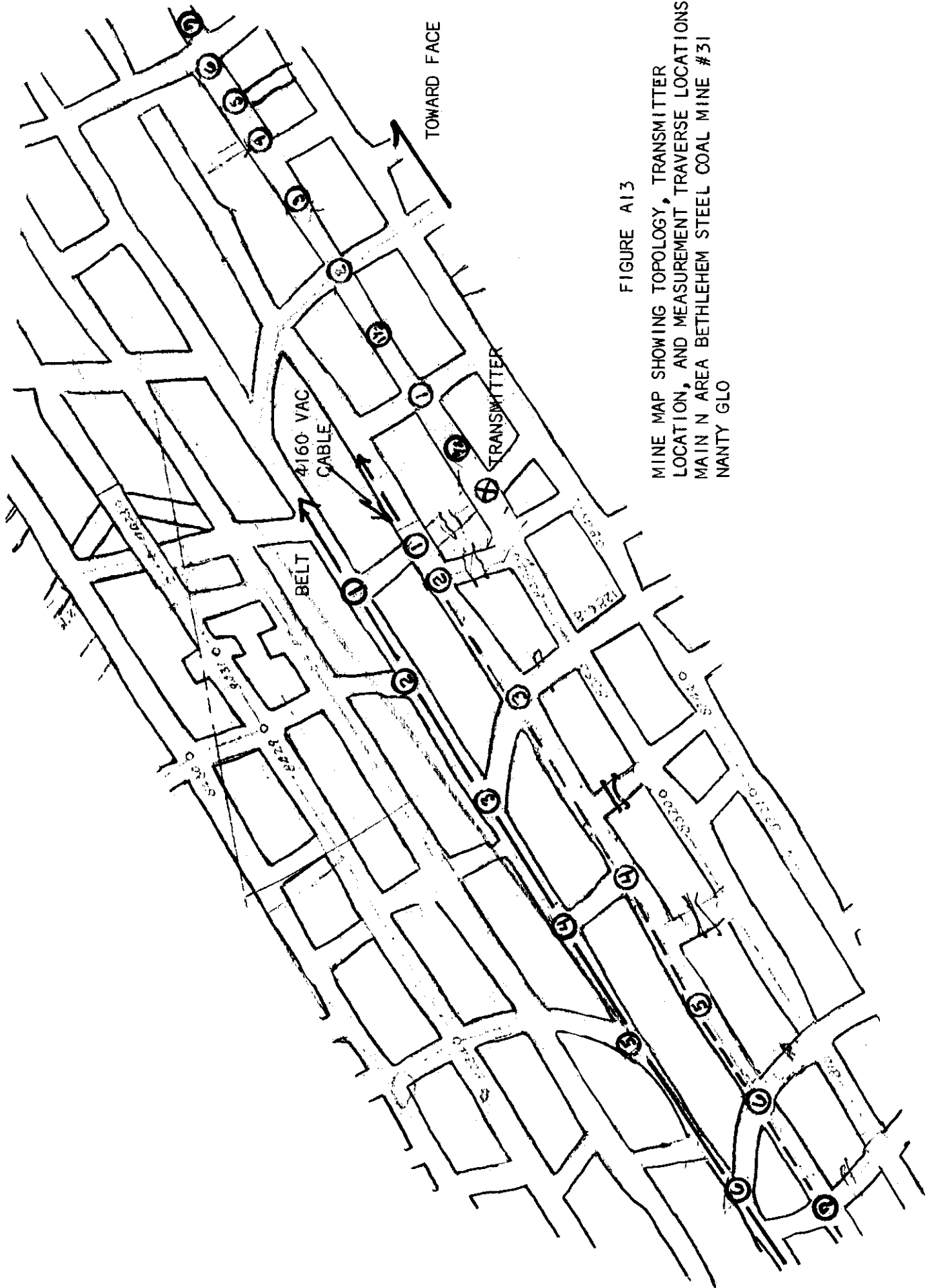


FIGURE A13
 MINE MAP SHOWING TOPOLOGY, TRANSMITTER
 LOCATION, AND MEASUREMENT TRAVERSE LOCATIONS
 MAIN N AREA BETHLEHEM STEEL COAL MINE #31
 NANTY GLO

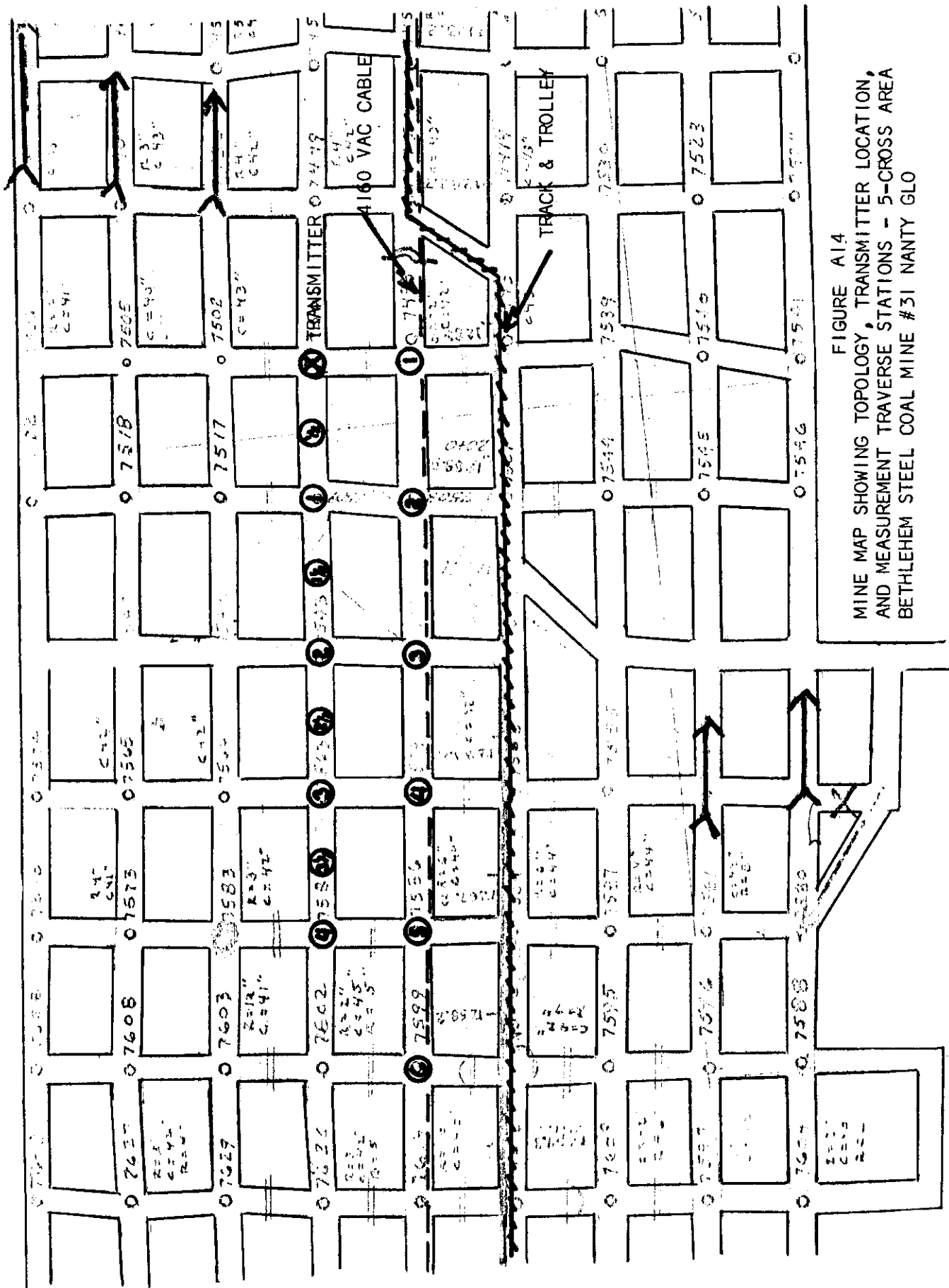


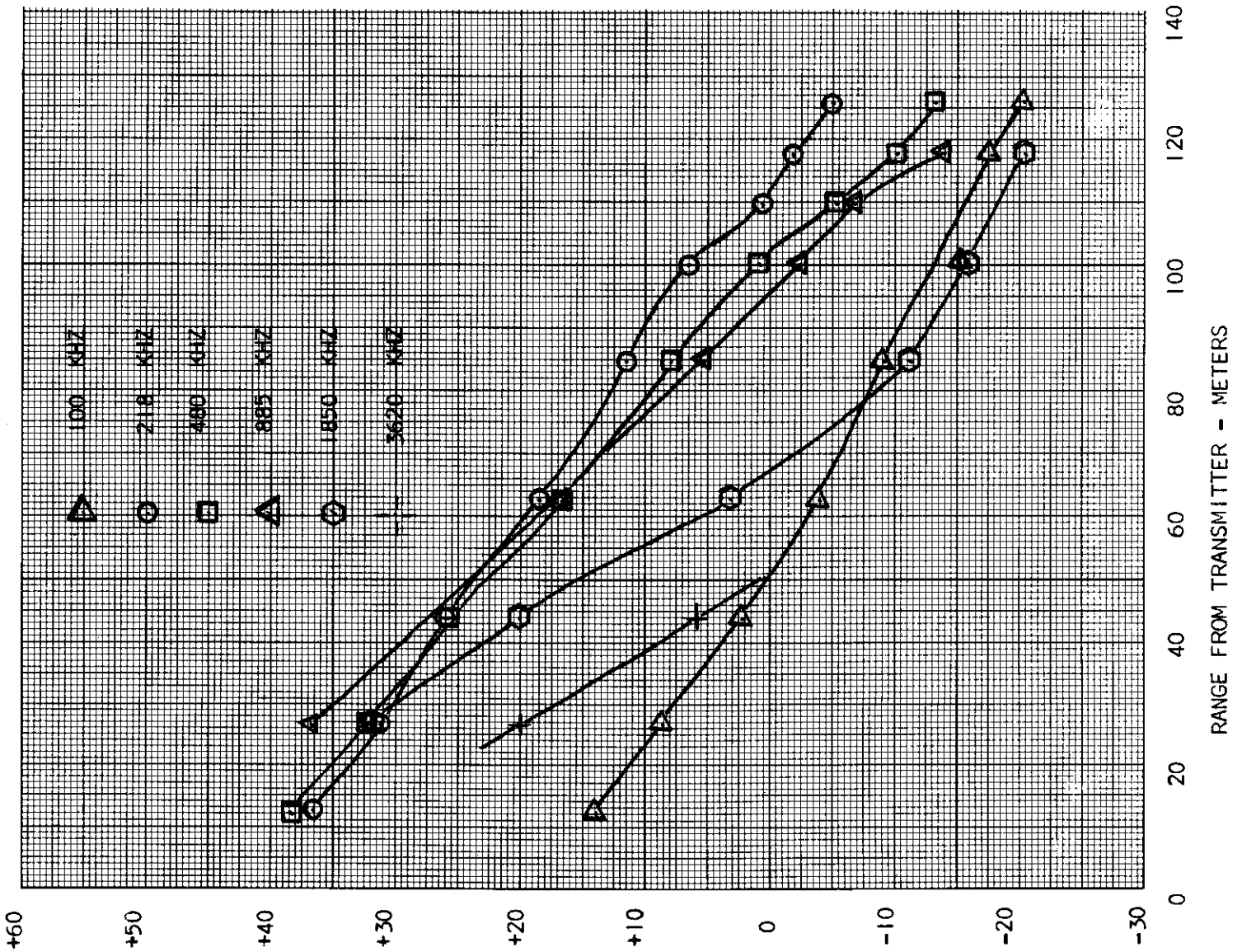
FIGURE A14
 MINE MAP SHOWING TOPOLOGY, TRANSMITTER LOCATION,
 AND MEASUREMENT TRAVERSE STATIONS - 5-CROSS AREA
 BETHLEHEM STEEL COAL MINE #31 NANTY GLO

FIGURE A15

MAGNETIC FIELD STRENGTH VS RANGE IN QUASI-
 CONDUCTOR-FREE FRESH AIR ENTRY CONTAINING
 TRANSMITTER; MAIN-N AREA
 BETHLEHEM STEEL COAL MINE NANTY GLO #31

NIA = 2.5

COPLANAR HMD ORIENTATION OF ANTENNAS



MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICROAMP PER METER

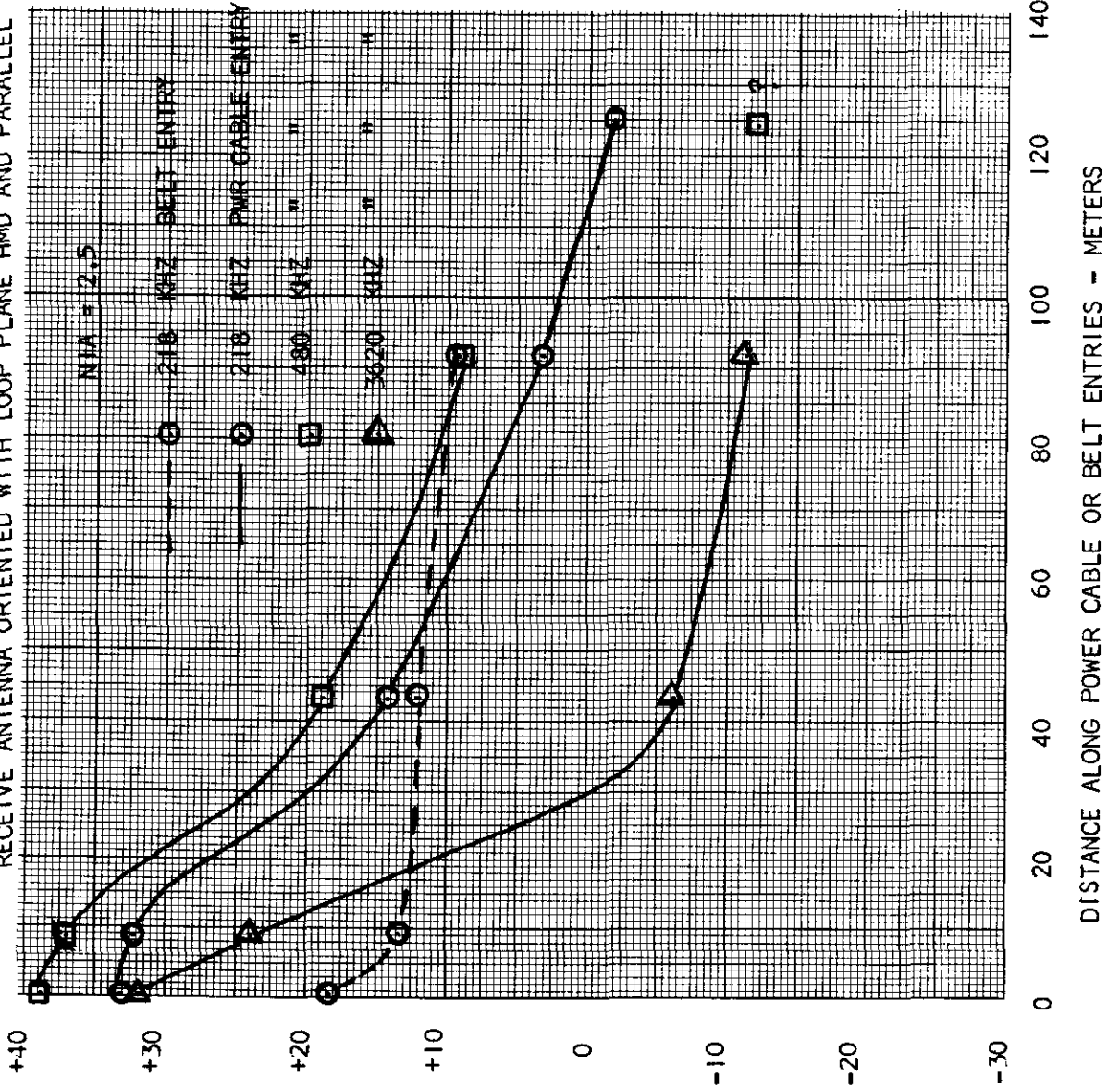
RANGE FROM TRANSMITTER - METERS

FIGURE A16

MAGNETIC FIELD STRENGTH VS RANGE ALONG CENTER OF POWER CABLE OR BELT ENTRIES,
 AS NOTED, TRANSMITTER LOCATED ONE ENTRY REMOVED FROM POWER CABLE ENTRY AND
 TWO ENTRIES REMOVED FROM BELT ENTRY, TRANSMIT ANTENNA LOOP PLANE PARALLEL TO ENTRIES

MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICRAMP PER METER

BETHLEHEM STEEL COAL MINE NANTY GLO #31 MAIN-N AREA
 RECEIVE ANTENNA ORIENTED WITH LOOP PLANE HMD AND PARALLEL TO ENTRY DIRECTION



MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICRAMP PER METER

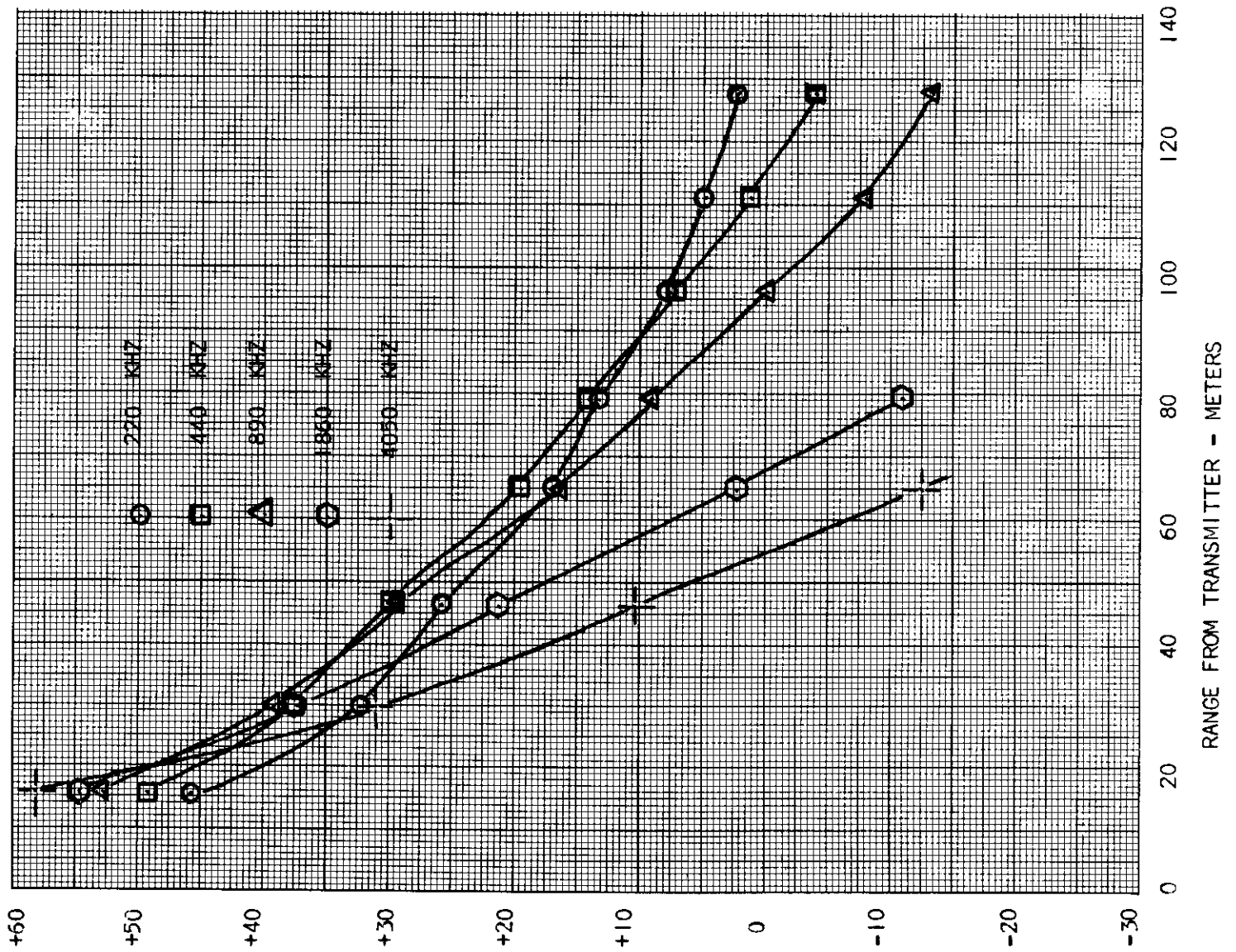


FIGURE A17
MAGNETIC FIELD STRENGTH VS RANGE IN QUASI-
CONDUCTOR-FREE FRSH AIR ENTRY CONTAINING
TRANSMITTER; 5-CROSS AREA
EETHLEHEM STEEL COAL MINE NANTY GLO #31
NIA = 2.5
COPLANAR HMD ORIENTATION OF ANTENNAS

FIGURE A18

MAGNETIC FIELD STRENGTH VS RANGE ALONG POWER CABLE ONE ENTRY REMOVED FROM TRANSMITTER; TRANSMIT ANTENNA LOOP PLANE PARALLEL TO CABLE NIA = 2.5

BETHLEHEM STEEL COAL MINE NANTY GLO #31 5-CROSS AREA

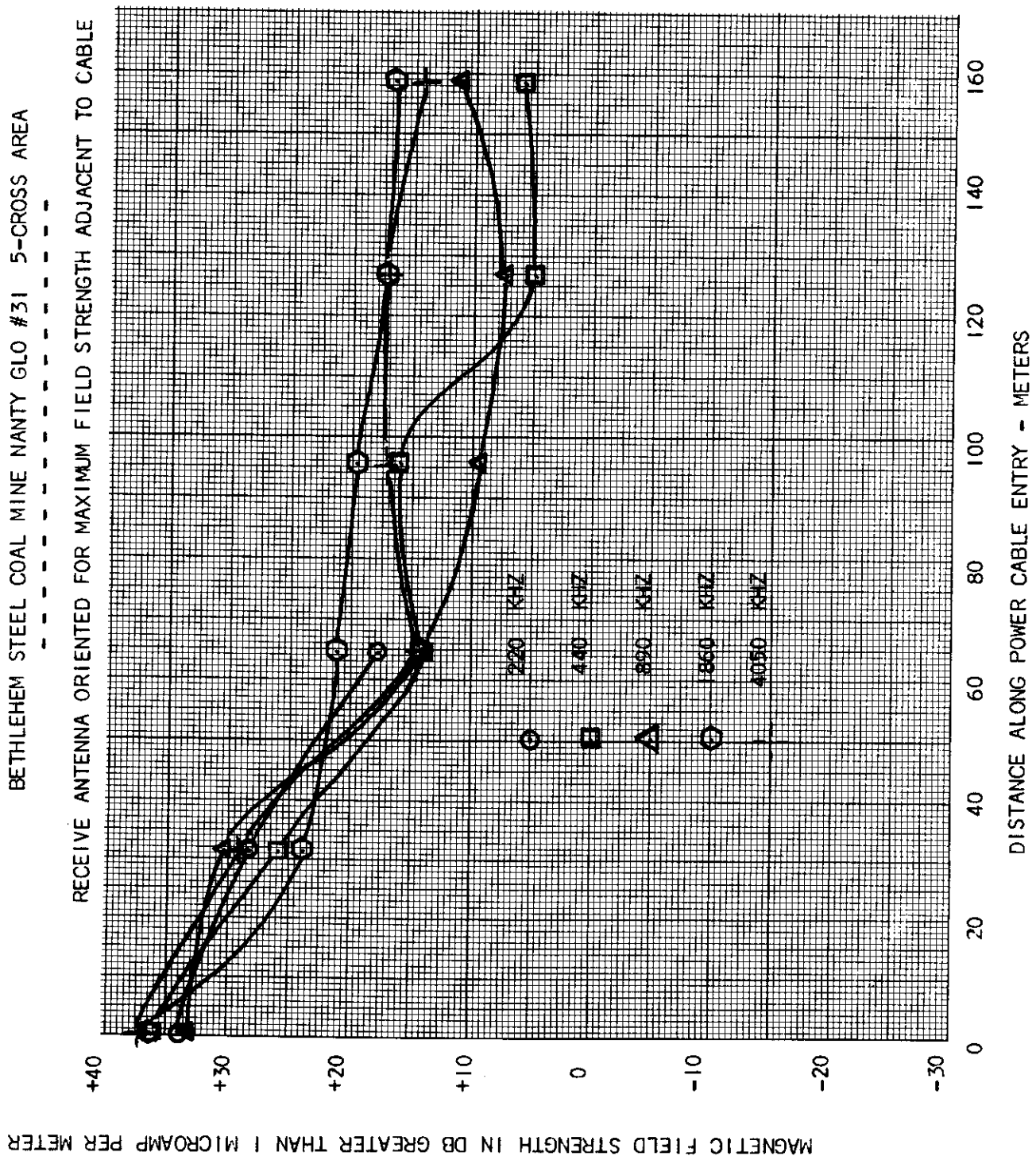
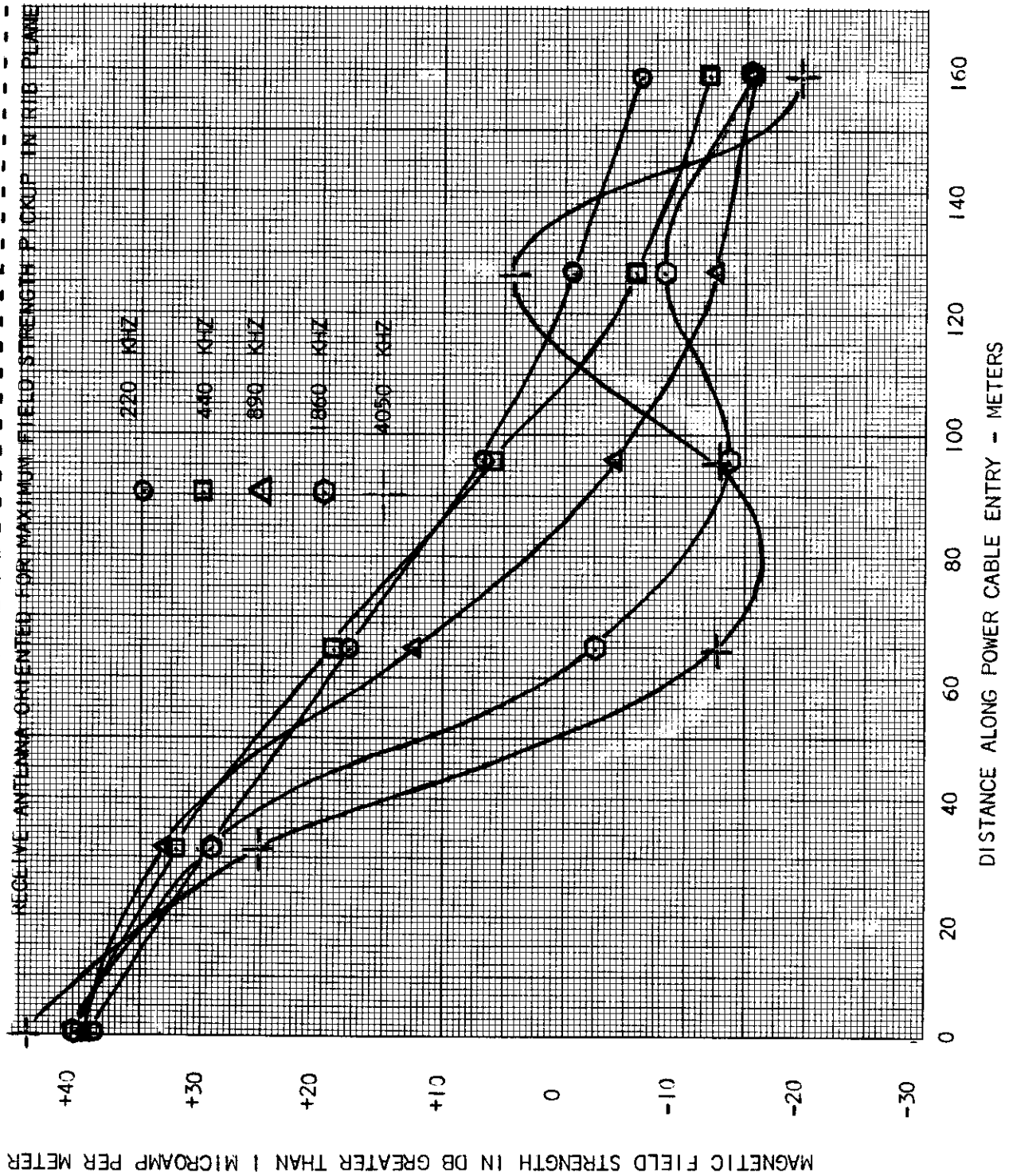


FIGURE A19

MAGNETIC FIELD STRENGTH VS RANGE ALONG RIB PLANE OF POWER CABLE ENTRY, ONE ENTRY REMOVED FROM TRANSMITTER; TRANSMIT ANTENNA LOOP PLANE PARALLEL TO CABLE NIA = 2.5 BETHLEHEM STEEL COAL MINE NANTY GLO #31 5-CROSS AREA



A-4

EHRENFELD #38D MINE TEST DATA AT MEDIUM FREQUENCY

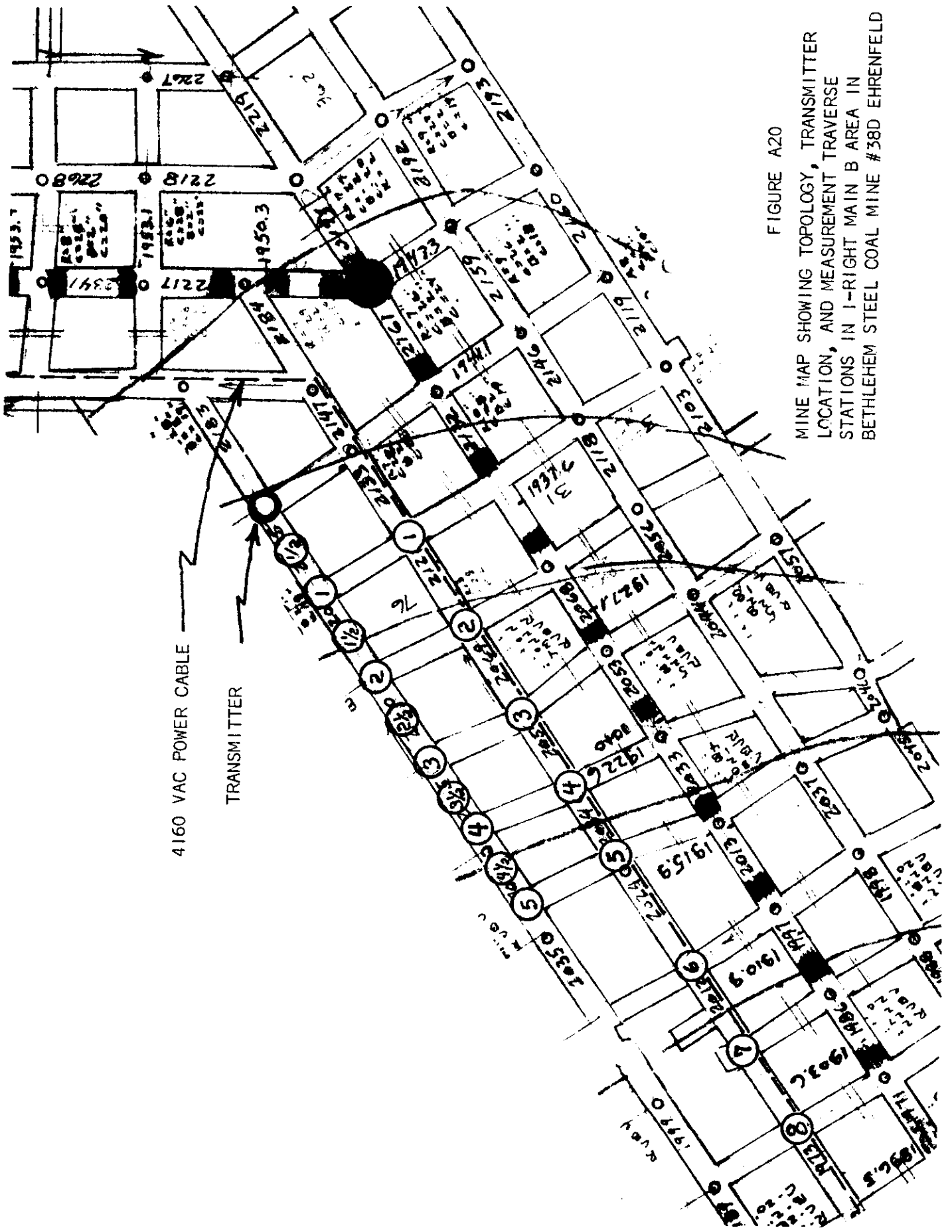


FIGURE A20
 MINE MAP SHOWING TOPOLOGY, TRANSMITTER
 LOCATION, AND MEASUREMENT TRAVERSE
 STATIONS IN I-RIGHT MAIN B AREA IN
 BETHLEHEM STEEL COAL MINE #38D EHRENFELD

FIGURE A21

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

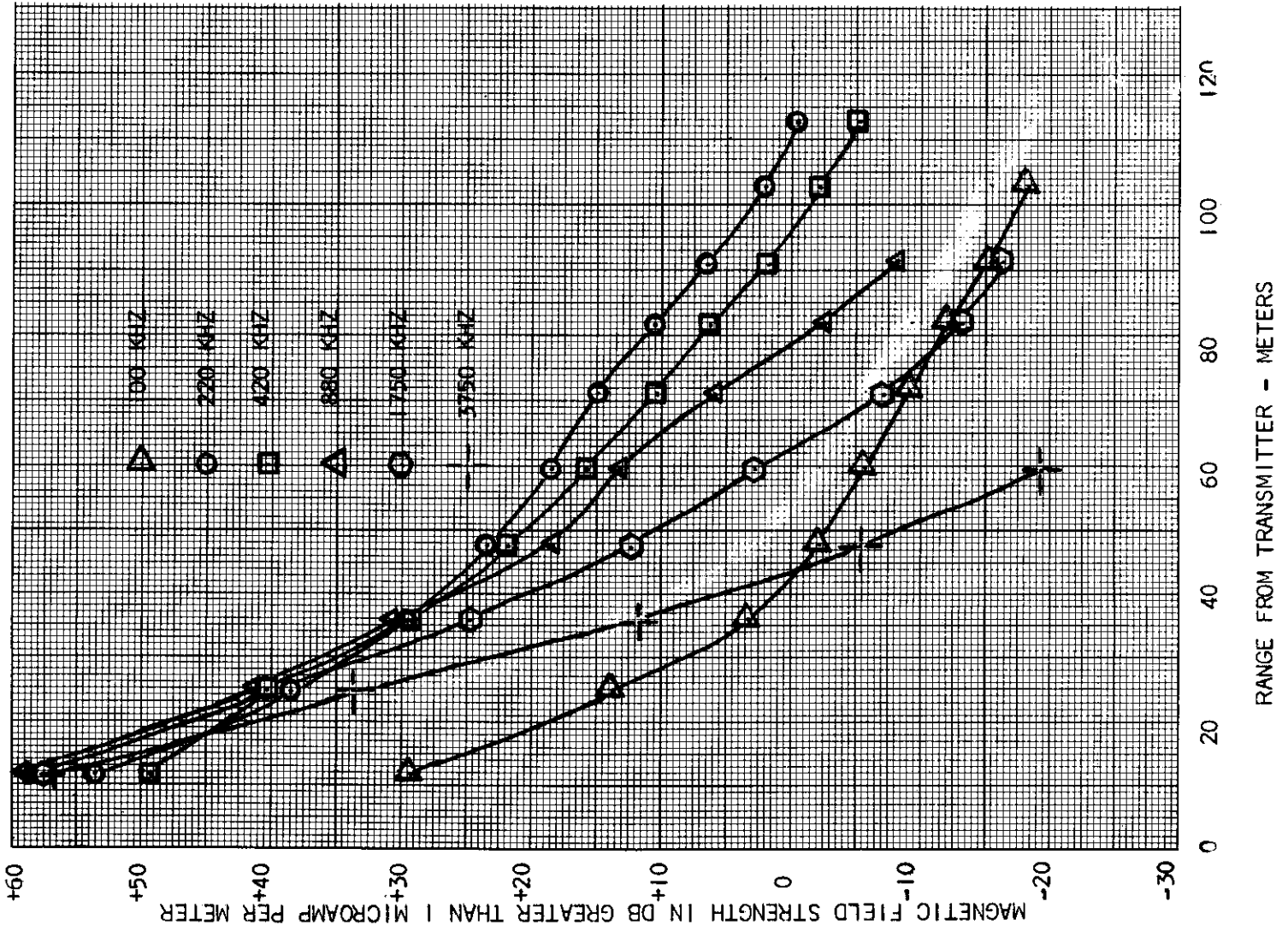


FIGURE A22

MAGNETIC FIELD STRENGTH VS RANGE ALONG POWER CABLE ONE ENTRY REMOVED FROM TRANSMITTER; TRANSMIT ANTENNA LOOP PLANE PARALLEL TO CABLE NIA = 2.5

BETHLEHEM STEEL COAL MINE EHRENFELD #38(D) 1-RIGHT MAIN B

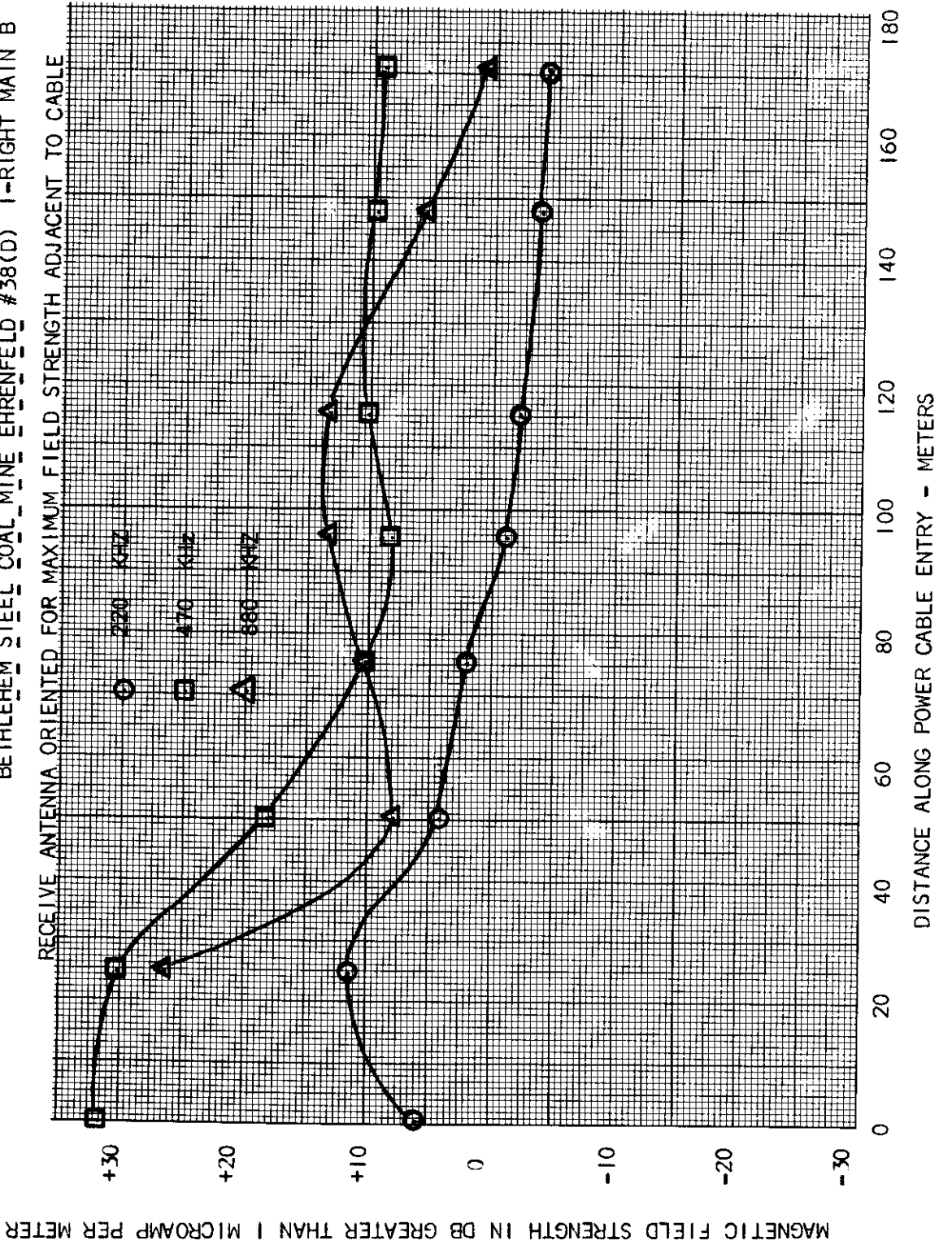
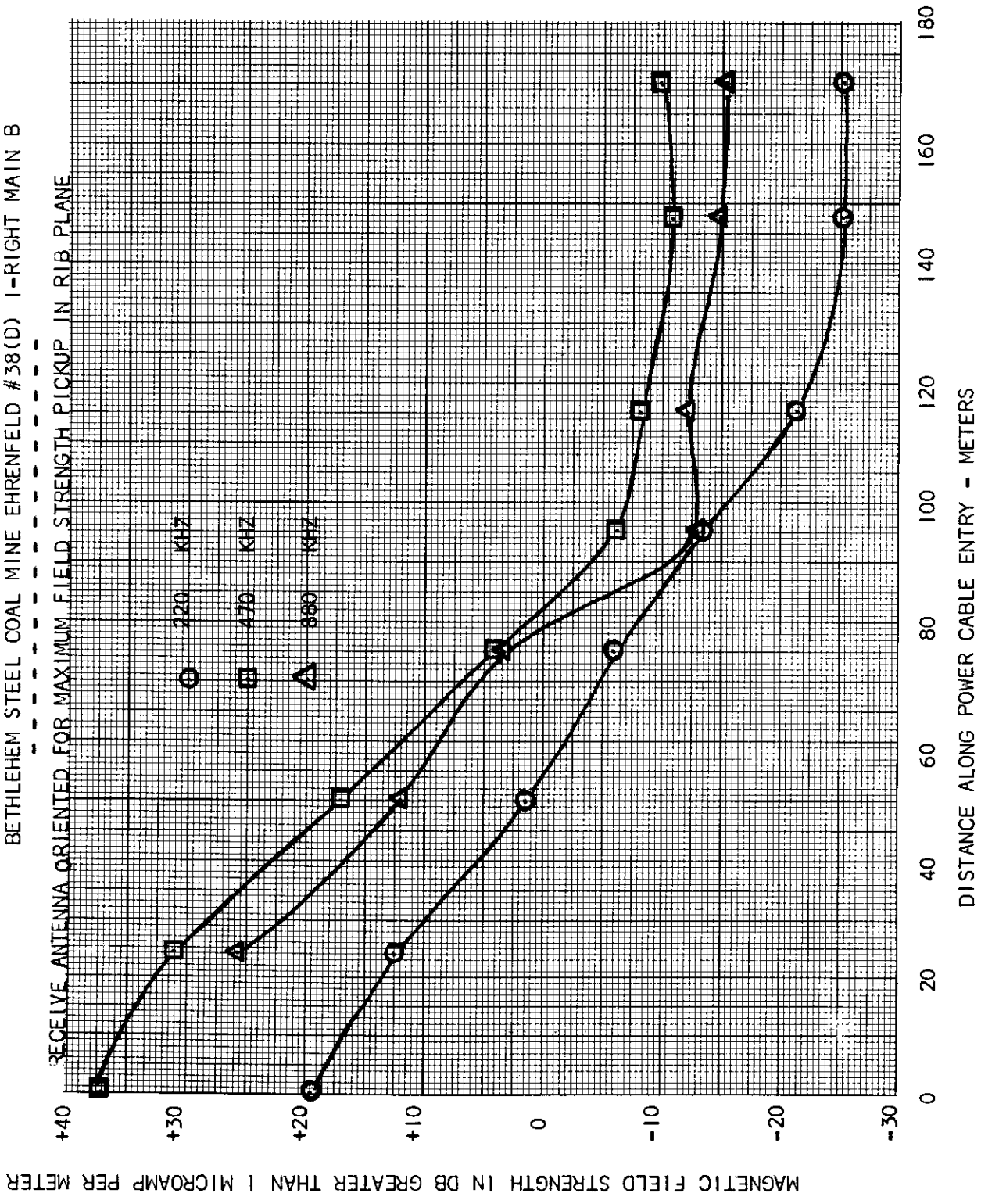


FIGURE A23

MAGNETIC FIELD STRENGTH VS RANGE ALONG RIB PLANE OF POWER CABLE ENTRY, ONE ENTRY REMOVED FROM TRANSMITTER; TRANSMIT ANTENNA LOOP PLANE PARALLEL TO CABLE NIA = 2.5

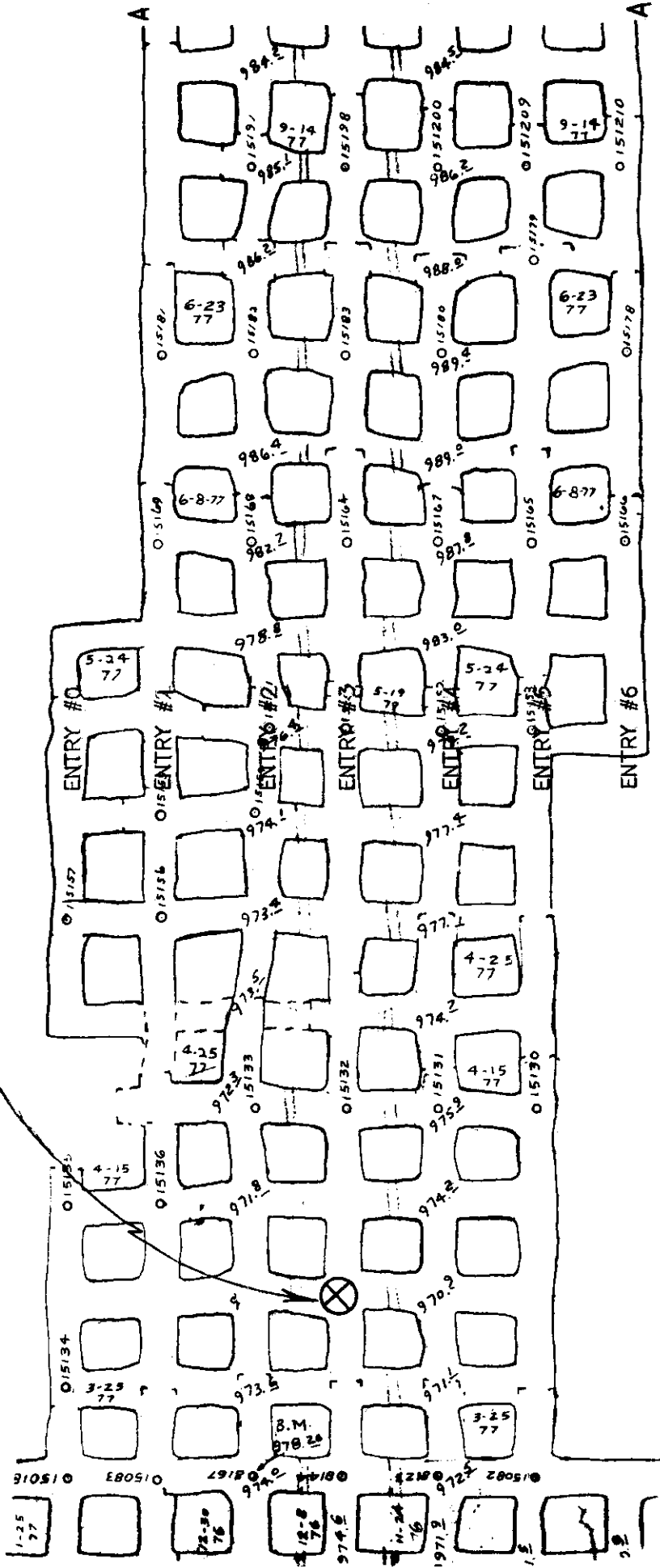
BETHLEHEM STEEL COAL MINE EHRENFELD #38(D) I-RIGHT MAIN B



A-5

STINSON #3 MINE TEST DATA AT MEDIUM FREQUENCY

TRANSMITTER LOCATION FOR CONDUCTOR-PROXIMITY POLARIZATION TESTS

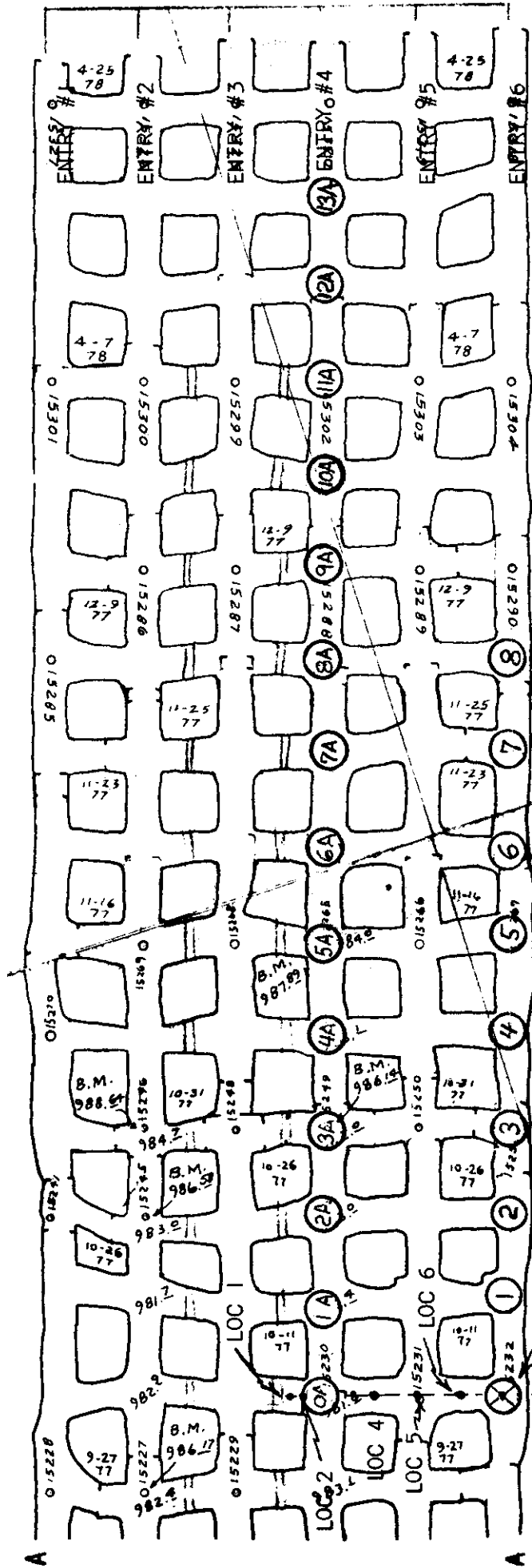


SCALE: 1 INCH = 100 FEET

FIGURE A24

MINE MAP SHOWING PORTION OF C SECTION STINSON #3 MINE NEAREST TO SUBMAIN WITH TRANSMITTER LOCATION FOR CONDUCTOR-PROXIMITY POLARIZATION TESTS

SCALE: 1 INCH = 100 FEET



TRAVERSE FOR
 COND.-PROX.
 POL. TESTS

FIGURE A25

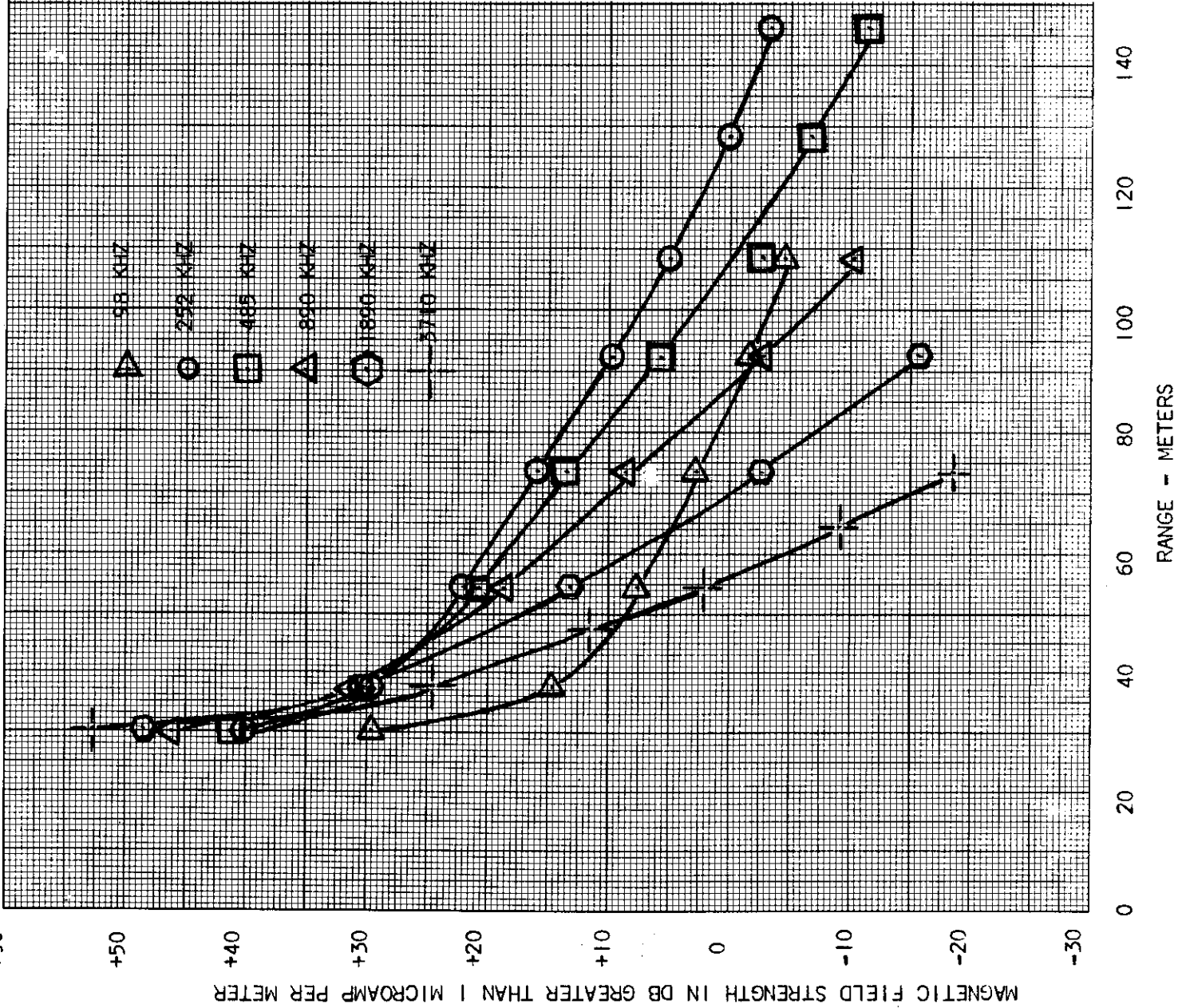
MINE MAP SHOWING PORTION OF C SECTION STINSON #3 MINE FARTHEST FROM SUBMAIN
 WITH MEASUREMENT TRAVERSE & STATION LOCATIONS AND TRANSMITTER LOCATION FOR
 QUASI-CONDUCTOR-FREE AND CONDUCTOR-PROXIMITY TESTS

FIGURE A26

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



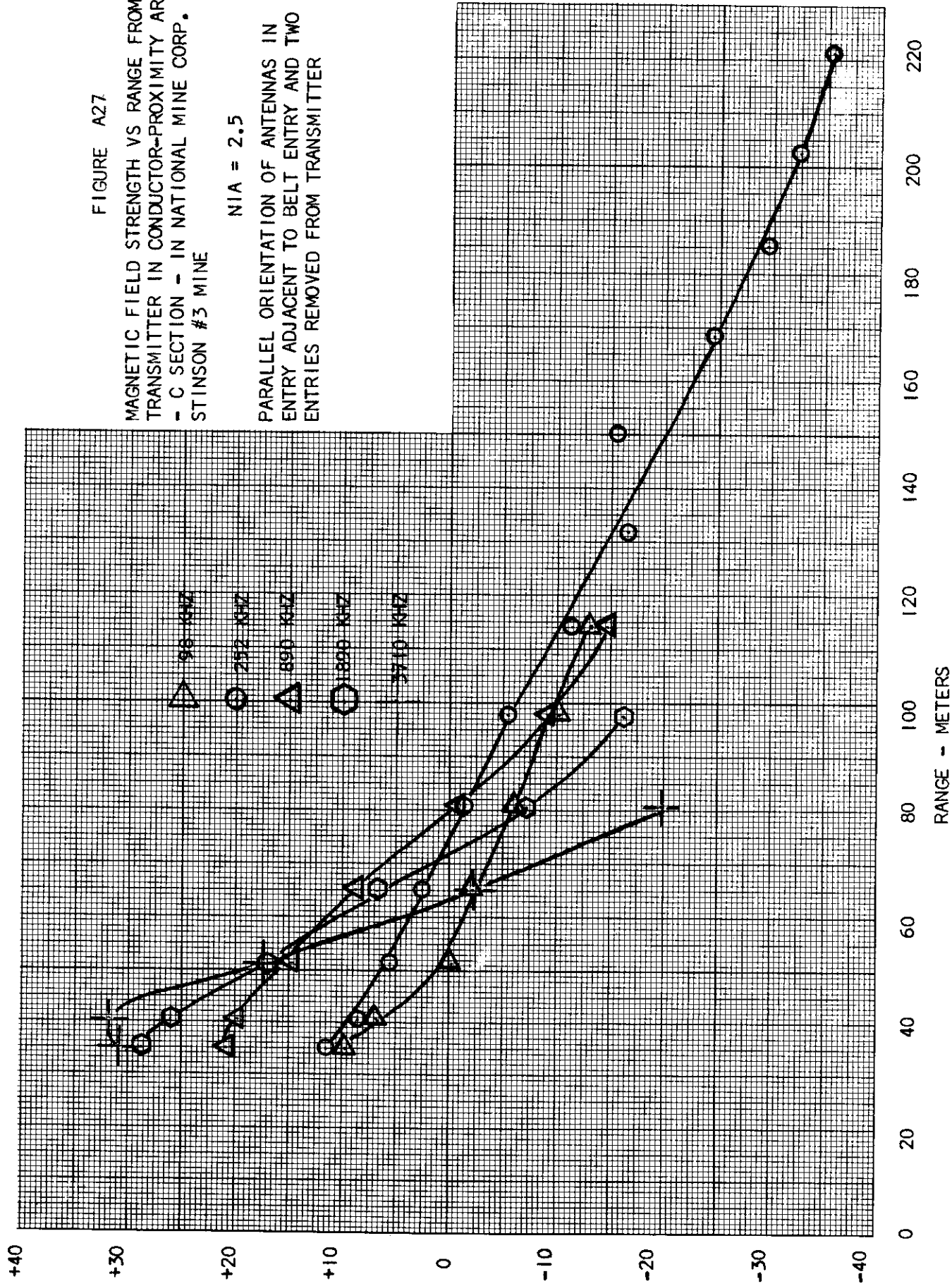


FIGURE A27

MAGNETIC FIELD STRENGTH VS RANGE FROM
 TRANSMITTER IN CONDUCTOR-PROXIMITY AREA
 - C SECTION - IN NATIONAL MINE CORP.
 STINSON #3 MINE

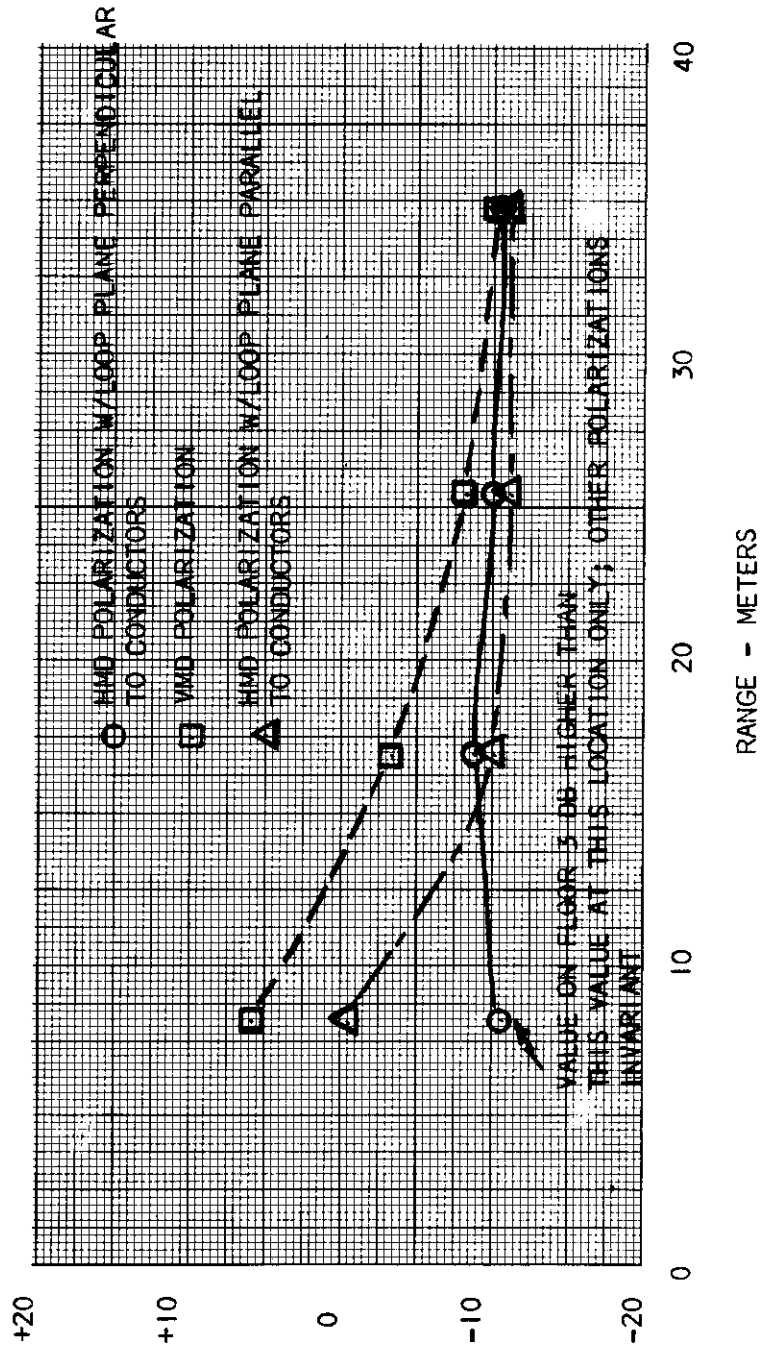
NIA = 2.5

PARALLEL ORIENTATION OF ANTENNAS IN
 ENTRY ADJACENT TO BELT ENTRY AND TWO
 ENTRIES REMOVED FROM TRANSMITTER

FIGURE A2E

MAGNETIC FIELD STRENGTH VS RANGE AWAY FROM CONDUCTORS (REFERENCED TO VIRTUAL TRANSMIT ANTENNA LOCATION) ON TRAVERSE PERPENDICULAR TO CONDUCTOR ENTRY @ 258 KHZ FOR THREE ORTHOGONAL RECEIVE ANTENNA POLARIZATIONS NIA = 2.5

MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICRAMP PER METER



MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICRAMP PER METER

FIGURE A29
 MAGNETIC FIELD STRENGTH VS RANGE AWAY FROM CONDUCTORS (REFERENCED TO VIRTUAL TRANSMIT ANTENNA LOCATION) ON TRAVERSE PERPENDICULAR TO CONDUCTOR ENTRY @ 486 KHZ FOR THREE ORTHOGONAL RECEIVE ANTENNA POLARIZATIONS NIA = 2.5

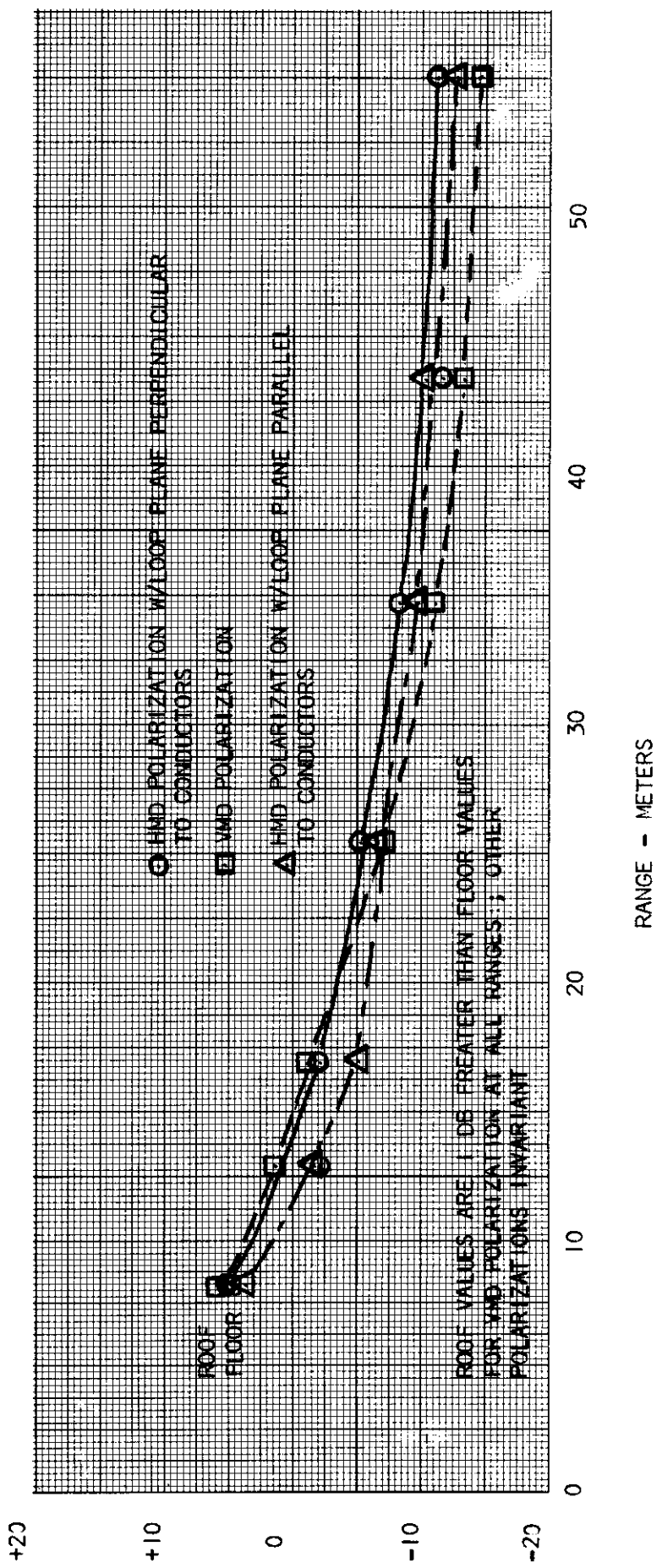
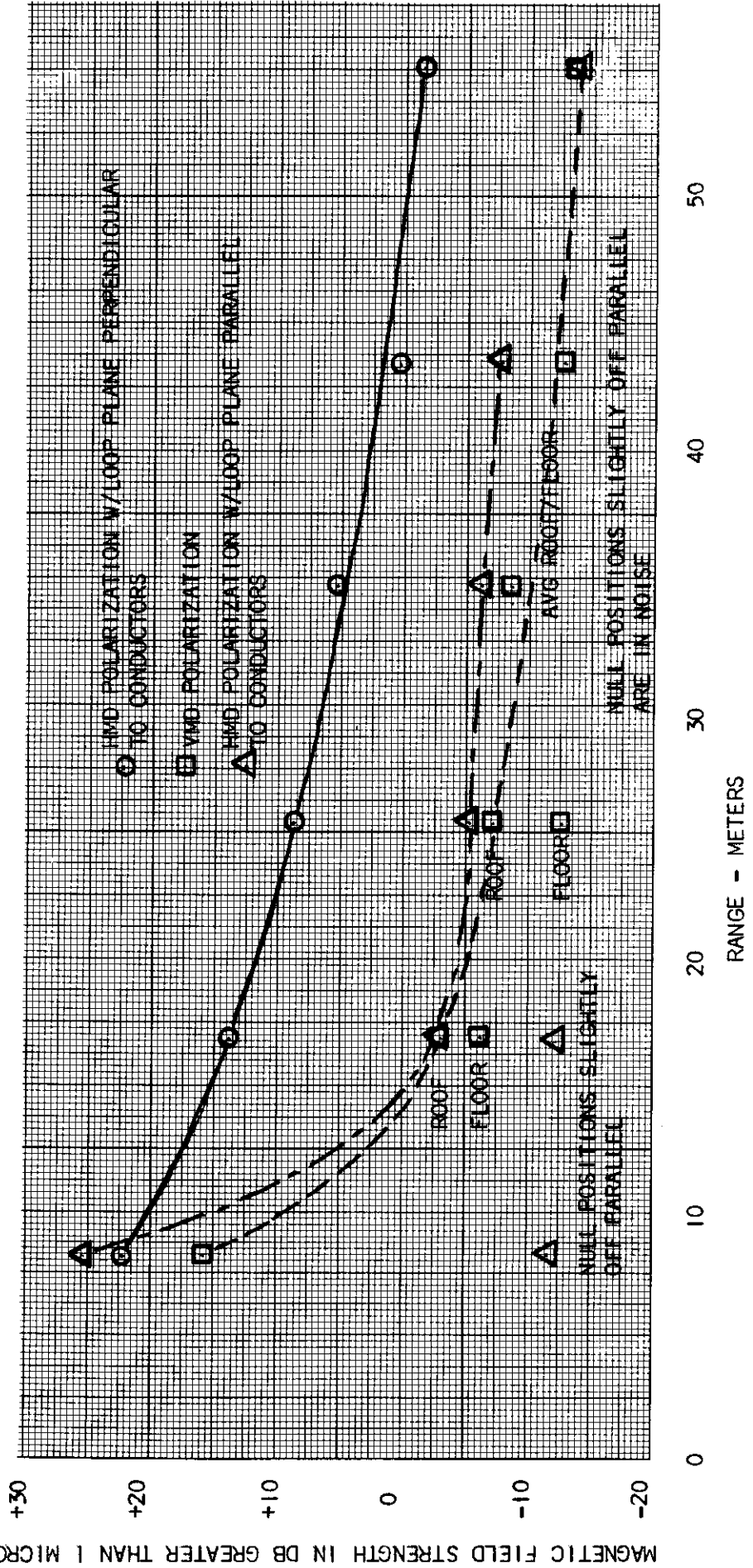


FIGURE A30

MAGNETIC FIELD STRENGTH VS RANGE AWAY FROM CONDUCTORS (REFERENCED TO VIRTUAL TRANSMIT ANTENNA LOCATION) ON TRAVERSE PERPENDICULAR TO CONDUCTOR ENTRY @ 890 KHZ FOR THREE ORTHOGONAL RECEIVE ANTENNA POLARIZATIONS NIA = 2.5



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- (6) Loc. Cit. R.L. Lagace, A.G. Emslie, M.A. Grossman.
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- (8) A.G. Emslie, R.L. Lagace, R.H. Spencer, P.F. Strong, "Theory of the Dedicated Wire as a Means of Aiding Propagation on a Trolley Wire", Arthur D. Little, Inc., Working Memorandum I-8, Bureau of Mines Contract H0346045.
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SPECIAL TECHNICAL REPORT

IN-SITU MEASUREMENT OF COAL SEAM CONDUCTIVITY
USING A PARALLEL WIRE TRANSMISSION LINE METHOD

Technique Development
Technique Application in Two Mines

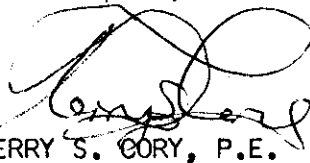
PREPARED FOR:

Collins Groups
Rockwell International Corporation
400 Collins Road N.E.
Cedar Rapids, Iowa 52406

Under: Bureau of Mines Contract H0377053
Terry S. Cory, P.E. Subcontract C-651672

PREPARED BY:

Terry S. Cory, P.E.
2857 West, Mount Vernon Road S.E.
Cedar Rapids, Iowa 52403


TERRY S. CORY, P.E.



18 May 1978

1.0 INTRODUCTION

The conductivity of coal seams greatly affects the ability to transmit radio waves underground to any significant distance. Recent field strength measurements and testing of two-way radios at medium frequency in coal mines under Bu Mines sponsorship have demonstrated communication ranges as great as 1600 feet (in the Pittsburgh seam) and as little as 400 feet (in the Herrin #6 seam and others) in areas without conductors. The difference in range is due in part to differences in coal seam conductivity in the "parallel plate waveguide " formed by the seam sandwiched between the overburden/underburden rock.

Two-way radio transmission at medium frequency is expected to have a significant impact on future underground coal mine operations in some mines. The design of systems embodying this type of transmission will require a knowledge of coal seam conductivity (as well as, for that matter, overburden/underburden conductivity) and a means to simply obtain it in particular mines.

This report presents the results of in-situ conductivity measurements in two seams employing a simple empirical technique which may have wide applicability in the future. The results of these measurements confirm the low conductivity values expected based on computer modeling analysis of extensive field strength measurements by ADL.

Previous measures of coal seam conductivity have been made largely on samples analysed in the laboratory following removal from the mine. These results suggest that the conductivity is a strong function of frequency down to at least 1 MHz, is strongly affected by water and ash content, and could be in the 10^{-5} to 10^{-4} mho/meter range. The in-situ estimates of coal seam conductivity derived from the field strength measurements suggest that the conductivity is at most weakly dependent on frequency in the medium frequency range. The results reported herein support this suggestion.

The technique for conductivity determination involves measurement of the open and short circuit impedance magnitudes of a parallel wire transmission line in close proximity to the coal using two pieces of simple battery operated equipment, a current probe, and the transmission line. This data is easily reduced to provide a measure of the normalized phase constant along the line as a function of frequency. The conductivity is then determined by fitting the measured data with a computed curve; the algorithm, for which, is a function of conductivity. The accuracy of the results are not significantly dependent on the precise spacing of the test line from the coal.

The technique has been demonstrated to be effective for use in both conventional and continuous mining sections.

The results reported herein were obtained in March, 1978 in the Bethlehem Steel Coal Mine(Ehrenfeld)#38D (Lower Freeport seam) in Cambria County Pennsylvania, and in May 1978 in the National Mine Corp. Stinson #3 Mine (Elkhorn #3 seam).

2.0 SUMMARY

The results of the testing reported herein are significant in two areas; namely, the technique - its applicability and accuracy, and the results themselves - their values and frequency dependence.

2.1 MEASURED RESULTS

- (1) The conductivity in the Lower Freeport seam data sample is estimated to be 1.05×10^{-4} mho/meter $\pm 10\%$ and essentially independent of frequency. The coal seam relative dielectric constant is estimated to be about 2.3.
- (2) The results of (1) are applicable over the frequency range of at least 100-600 KHz.
- (3) The conductivity in the Elkhorn #3 seam data sample is estimated to be $.7 \times 10^{-4}$ mho/meter $\pm 10\%$ and essentially independent of frequency. The coal seam relative dielectric constant is estimated to be about 2.0.
- (4) The results of (1) are applicable over the frequency range of at least 100-800 KHz.

2.2 MEASUREMENT TECHNIQUE

- (1) The dynamic frequency range of measurement is between some low frequency (typically 80-100 KHz for 10^{-4} mho/meter conductivity) where the conductivity dependence of the normalized phase constant becomes weak, and the frequency at which the relative dielectric constant predominates over the conductivity, ω/ω_0 (for 10^{-4} mho/meter and relative dielectric constant of 2-2.5, the range is typically 600-800 KHz).

- (2) The technique is relatively independent of the precise spacing of the test line from the coal. For the smoother continuously mined Lower Freeport data sample, the low frequency normalized phase constant was about 1.88 for an average spacing of the wires from the coal of 9.5 wire radii (0.3 inches). For the rougher conventionally mined Elkhorn #3 data sample, the low frequency normalized phase constant was about 1.55 for an average spacing of the wires from the coal of about 22.2 wire radii (0.71 inch).
- (3) The phase constant accuracy based on the low frequency limit of impedance measurement is a function of line length. To obtain accurate measurements below 100 KHz, a line length of at least 200 feet is required.
- (4) The quasi-frequency independence of the conductivity was established by observing the "goodness of fit" of computed and measured results curves having the same shape and by observing the difference in shape of curves where the conductivity is changing with frequency. If the conductivity increased substantially with frequency, instead of giving an abrupt rolloff with frequency and a monotonic decrease in phase constant, the plot of B/B_0 with frequency would either be nearly linear (decade increase in conductivity for decade frequency increase) or exhibit a region of increased negative slope between regions of lesser negative slope.

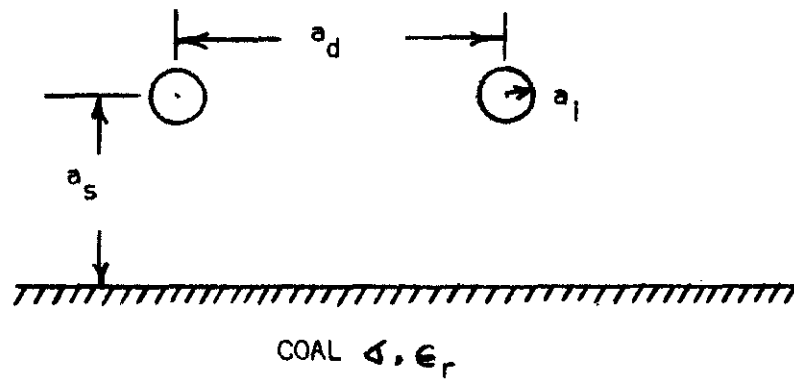


FIGURE 1
GEOMETRY OF PARALLEL WIRE LINE NEAR COAL FOR CALCULATIONS

3.0 TECHNICAL APPROACH

The technique consists of measuring short and open circuit impedance magnitudes on a balanced-fed parallel wire line with frequency using simple instrumentation from which the normalized phase constant with frequency is derived, and then fitting a computed curve to the measured data using an algorithm where the normalized phase constant is a function of conductivity.

3.1 COMPUTATION ALGORITHM

The formal derivation for the phase constant of the parallel wire line is beyond the intended scope of this report. The expression was derived considering the lowest order TM mode on a coaxial line with a lossy outer conductor. The determinantal equation for the complex propagation constant was reduced to a form containing logarithms by making small angle approximations to the Hankle functions. Then, using static field mapping, the geometry was successively mapped to a single conductor over a lossy halfspace (assuming that the spacing from the halfspace was much greater than the conductor radius) and then to a balanced line pair over the lossy halfspace (assuming that the conductor spacing was much greater than the wire radii). The geometry of the line over the lossy halfspace is illustrated in Figure 1.

The resulting expression for the normalized phase constant is implicit. The expression was solved on an HP-67 iteratively assuming a starting value for the phase constant, computing the result explicitly, and then adjusting the starting value each time until convergence was obtained.

The expression for the normalized phase constant is;

$$\frac{\beta}{\beta_0} = \frac{\ln\left(\frac{2a_d}{a_i}\right) + F^{\frac{1}{2}} \ln\left(\frac{2a_s}{a_i}\right) - \frac{1}{2} \ln\left[\left(\frac{2a_d}{a_i}\right)^2 + \exp\left(2F^{\frac{1}{2}} \ln\left(\frac{2a_s}{a_i}\right)\right)\right]}{\ln\left(\frac{2}{a_i} \sqrt{\frac{a_s a_d}{a_s^2 + a_d^2}}\right)}$$

where,

$$F^2 = \frac{\left[\epsilon_r - j\frac{\sigma}{\omega\epsilon_0}\right] \left[\ln\left(\frac{2a_s}{a_i}\right) - \ln(A)\right]}{\ln(A) + \left(-\epsilon_r + j\frac{\sigma}{\omega\epsilon_0}\right) \ln\left(\frac{2a_s}{a_i}\right)}$$

where,

$$\ln(A) = \ln(2 \times 0.89 \times a_s) + \frac{1}{2} \ln\left(\frac{\beta}{\beta_0} - j\frac{\sigma}{\omega\epsilon_0}\right) + \frac{1}{2} \ln(\omega^2 \mu \epsilon_0)$$

a_s is the spacing of each conductor from the halfplane

a_d is the spacing of the parallel conductors

a_i is the conductor radius

σ, ϵ_r are the conductivity and relative dielectric constant of the halfplane

The expression is of the form

$$\frac{\beta}{\beta_0} = f\left(\frac{\beta}{\beta_0}\right),$$

solving iteratively on an HP-67 with a starting value of $\sqrt{\frac{\sigma}{\omega\epsilon_0}} = \sqrt{R}$ for β/β_0 and modified in each step as

$$R_{\text{new}} = \frac{\frac{\beta}{\beta_0} + R_{\text{old}}}{2} \quad \text{until} \quad \frac{\beta}{\beta_0} = R$$

within a specified degree of accuracy.

The normalized phase constant is taken to be the magnitude of the complex result.

3.2 EMPIRICAL TECHNIQUE

The line parameters were chosen to confine the transverse fringing fields of the line to the coal seam so that the much higher overburden/underburden conductivity would not influence the results. A line spacing of 6 inches was chosen with the line conductors being #14 wire. The line was attached as close as possible to the rough coal rib face using nails or spads through spacers supporting the line. The line was driven balanced from an HP-204C signal generator. The impedance magnitude data was obtained by separate measurement of the input line voltage and the input line current (and then, of course, taking the ratio of voltage to current). The current was measured using a Stoddard current probe with a prior calibrated relationship between the line current and the probe output voltage. The probe output voltage and the balanced line voltage were both measured using an HP-403B voltmeter. The arrangement of the measuring equipment is illustrated in Figure 2. The current and voltage were measured for both open circuit and short circuit conditions of the transmission line. The calibration curves for the Stoddard current probe are given in Figure 3.

3.3 REDUCTION OF MEASURED DATA

The normalized phase constant was determined from the measured impedance data through the use of a Smith Chart. The open circuit and short circuit impedances always lie on opposite sides of the chart such that they are joined by a straight edge through the chart center. For a given data point, and using a normalized Smith Chart (unity Z_0 at the center), the straight edge is rotated until alignment is obtained between a normalized short circuit reactance value (on the right-hand edge of the chart) and a normalized open circuit reactance value equal to the short circuit value multiplied by the

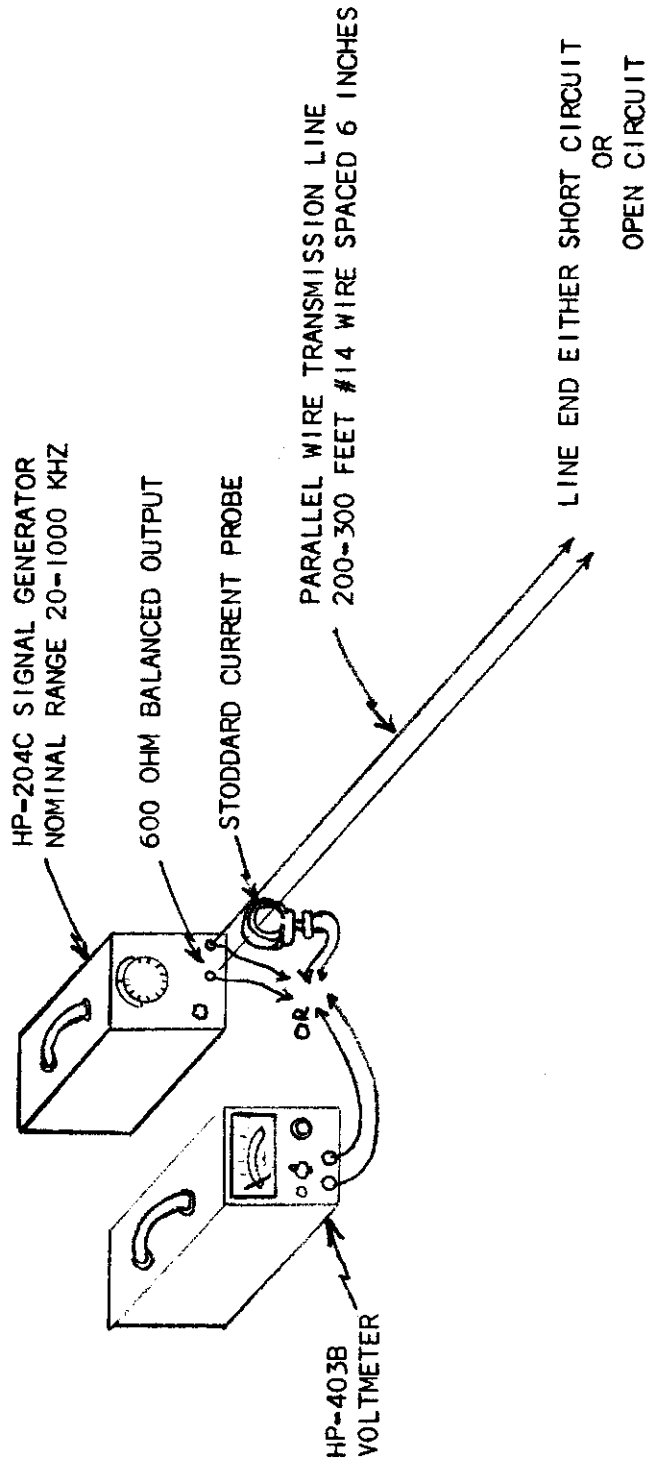
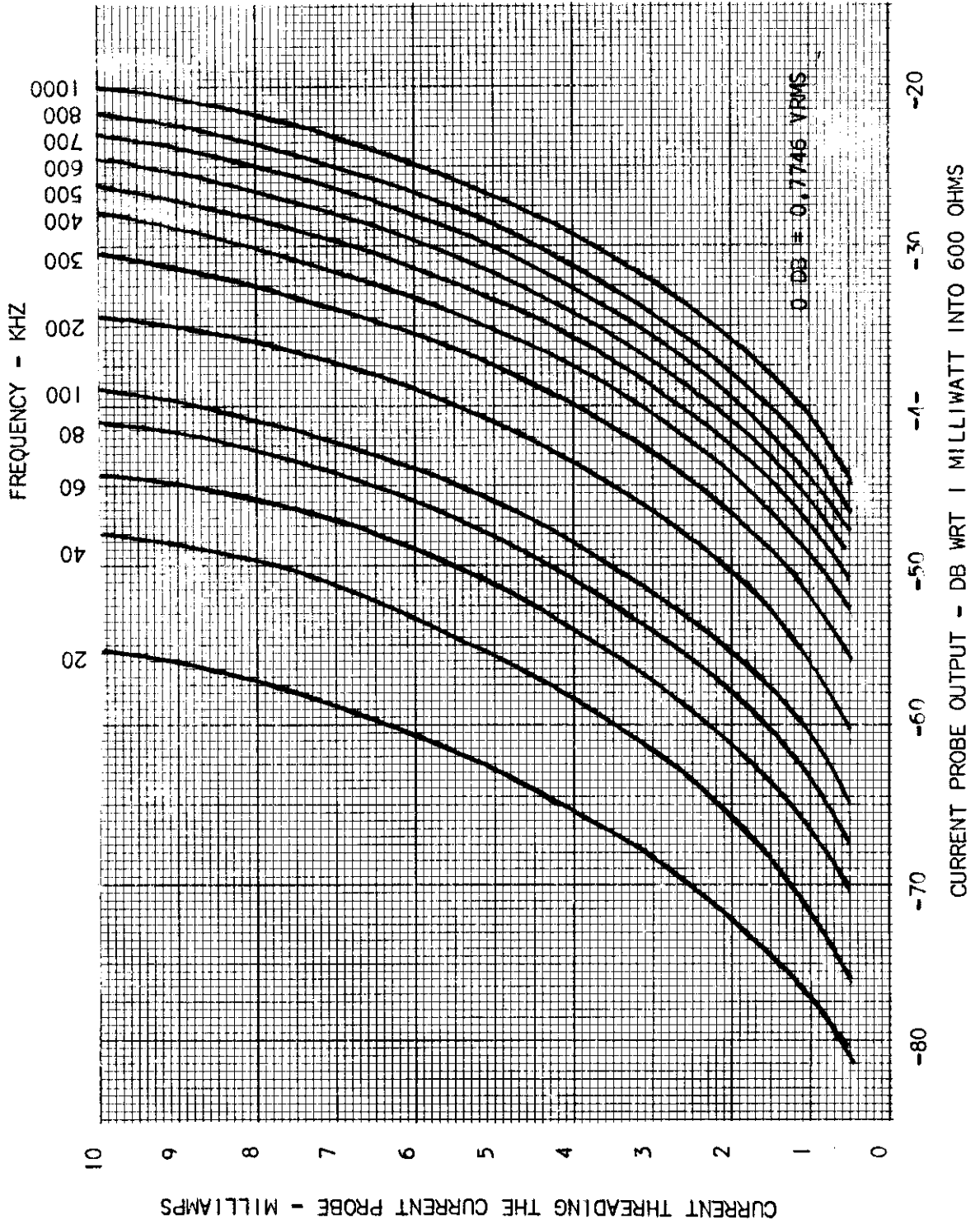


FIGURE 2
MEASUREMENT EQUIPMENT ARRANGEMENT FOR DETERMINING THE MAGNITUDE OF
THE OPEN AND SHORT CIRCUIT LINE IMPEDANCE OF PARALLEL WIRE TEST LINE

FIGURE 3
 CALIBRATION CURVES FOR STODDARD CURRENT PROBE - CURRENT VS OUTPUT POWER



ratio of the measured open circuit-to-short circuit impedance magnitudes. Once this alignment is obtained, the line electrical length is given either as the wavelengths from the chart top (short circuit) to the right-hand alignment point or as the wavelengths from the chart bottom (open circuit) to the left-hand alignment point. The normalized phase constant is then this electrical length divided by the calculated free space electrical length knowing the physical length of the line and the frequency. The Smith Chart alignment process is illustrated in Figure 4.

It should be noted that only the ratio of the open circuit-to-short circuit impedance magnitudes is required to implement the technique. If the same value of driving current can be maintained for both short and open circuit conditions, then a simplification of the empirical and data reduction methods results. Under this condition, this ratio is just the ratio of open circuit-to-short circuit line voltage.

In obtaining a computed fit, a low frequency plus an arbitrary conductivity and dielectric constant in the expected range are taken first and the ratio of a_s/a_i is varied until computed and measured values match. The conductivity is then varied until a fit is obtained over the central portion of the frequency range. The dielectric constant is then varied for best fit over the high frequency portion. The final fit is obtained considering small incremental changes in both a_s/a_i and conductivity.

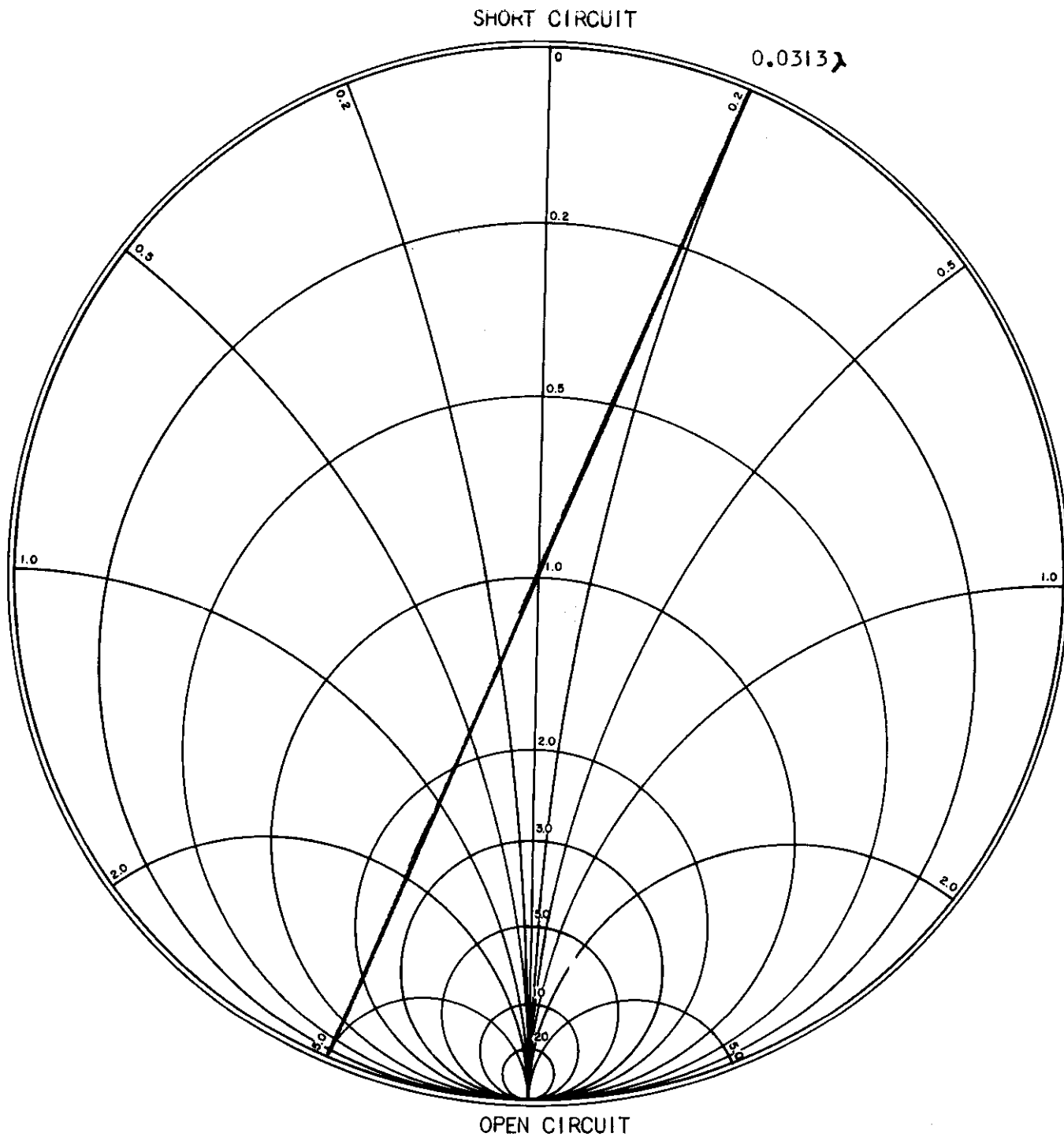


FIGURE 4

ILLUSTRATION OF THE USE OF THE SMITH CHART TO OBTAIN THE TRANSMISSION LINE ELECTRICAL LENGTH FOR A RATIO OF Z_{oc} / Z_{sc} OF 25

4.0 PRESENTATION OF DATA

The raw data for each of the two sets of measurements are given in the Appendix to this report.

Summaries of the reduced data in tabular form for the two measurement sets are shown in Tables 1 and 2.

The Ehrenfeld #38D reduced data is shown only for 80-600 KHz although data was measured from 20-1200 KHz. This is because this was the first set of data reduced and the frequency "edges" result in small electrical lengths on the Smith Chart which are hard to read accurately unless extreme care is taken. For this first set, a very close fit was obtained using only the "easy-to-reduce" data. The Stinson #3 data was reduced from 40-800 KHz exercising greater care with the Smith Chart as the measured data sample was more scattered.

The Ehrenfeld #38D data is given in Figure 5 showing both the nominal fit assuming the conductivity was frequency invariant plus the fit with small excursions in conductivity from nominal. The accuracy of the nominal fit was, thus, estimated to be $\pm 10\%$.

The Stinson #3 data is given in Figure 6 showing both the nominal fit assuming the conductivity was frequency invariant plus the fit with small excursions in the conductivity from nominal. The accuracy of the nominal fit was, again, estimated to be $\pm 10\%$.

To illustrate the effect of conductivity which increases linearly with frequency, computations were made for comparison with the Ehrenfeld #38D nominal fit assuming linear increases of $\times 10$ and $\times 5$ for a decade in frequency matched to the geometric mean frequency of the 80-600 KHz range. This data is given in Figure 7. By noting the shapes of the $\times 10$ and $\times 5$ curves and the fact that the measured data was very closely fit with the model on a frequency invariant basis, the conductivity was judged to be quasi-frequency independent.

TABLE I
 REDUCED DATA FOR CONDUCTIVITY MEASUREMENTS IN BETHLEHEM STEEL COAL MINE
 #38D EMPLOYING THE PARALLEL WIRE TRANSMISSION LINE TECHNIQUE

FREQ(KHZ)	SHORT CIRCUIT		OPEN CIRCUIT				β/β_0			
	I (MA)	V (VOLTS)	Z	I (MA)	V (VOLTS)	Z		$ Z_{OC}/Z_{SC} $	β	β_0
80	8.25	0.77	93.3	3.20	4.8	1500	16.08	0.0382	0.02032	1.880
100	7.85	0.99	126.1	3.43	4.6	1341.1	10.634	0.0475	0.0254	1.870
200	8.60	2.15	250.0	5.65	3.4	601.8	2.407	0.0905	0.0508	1.782
400	6.75	4.8	711.1	7.20	1.7	236.1	0.332	0.1670	0.1016	1.644
600	0.90	4.0	4444	8.50	0.33	38.8	0.0087	0.2350	0.1524	1.542

TABLE 2

REDUCED DATA FOR CONDUCTIVITY MEASUREMENTS IN NATIONAL MINE CORP.
STINSON #3 MINE EMPLOYING THE PARALLEL WIRE TRANSMISSION LINE TECHNIQUE

F REQ(KHZ)	SHORT CIRCUIT		OPEN CIRCUIT		Z	Z _{OC} /Z _{SC}	ρ	ρ ₀	ρ/ρ ₀
	I(MA)	V(VOLTS)	I(MA)	V(VOLTS)					
40	6.7	0.235	35.1	0.90	5222	148.8	0.0127	0.00817	1.554
60	6.5	0.36	55.4	1.30	3769	68.0	0.0190	0.01225	1.551
80	7.38	0.58	78.6	1.65	2970	37.8	0.0257	0.01634	1.545
100	7.10	0.70	98.6	1.42	2465	25.0	0.0313	0.0204	1.534
200	6.60	1.21	183.3	3.90	1128.2	6.15	0.0610	0.0408	1.494
300	8.85	2.60	293.8	4.85	744.3	2.533	0.0895	0.06126	1.461
400	6.65	2.85	428.6	3.76	531.9	1.241	0.1167	0.08169	1.428
500	5.75	3.15	547.8	5.75	386.1	0.705	0.1390	0.1021	1.361
600	4.90	3.70	755.1	4.85	257.7	0.341	0.1660	0.1225	1.355
700	2.37	2.55	1075.9	5.85	188.0	0.175	0.1870	0.14295	1.308
800	1.80	3.40	1889.0	6.70	109.0	0.058	0.212	0.16337	1.298

FIGURE 5
 RESULTS OF IN-SITU CONDUCTIVITY MEASUREMENTS IN BETHLEHEM STEEL COAL MINE #38 D (EHRENFELD) DEMONSTRATING THE SENSITIVITY OF THE NORMALIZED PHASE VELOCITY CURVE FITTING TECHNIQUE ALONG A BALANCED PARALLEL WIRE LINE

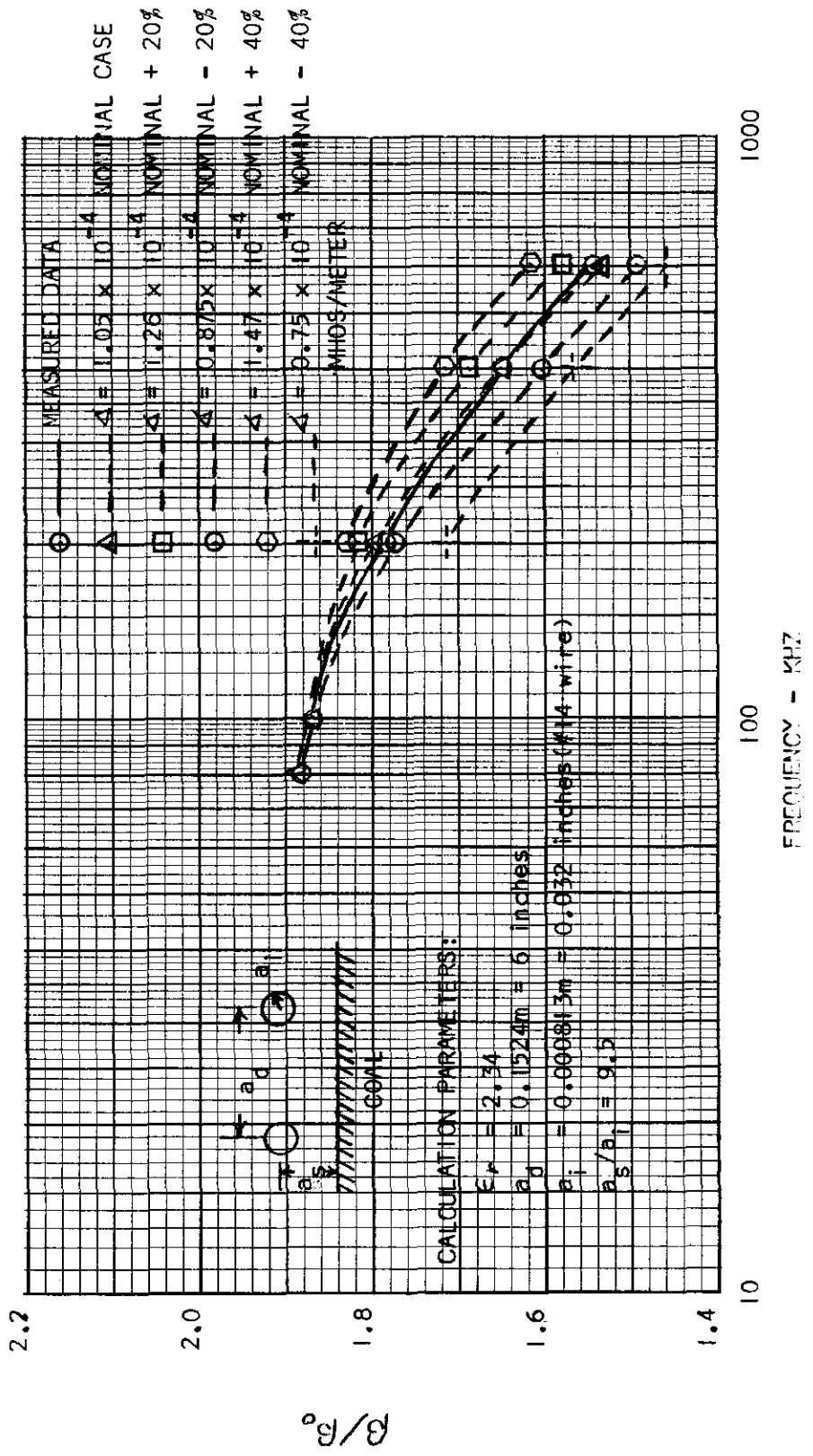


FIGURE 6

RESULTS OF IN-SITU CONDUCTIVITY MEASUREMENTS IN NATIONAL MINE CORP. STINSON #3 MINE DEMONSTRATING THE SENSITIVITY OF THE NORMALIZED PHASE VELOCITY CURVE FITTING TECHNIQUE ALONG A BALANCED PARALLEL WIRE LINE

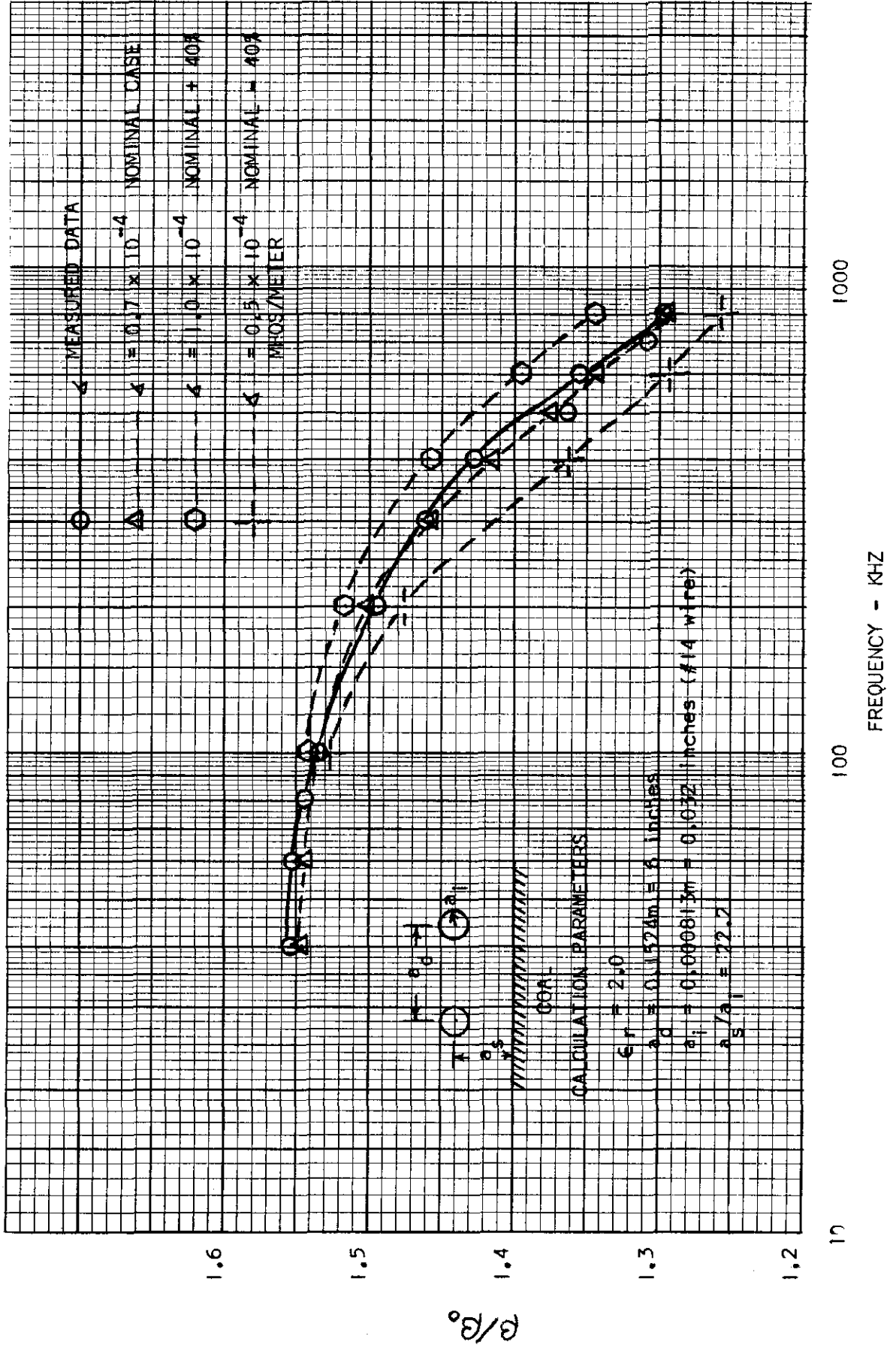
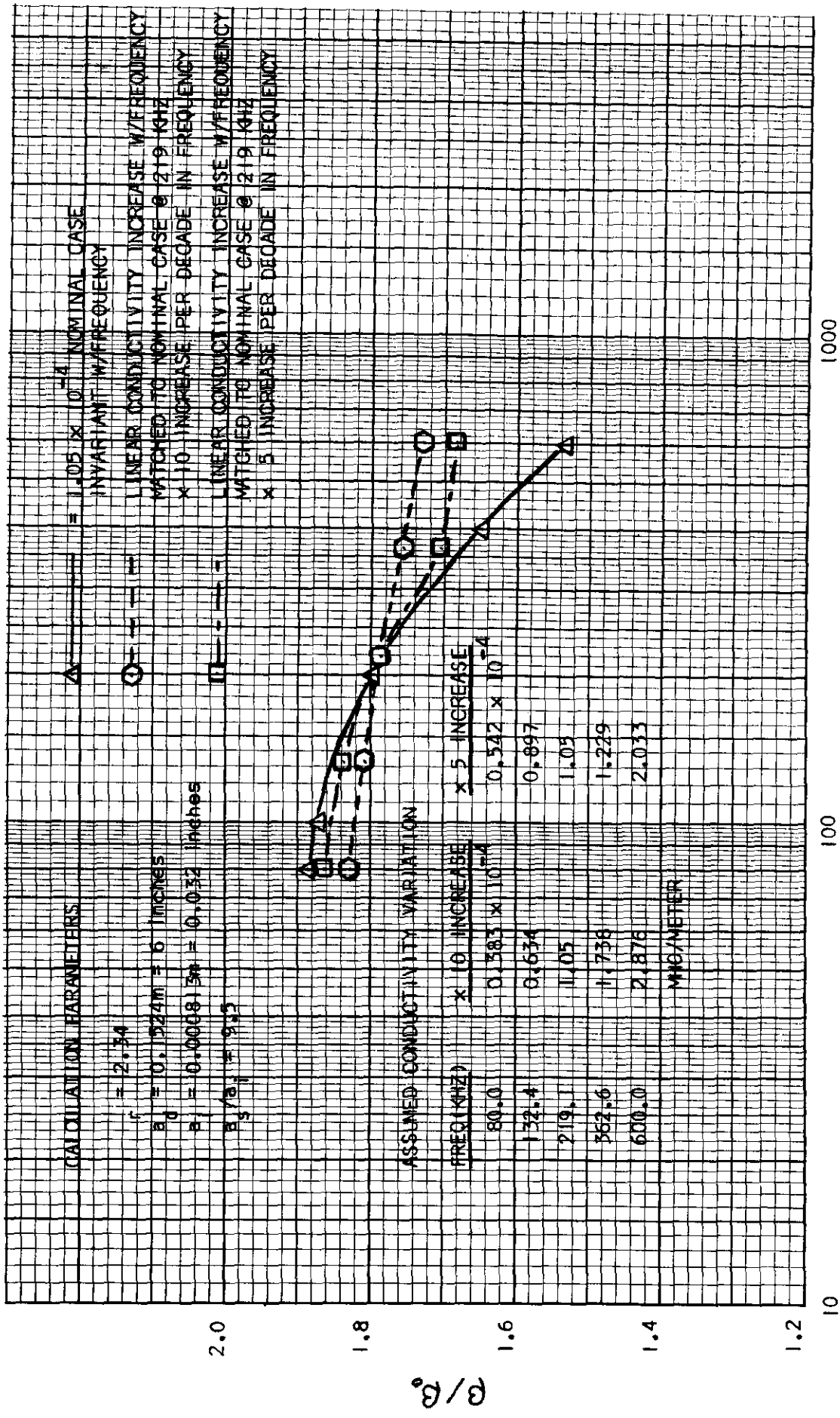


FIGURE 7

COMPUTED RESULTS BASED ON EHRENFELD #38D DATA ILLUSTRATING THE SHAPE OF THE NORMALIZED PHASE VELOCITY CURVES WITH FREQUENCY FOR THE FREQUENCY INVARIANT NOMINAL FIT AND FOR ASSUMED LINEAR INCREASE IN CONDUCTIVITY WITH FREQUENCY



- APPENDIX -

RAW DATA FROM COAL SEAM CONDUCTIVITY MEASUREMENTS VIA OPEN & SHORT
CIRCUIT IMPEDANCE MEASUREMENTS ON PARALLEL WIRE TRANSMISSION LINE

A DATA FROM BETHLEHEM STEEL COAL MINE #38D EHRENFELD IN LOWER
FREEPORT SEAM

250.3 FEET OF LINE DEPLOYED AROUND COAL PILLAR

<u>FREQ(KHZ)</u>	<u>SHORT CIRCUIT HP-403B READING CURRENT PROBE</u>	<u>LINE VOLTAGE</u>	<u>OPEN CIRCUIT HP-403B READING CURRENT PROBE</u>	<u>LINE VOLTAGE</u>
1200	0.066 VOLTS	0.7 VOLTS	0.03 VOLTS	3.4 VOLTS
1000	0.042	1.55	0.068	4.62
800	0.0225	2.60	0.057	1.90
600	0.0037	4.0	0.037	0.33
500	0.014	5.0	0.030	1.00
400	0.020	4.8	0.022	1.70
300	0.019	3.40	0.015	2.55
200	0.0135	2.15	0.008	3.40
100	0.0068	0.99	0.0024	4.60
80	0.0054	0.77	0.0016	4.80
60	0.0040	0.57	0.00095	5.0
40	0.0028	0.38	0.00043	5.2
20	0.00044	0.295	0.00010	5.3

B DATA FROM NATIONAL MINE CORP. STINSON #3 IN ELKHORN #3 SEAM

201 FEET OF LINE DEPLOYED ALONG RIB

<u>FREQ(KHZ)</u>	<u>SHORT CIRCUIT HP-403B READING CURRENT PROBE</u>	<u>LINE VOLTAGE</u>	<u>OPEN CIRCUIT HP-403B READING CURRENT PROBE</u>	<u>LINE VOLTAGE</u>
1200	0.020 VOLTS	2.20 VOLTS	0.100 VOLTS	2.80 VOLTS
1000	0.007	3.15	0.060	0.540
900	0.002	2.63	0.050	0.205
800	0.009	3.40	0.040	0.73
700	0.010	2.55	0.030	1.10
600	0.020	3.70	0.020	1.25
500	0.020	3.15	0.020	2.22
400	0.020	2.85	0.010	2.00
300	0.020	2.60	0.010	3.61
200	0.010	1.21	0.0050	4.40
100	0.0060	0.70	0.0010	3.50
80	0.0050	0.58	0.00090	4.90
60	0.0031	0.36	0.00050	4.90
40	0.0020	0.235	0.00020	4.70
20	0.0010	0.1175	0.00015	5.35