ELECTROMAGNETIC PROPAGATION IN

LOW COAL MINES AT

MEDIUM FREQUENCIES

Prepared for

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

by

Collins Communications Switching Systems Division
Commercial Telecommunications Group
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Rockwell International

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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.

17. Originator's Key Words

MF wireless radio propagation; maximum communication range; conductor-free areas; conductor-proximity areas; set limited noise; median mine noise

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FOREWORD

This report was prepared by Terry S. Cory, P.E., for Collins
Communications Switching Systems Division, Commercial Telecommuni-
cations 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 direc-
tion 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 [1] 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 compended 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.

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*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) December1977, 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[3],[4] EM Signalling
Program and conductivity data derived from ADL's 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 obstensibly 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

TX NIA = 2.5
RX SENSITIVITY
0.02 uAMP/M
12 DB SINAD
BW = 12 KHZ

PITTSBURGH SEAM
POCAHONTAS #3 SEAM
HERRIN #6 SEAM
ELKHORN #3 SEAM
LOWER FREEPORT SEAM
UPPER FREEPORT SEAM
LOWER KITTANNING SEAM

FREQUENCY – KHZ

RANGE – METERS
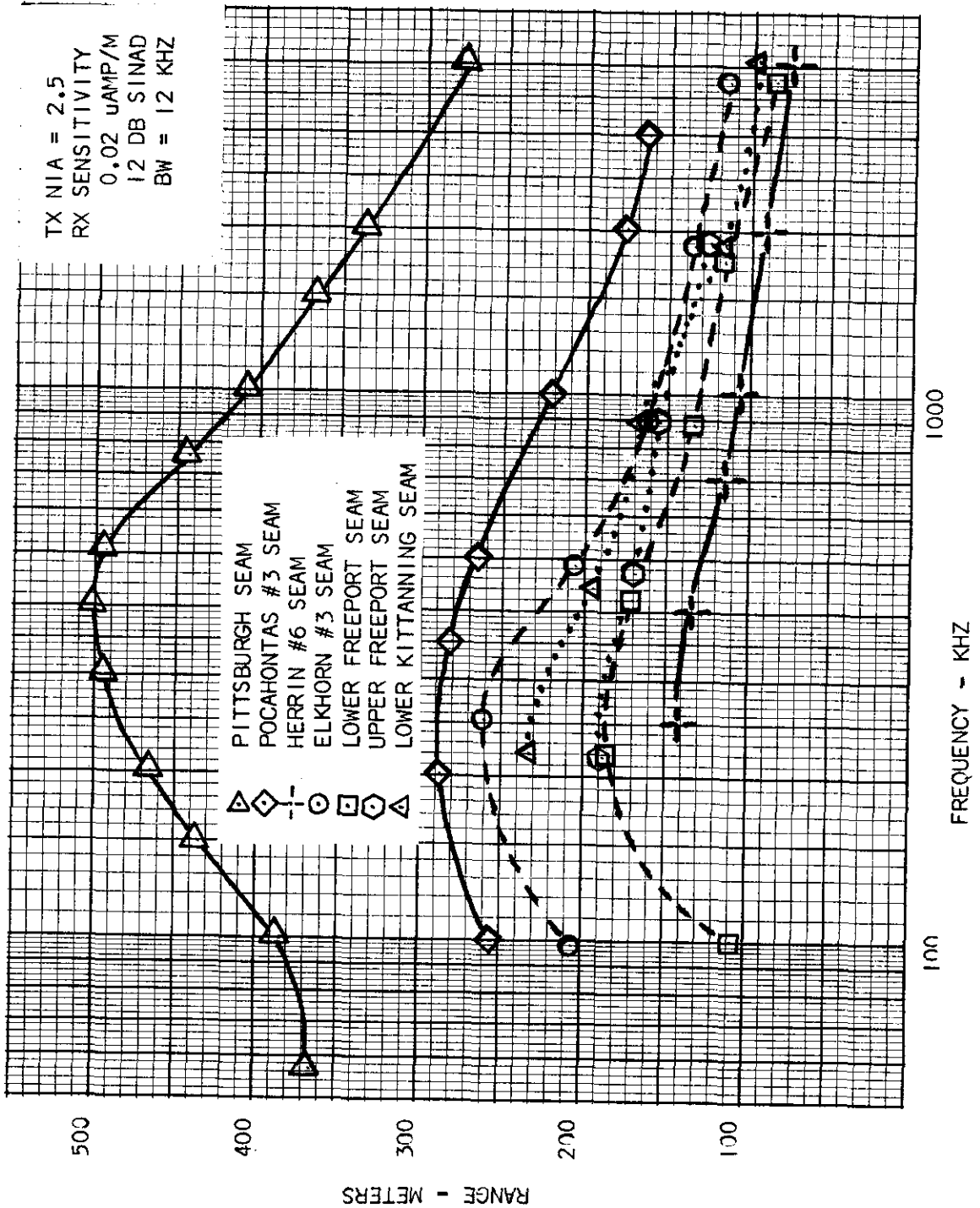
FIGURE 2

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

TX NIA = 2.5
RX SENSITIVITY
  0.02 uAMP/M
  12 DB SINAD
  BW = 12 KHZ

△ PITTSBURGH SEAM
◇ POCAHONTAS #3 SEAM
—·— HERRIN #6 SEAM
O ELKHORN #3 SEAM
□ LOWER FREEPORT SEAM
⬡ UPPER FREEPORT SEAM
◁ LOWER KITTANNING SEAM

RANGE — METERS

FREQUENCY — KHZ

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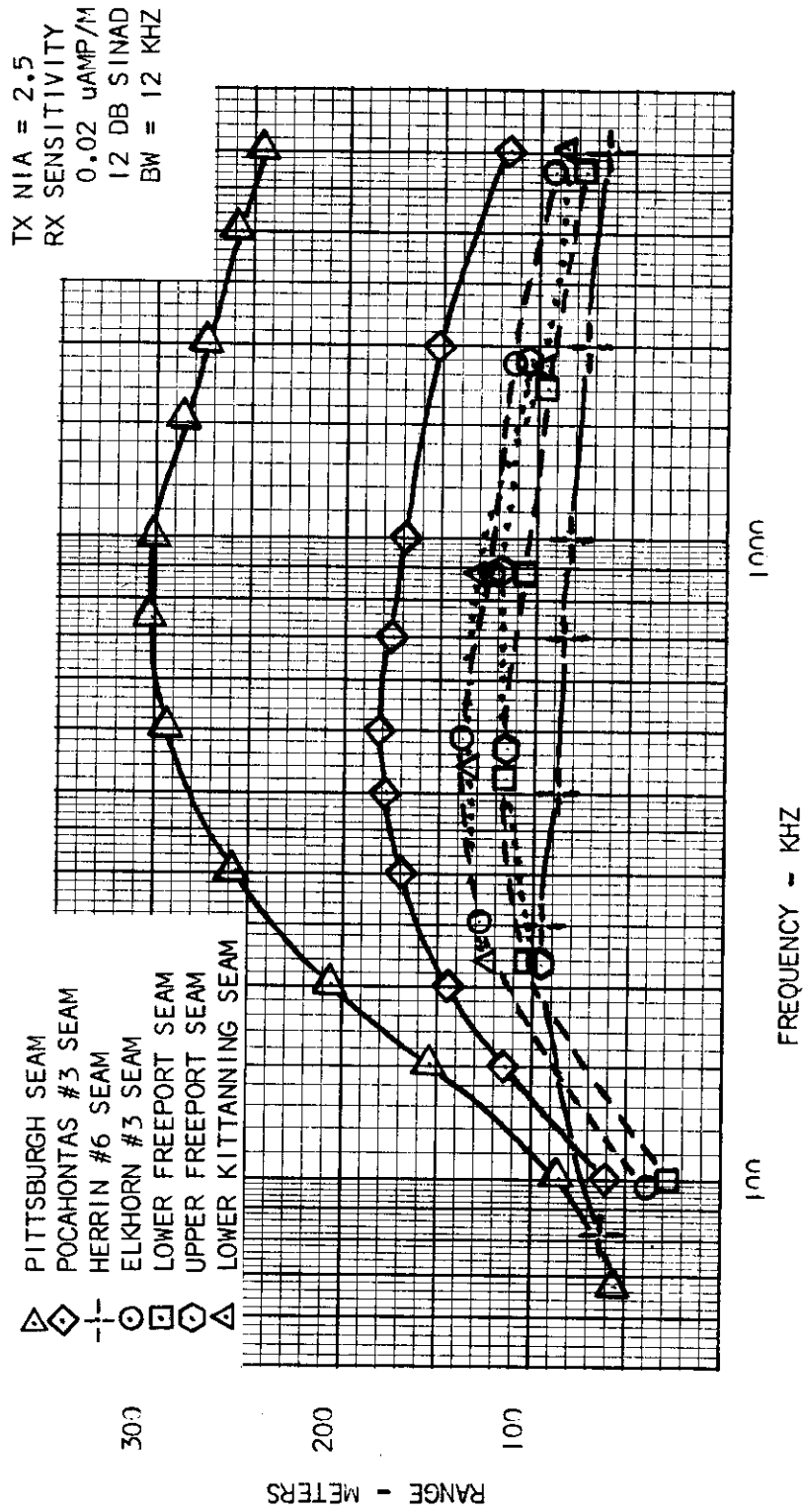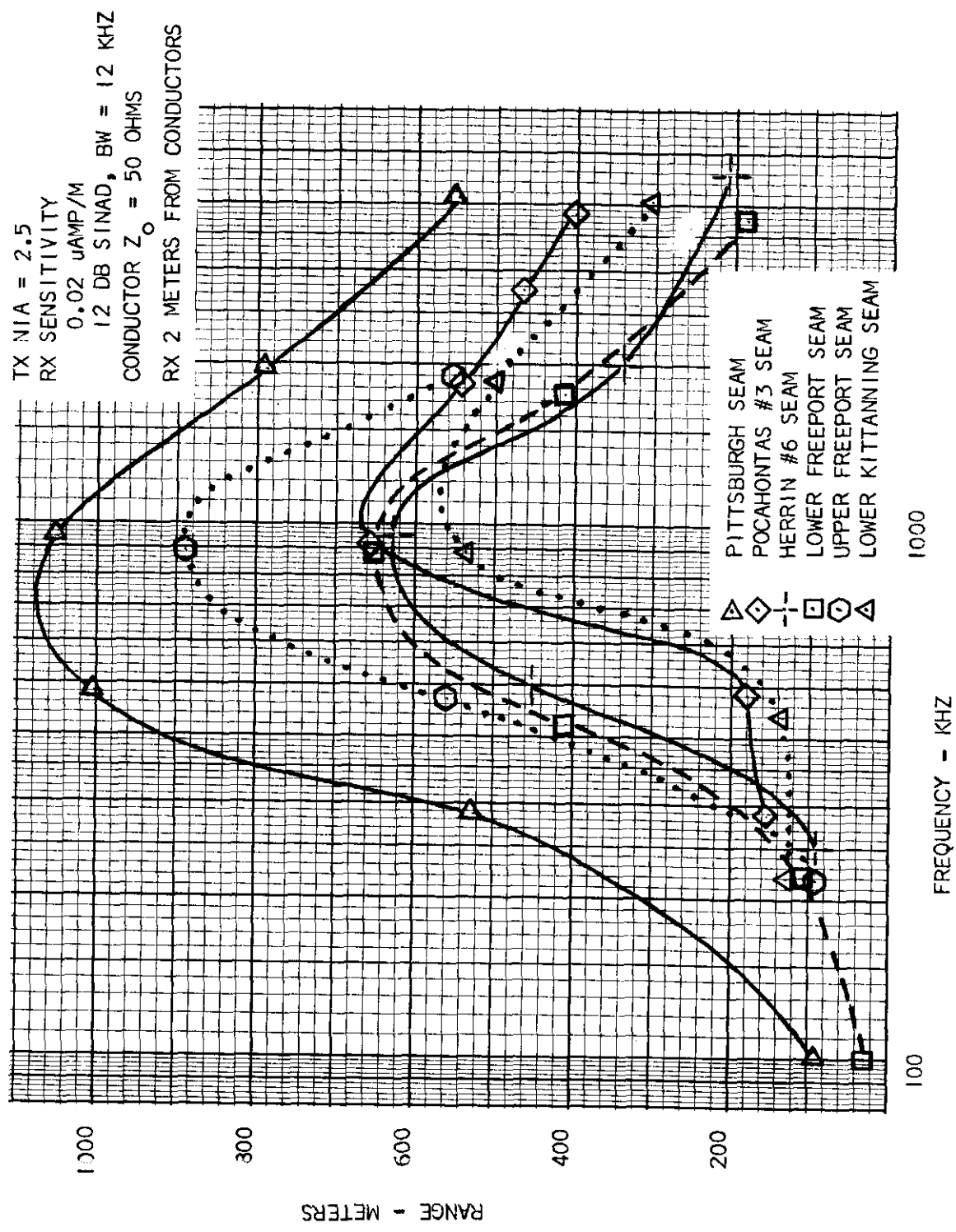
FIGURE 3
MAXIMUM COMMUNICATION RANGE VS OPERATING FREQUENCY IN COAL MINES
IN PROXIMITY TO CONDUCTOR(S) — TX LOCATED REMOTELY — MEDIAN MINE NOISE

TX NIA = 2.5
RX SENSITIVITY
0.02 uAMP/M
12 DB SINAD, BW = 12 KHZ
CONDUCTOR Z_o = 50 OHMS
RX 2 METERS FROM CONDUCTORS

PITTSBURGH SEAM
POCAHONTAS #3 SEAM
HERRIN #6 SEAM
LOWER FREEPORT SEAM
UPPER FREEPORT SEAM
LOWER KITTANNING SEAM

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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 prototype fm radios developed for the Bureau and the NBS noise study[5] (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

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

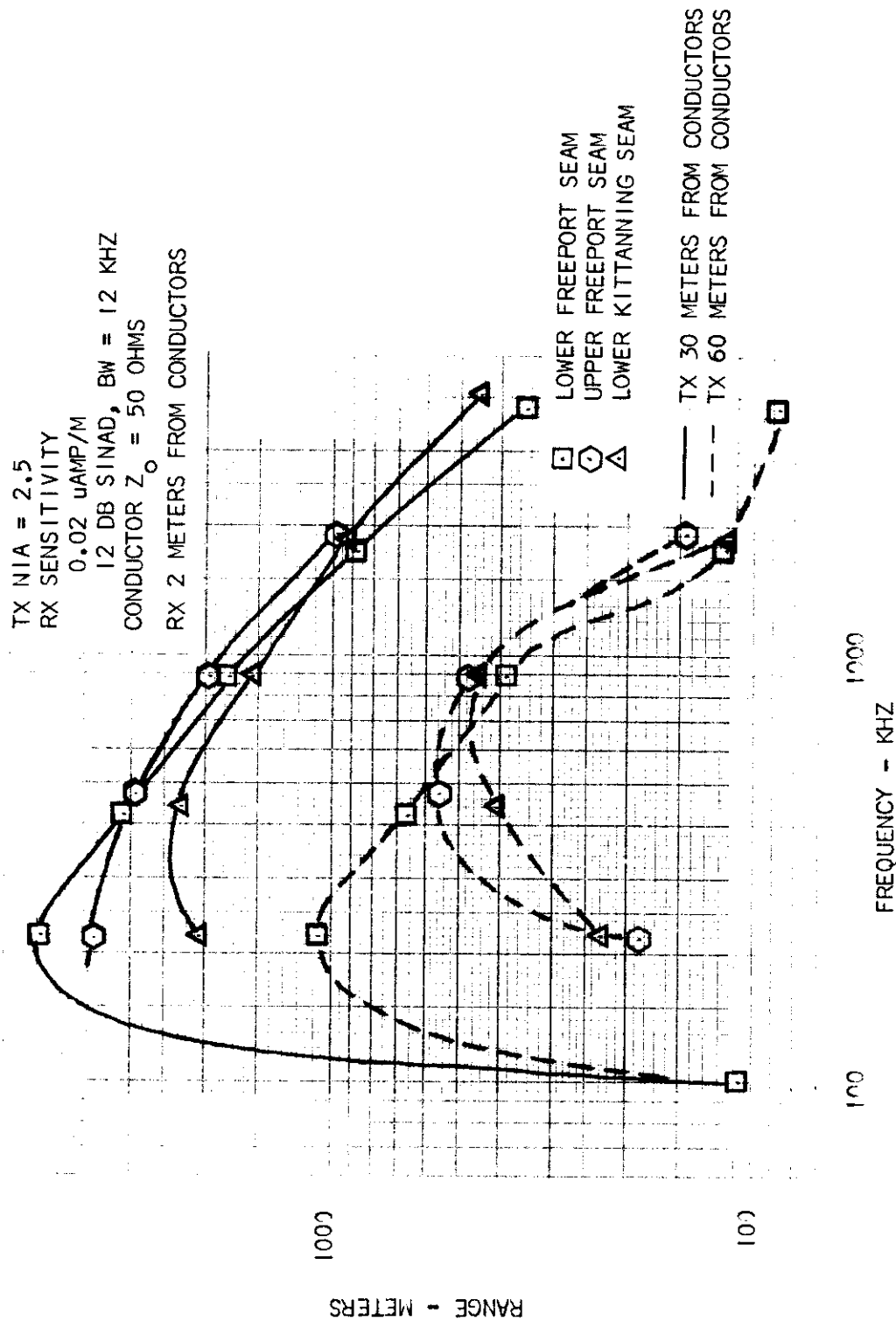where, Δf is the 12 KHz bandwidth
Q is the antenna "Q" made as narrow as possible to be consistent with transmission; Q = 44 for the Collins prototype fm radio

A is the antenna area = 0.217 m^2

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

TX NIA = 2.5
RX SENSITIVITY
    0.02 uAMP/M
    12 DB SINAD, BW = 12 KHZ
CONDUCTOR Z_o = 50 OHMS

RX 2 METERS FROM CONDUCTORS

LOWER FREEPORT SEAM
UPPER FREEPORT SEAM
LOWER KITTANNING SEAM

TX 30 METERS FROM CONDUCTORS
TX 60 METERS FROM CONDUCTORS

FREQUENCY - KHZ

RANGE - METERS

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

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[6],[7] of the overburden/underburden, the attenuation constants given in Table I were obtained. Other line parameters assumed were:

$$a/a_i = 9$$

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

a_i is the conductor radius

$Z_o = 50$ 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
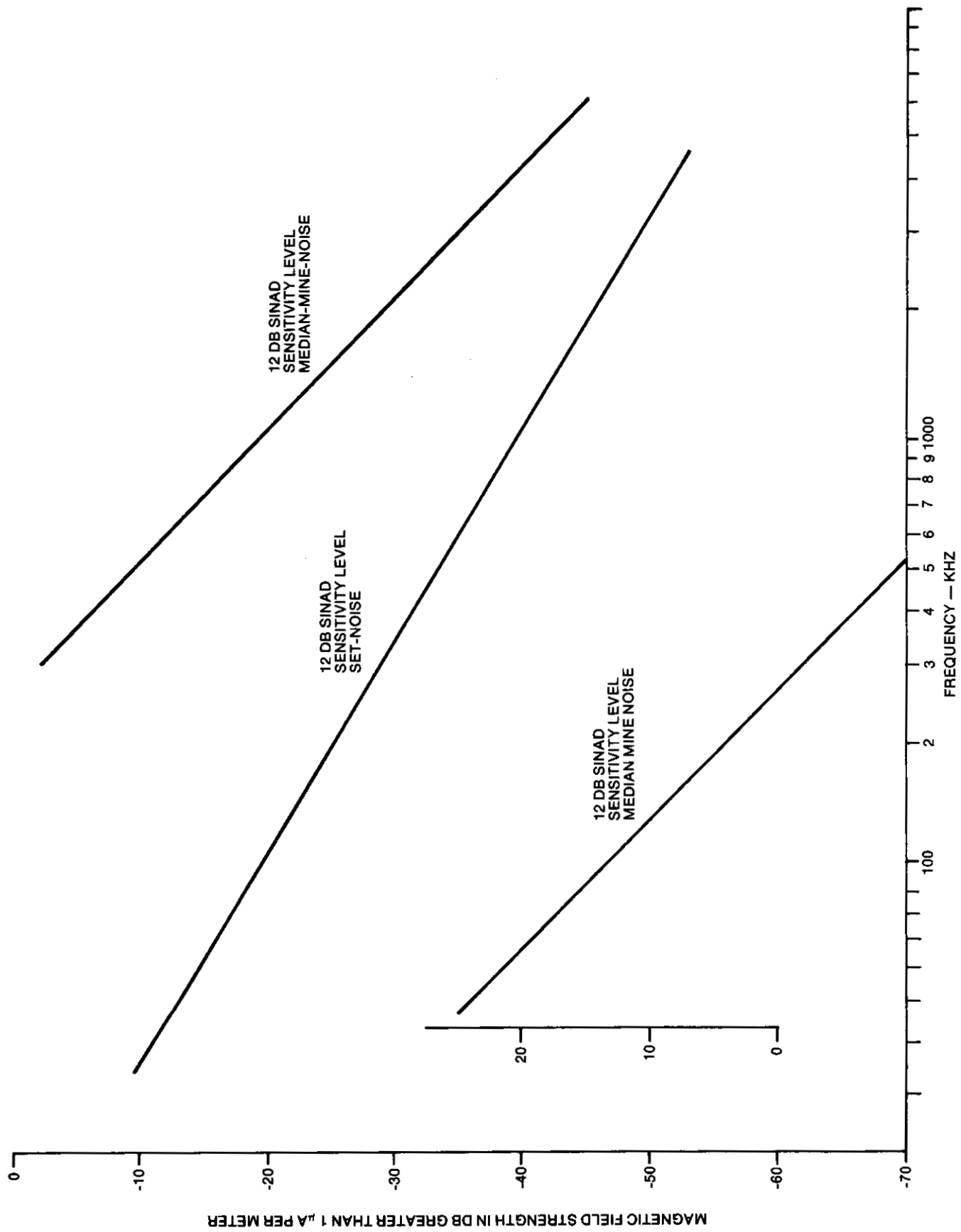
Figure 5   Required Field Strength Sensitivity Levels for Mine Wireless Radios Based on the Collins-Developed Mine Wireless Prototype Radios at 520 kHz.

TABLE   I

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

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

NOTE: ASSUME α IS PROPORTIONAL TO FREQUENCY

TABLE 2

SUMMARY OF SHORT FORMULAS FOR SCATTER GAIN CALCULATION VS COAL SEAM

SEAM   FORMULA

PITTSBURGH

$$G_S = \frac{9.53}{Z_o \sqrt{R_T} \; R_R}$$

POCAHONTAS #3

$$G_S = \frac{3.76 \; f_{MHZ}^{0.075}}{Z_o \sqrt{R_T} \; R_R}$$

HERRIN #6

$$G_S = \frac{7.0 \; f_{MHZ}^{0.25}}{Z_o \sqrt{R_T} \; R_R}$$

LOWER FREEPORT

$$G_S = \frac{4.324 f_{MHZ}^{-0.374}}{Z_o \sqrt{R_T} \; R_R}$$

UPPER FREEPORT

$$G_S = \frac{4.042 f_{MHZ}^{0.181}}{Z_o \sqrt{R_T} \; R_R}$$

LOWER KITTANNING

$$G_S = \frac{2.634 f_{MHZ}^{0.2071}}{Z_o \sqrt{R_T} \; R_R}$$

(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 magin of (4) by the conductor attenuation
as computed from Table I. 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[1]. Again, Singer NM-12 and NM-25 field strength meters were
used for reception. The single-turn shielded coaxial 0.73 m^2 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

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

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

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

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

FREQ(KHZ)	ANT TYPE(TURNS)	RX ANTENNA BAND SET #	RELATIVE FIELD STRENGTH(DB)
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

RX ANTENNA BAND SET #	FREQUENCY KHZ	FIELD STRENGTH MICROVOLTS/M
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 m^2 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

	Sensitivity, dB above 1 ua/m

(1) Collins fm radio for 12 dB
SINAD & 2 dB noise figure
@ 520 KHz, 12 KHz BW

	Sensitivity, dB above 1 ua/m
(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 Kittanning 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

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

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

$$\alpha + i\beta = \sqrt{\left(\frac{2Z_s}{h} + i\omega u_o\right)\left(\sigma_c + i \, K_c \, \epsilon_o\right)}$$

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

where, K_c is the dielectric constant = 6

σ_r is the rock conductivity

σ_c is the coal seam conductivity

h is the seam height

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

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

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 $\triangle$(DB)	SHORT FORM CALCULATED G_S(DB)	MEAS/CALC $\triangle$(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

$h = 1.30$ M

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

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

$Z_o = 50$ OHMS, FULL FORMULA
25 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

$h = 1.12$ M
$\sigma_c = 6.3 \times 10^{-5}$ MHO/M
$\sigma_r = 5.4 \times 10^{-3}$ MHO/M
$Z_o = 50$ OHMS

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TABLE 7

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 $\triangle$(DB)	SHORT FORM CALCULATED G_S(DB)	MEAS/CALC $\triangle$(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

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 amplitue. 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 9½ 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
crossectional 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 crossection. 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
crossectional 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, accomodate 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).

MARGARET #11 TEST DATA AT MEDIUM FREQUENCY
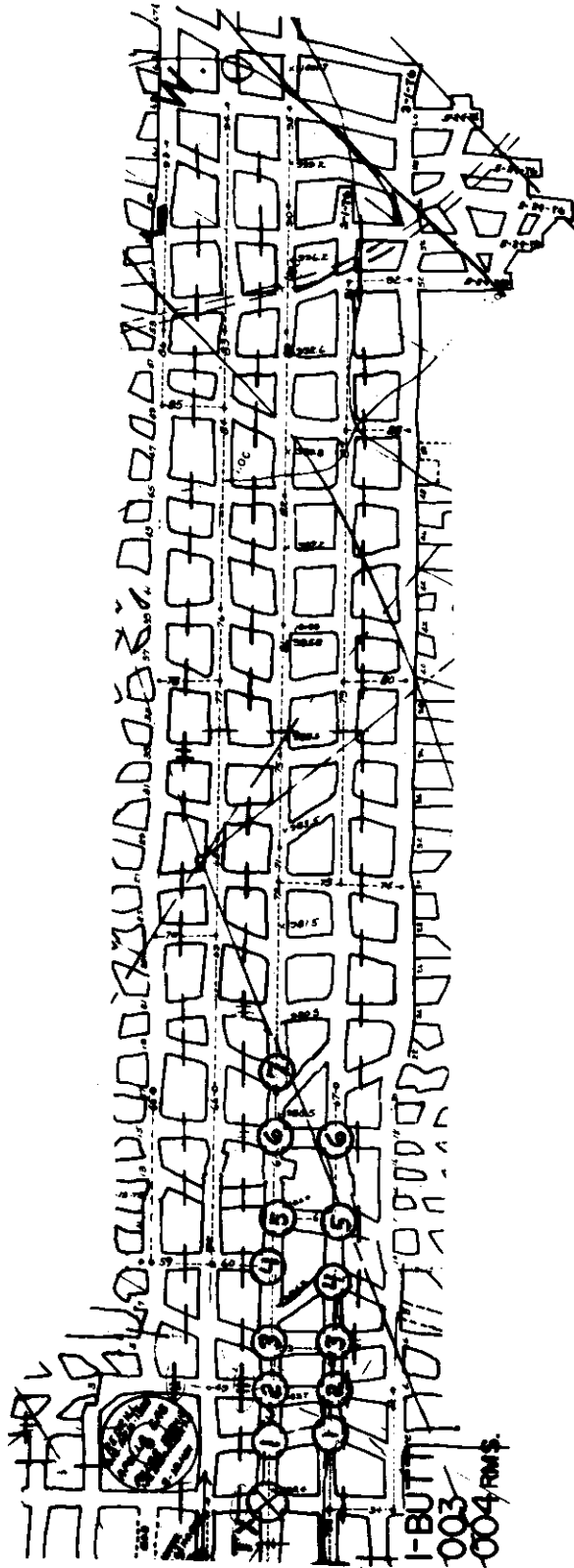
FIGURE A1

MINE MAP SHOWING TOPOLOGY, TRANSMITTER LOCATION, AND MEASUREMENT STATIONS FOR CONDUCTOR-FREE DATA IN 1-BUTT SECTION

HELVETIA COAL CO. MARGARET #11 MINE

TRANSMITTER LOCATION IN CROSSCUT BETWEEN
BELT AND POWER CABLE ENTRIES

TRANSMITTER LOCATION AT BARRIER ADJACENT
TO POWER CABLE ENTRY

BELT ENTRY

POWER CABLE ENTRY
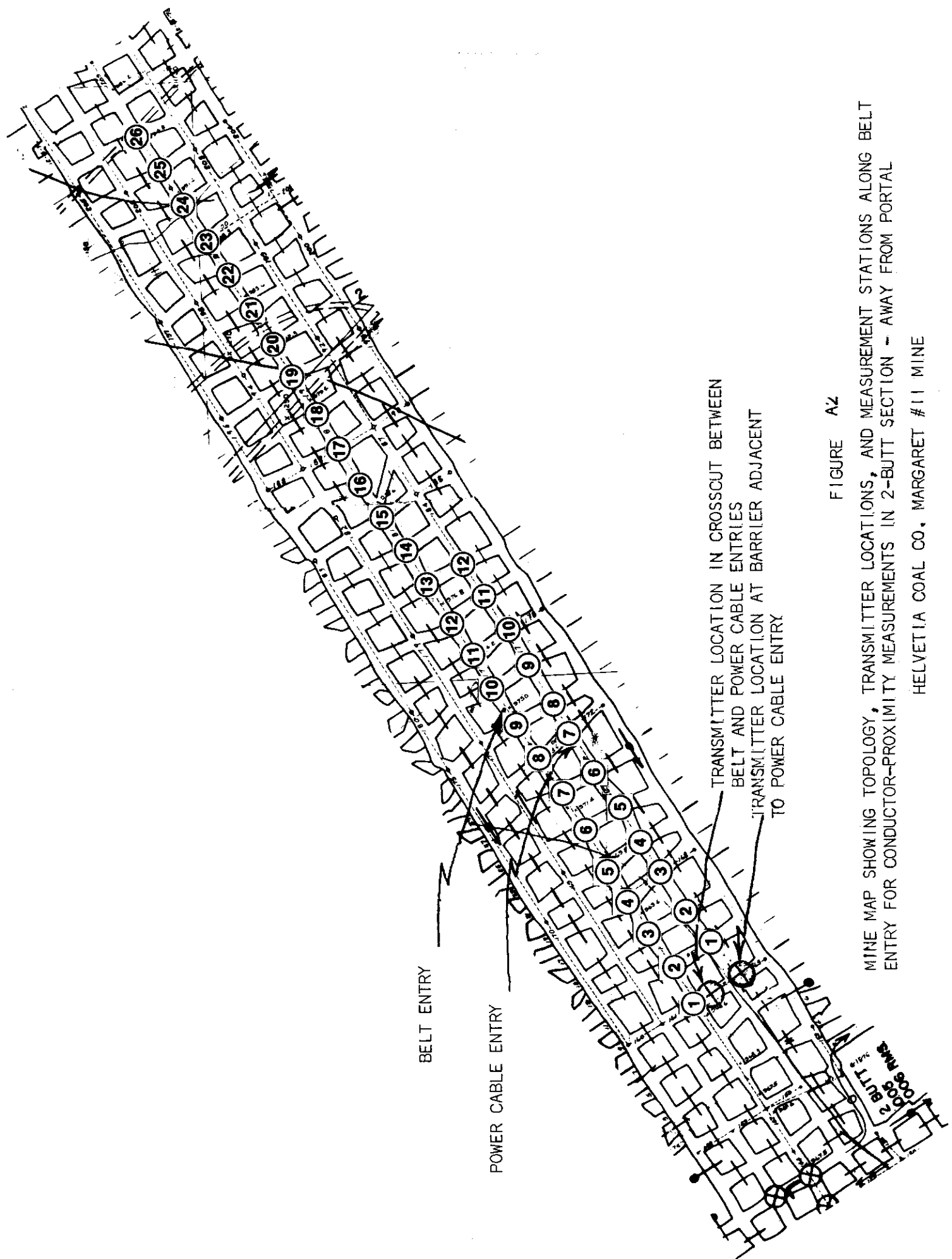
FIGURE A2

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

TRANSMITTER LOCATION IN CROSSCUT BETWEEN BELT AND POWER CABLE ENTRIES

TRANSMITTER LOCATION AT BARRIER ADJACENT TO POWER CABLE ENTRY

BELT ENTRY

POWER CABLE ENTRY
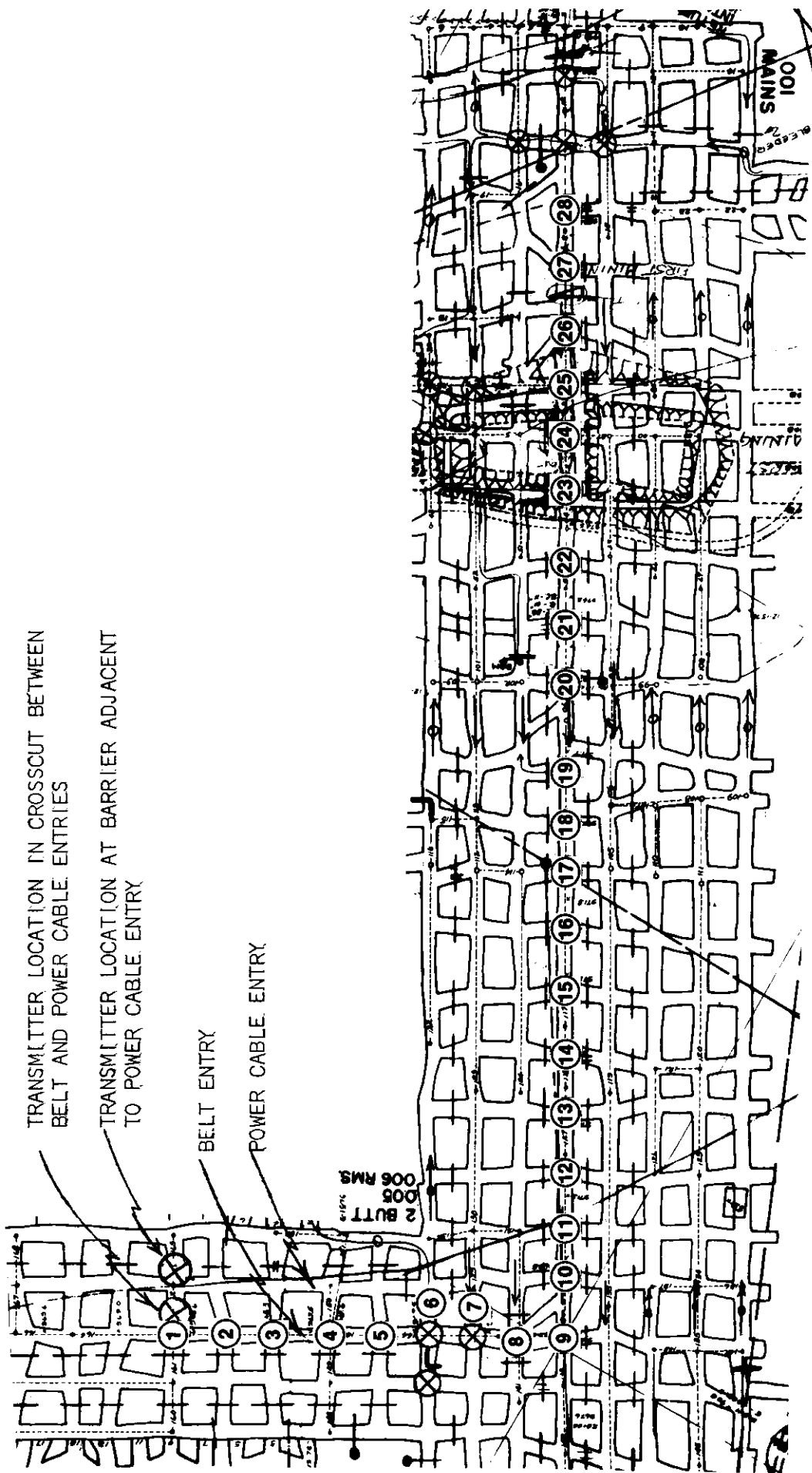
FIGURE A3

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

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FIGURE A4
MAGNETIC FIELD STRENGTH VS RANGE IN
CONDUCTOR-FREE I-BUTT SECTION OF
HELVETIA COAL CO. MARGARET #11 MINE
NIA = 2.5
DATA TAKEN IN ENTRY CONTAINING TRANSMITTER
COPLANAR HMD ORIENTATION OF ANTENNAS
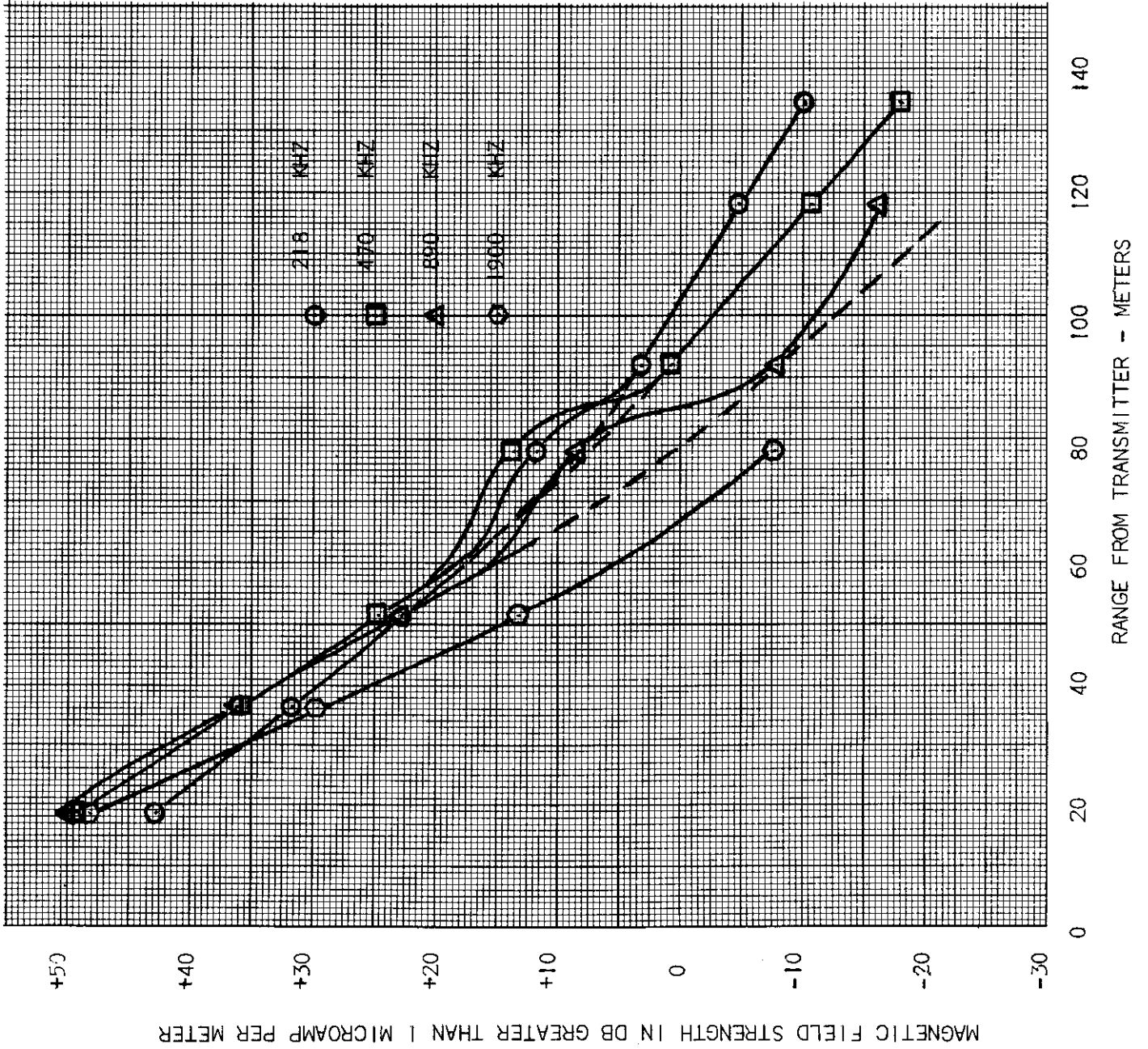
FIGURE A5

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

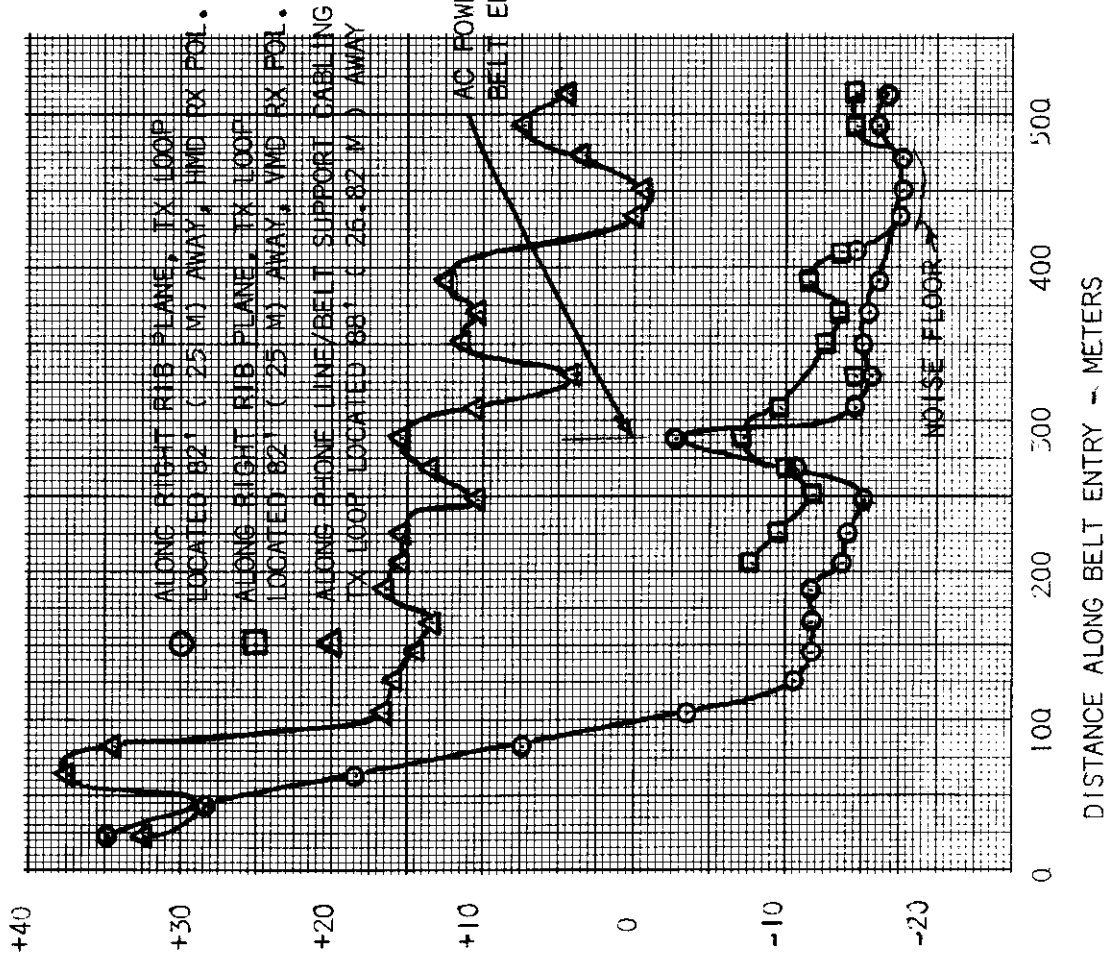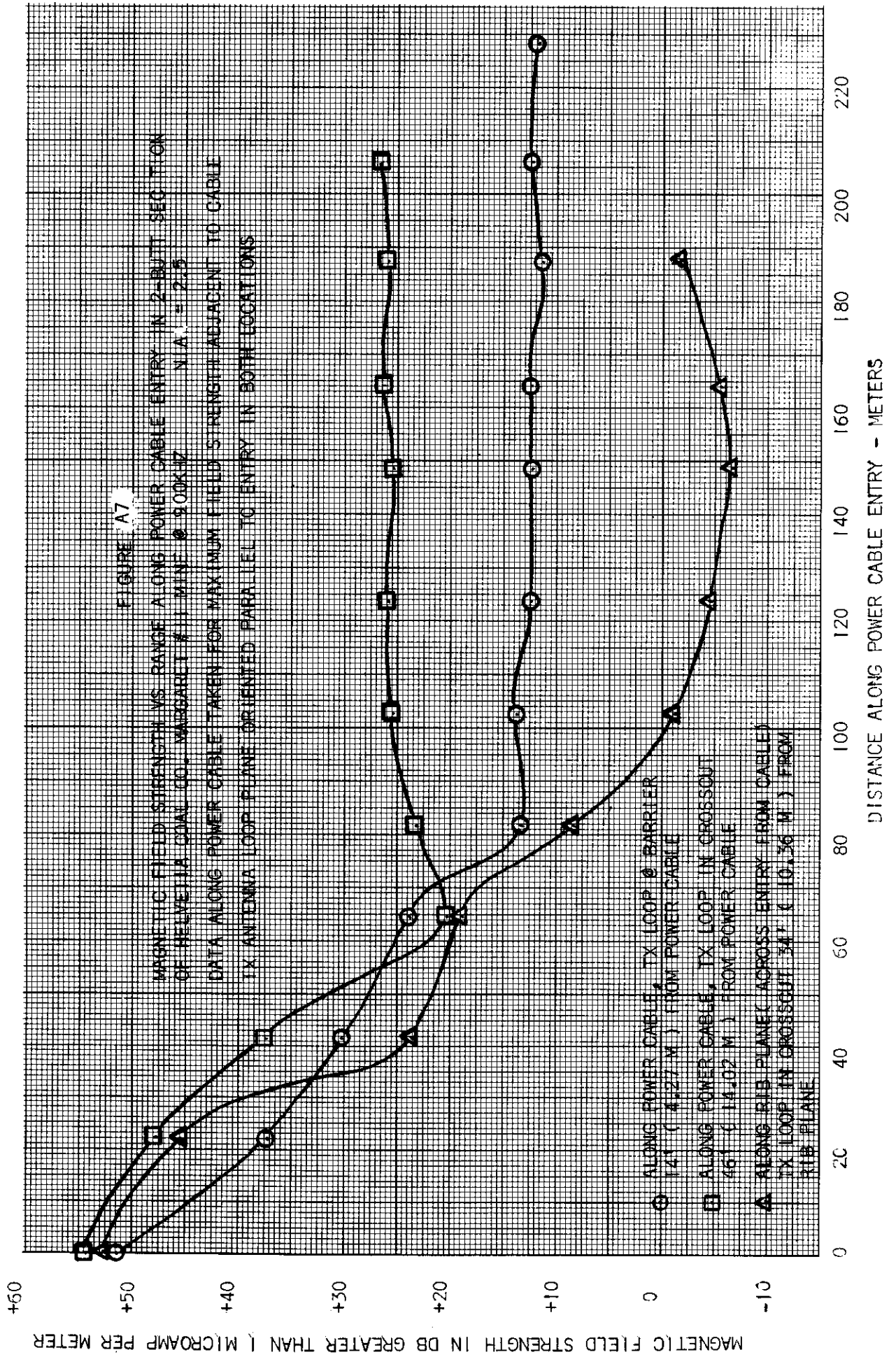COPLANAR HMD ORIENTATION OF ANTENNAS

42
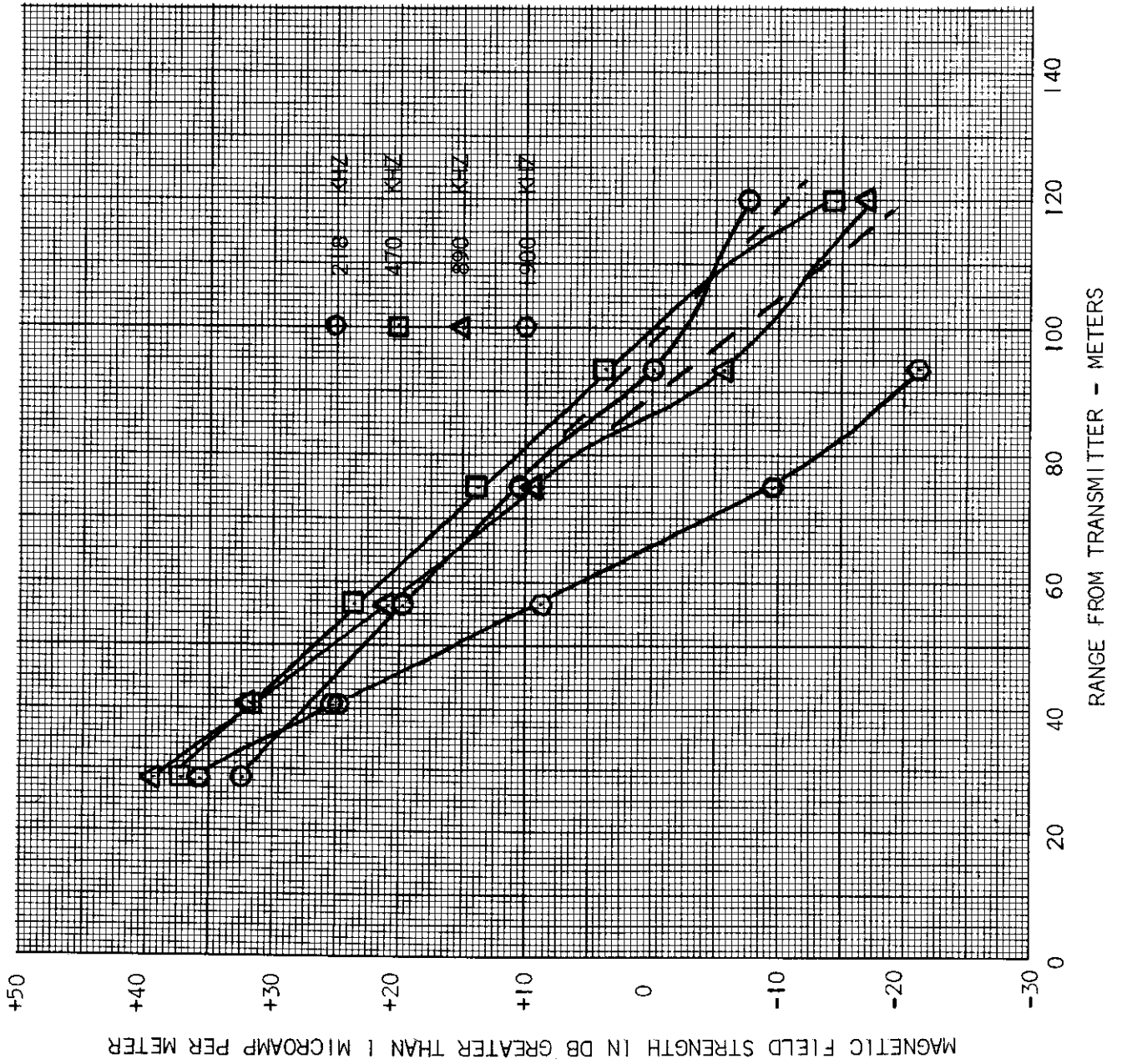
FIGURE A6

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 1½ ENTRIES

AWAY   NIA = 2.5

DATA TAKEN ALONG PHONE LINE/BELT SUPPORT CABLING IS

FOR MAXIMUM FIELD STRENGTH ADJACENT TO LINE/CABLING
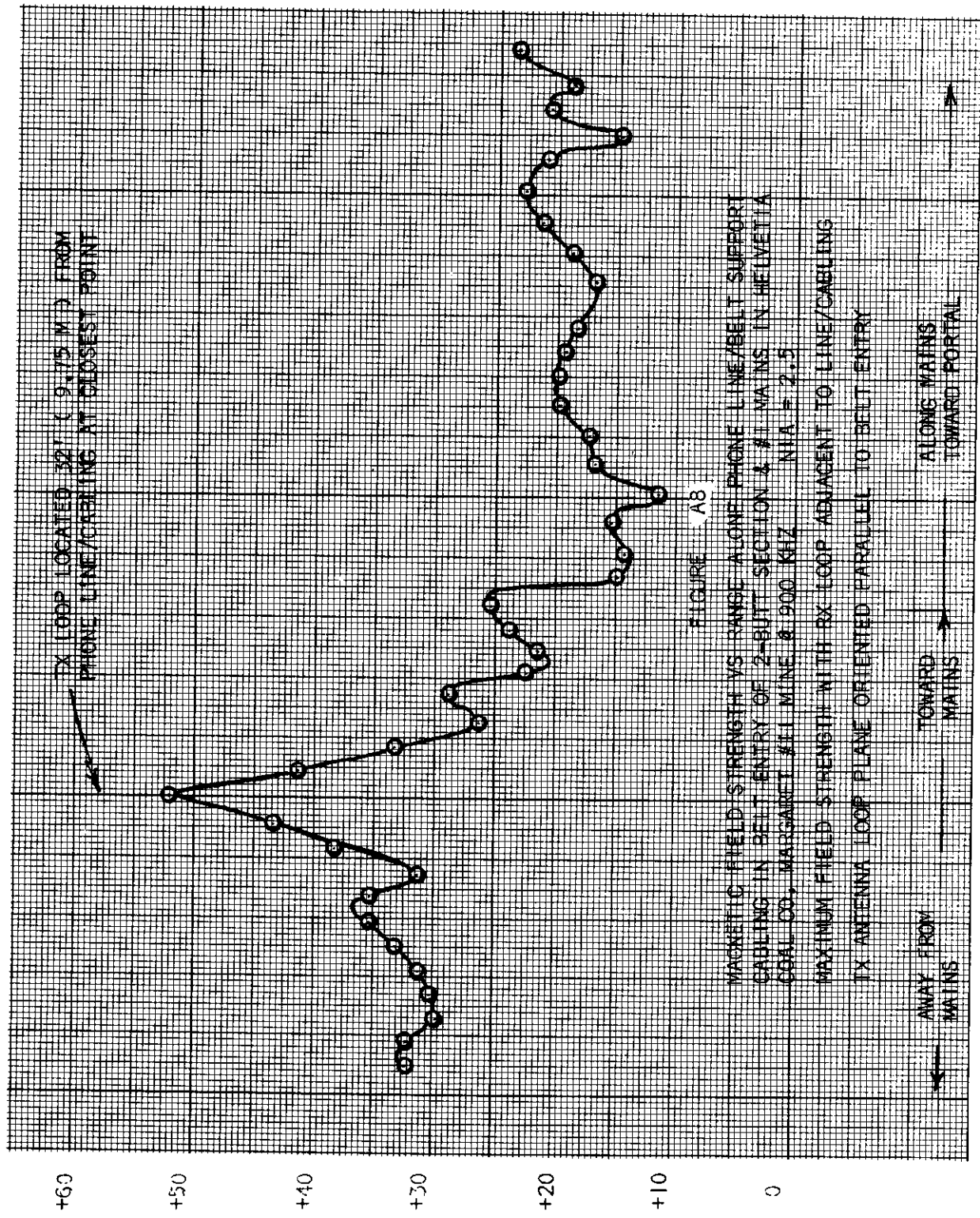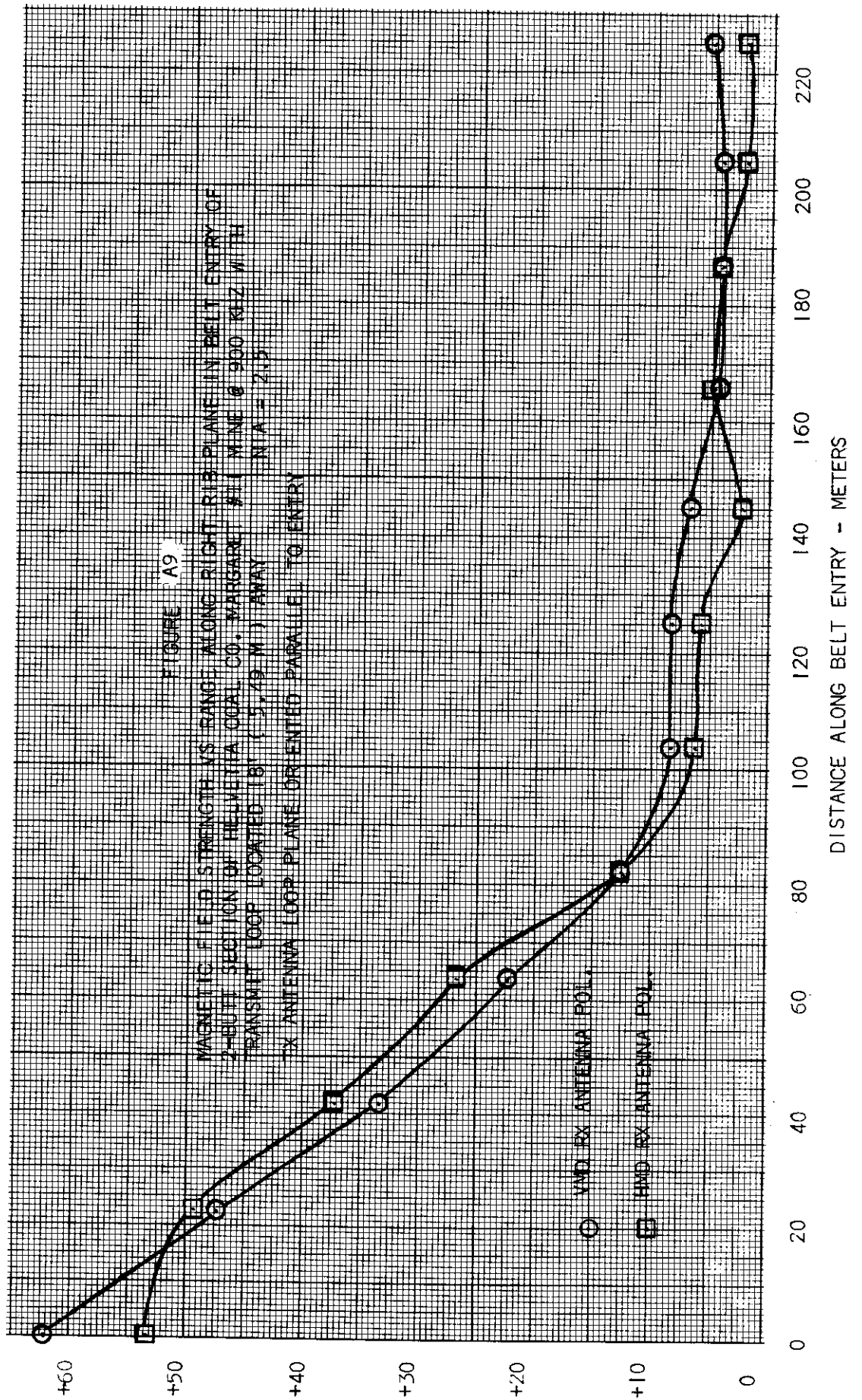
TX ANTENNA LOOP PLANE ORIENTED PARALLEL TO ENTRY

AC POWER CABLE CROSSES
BELT ENTRY @ POWER CENTER

○ ALONG RIGHT RIB PLANE, TX LOOP
  LOCATED 82' (25 M) AWAY, HMD Rx POL.

□ ALONG RIGHT RIB PLANE, TX LOOP
  LOCATED 82' (25 M) AWAY, VMD Rx POL.

△ ALONG PHONE LINE/BELT SUPPORT CABLING
  TX LOOP LOCATED 88' (26.82 M) AWAY

NOISE FLOOR

DISTANCE ALONG BELT ENTRY – METERS

MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICROAMP PER METER

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FIGURE A7

MAGNETIC FIELD STRENGTH VS RANGE ALONG POWER CABLE ENTRY IN 2-BUTT SECTION
OF HELVETIA COAL CO.'S WILDCAT #1 MINE @ 9.00kHz   N.A. = 2.5

DATA ALONG POWER CABLE TAKEN FOR MAXIMUM FIELD'S RENGTH ADJACENT TO CABLE

TX ANTENNA LOOP PLANE ORIENTED PARALLEL TO ENTRY IN BOTH LOCATIONS

⊙ ALONG POWER CABLE, TX LOOP @ BARRIER
  14' (4.27 M) FROM POWER CABLE

⊡ ALONG POWER CABLE, TX LOOP IN CROSSCUT
  46' (14.02 M) FROM POWER CABLE

△ ALONG RIB PLANE(ACROSS ENTRY FROM CABLE)
  TX LOOP IN CROSSCUT 34' (10.36 M) FROM
  RIB PLANE

DISTANCE ALONG POWER CABLE ENTRY – METERS

MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICROAMP PER METER

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FIGURE A8

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 #1 MINE, 8,900 KHZ   NIA = 2.5
MAXIMUM FIELD STRENGTH WITH RX LOOP ADJACENT TO LINE/CABLING
TX ANTENNA LOOP PLANE ORIENTED PARALLEL TO BELT ENTRY

TX LOOP LOCATED 32' (9.75 M) FROM
PHONE LINE/CABLING AT CLOSEST POINT

MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICROAMP PER METER

RANGE ALONG BELT ENTRY - METERS

AWAY FROM MAINS   TOWARD MAINS   ALONG MAINS TOWARD PORTAL

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FIGURE A9

MAGNETIC FIELD STRENGTH VS RANGE ALONG RIGHT RIB PLANE IN BELT ENTRY OF 2-BUTT SECTION OF HELVETIA COAL CO. MARGARET #11 MINE @ 900 KHZ WITH NIA = 2.5

TRANSMIT LOOP LOCATED 18 ft (5.49 m) AWAY
—— RX ANTENNA LOOP PLANE ORIENTED PARALLEL TO ENTRY

VERTICAL AXIS: MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICROAMP PER METER

HORIZONTAL AXIS: DISTANCE ALONG BELT ENTRY – METERS

VRD RX ANTENNA POL.   ○
HRD RX ANTENNA POL.   □

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ADRIAN MINE TEST DATA AT MEDIUM FREQUENCY
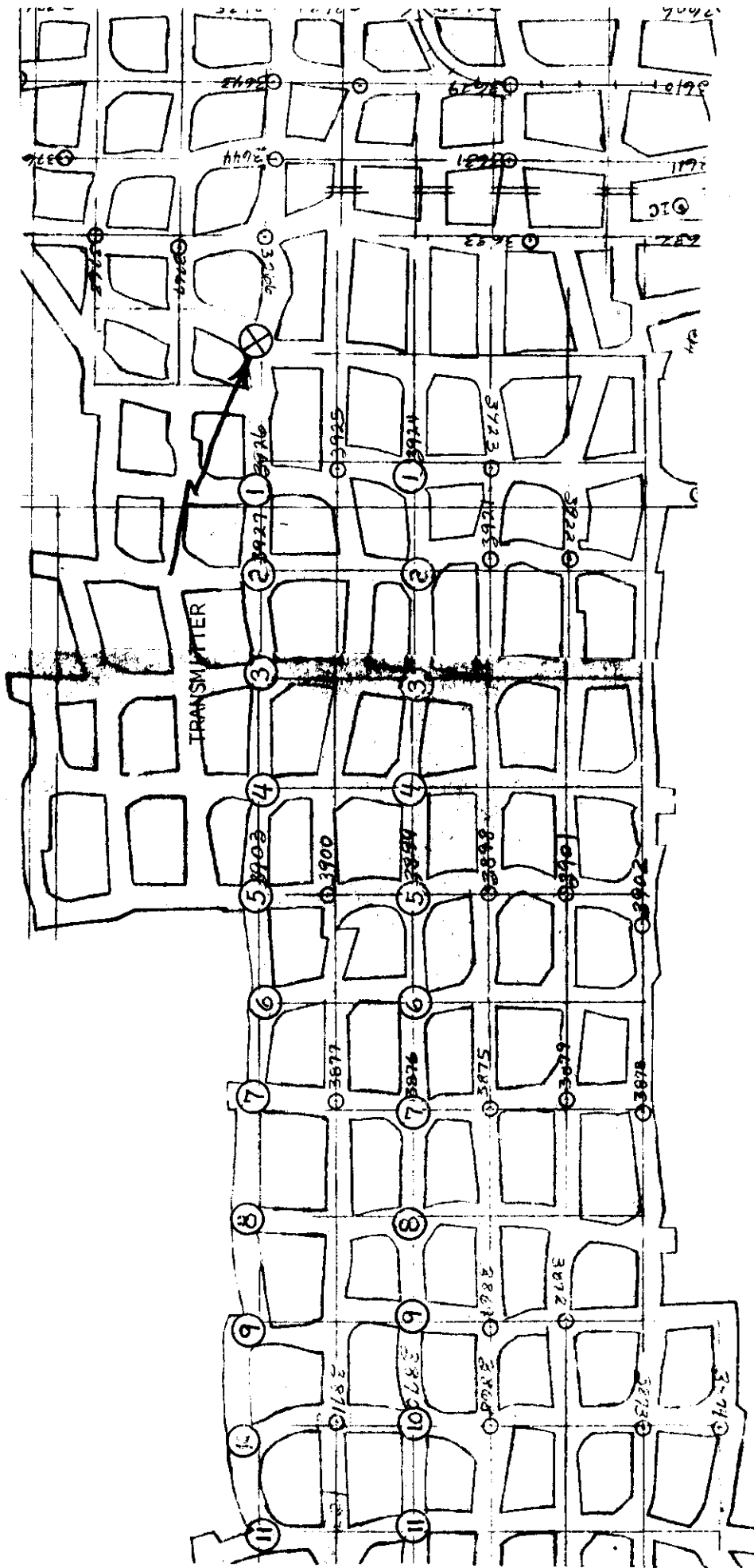
FIGURE A10

MINE MAP SHOWING TOPOLOGY, TRANSMITTER LOCATION, AND MEASUREMENT
TRAVERSE STATIONS IN AREA PARALLEL TO ROAD 83C BETWEEN 1ST-RIGHT
& 2ND-RIGHT IN UPSHUR COALS CORP. ADRIAN MINE

FIGURE AII

MAGNETIC FIELD STRENGTH VS RANGE IN CONDUCTOR-FREE AREA PARALLEL TO ROAD 83C

BETWEEN IST-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

49
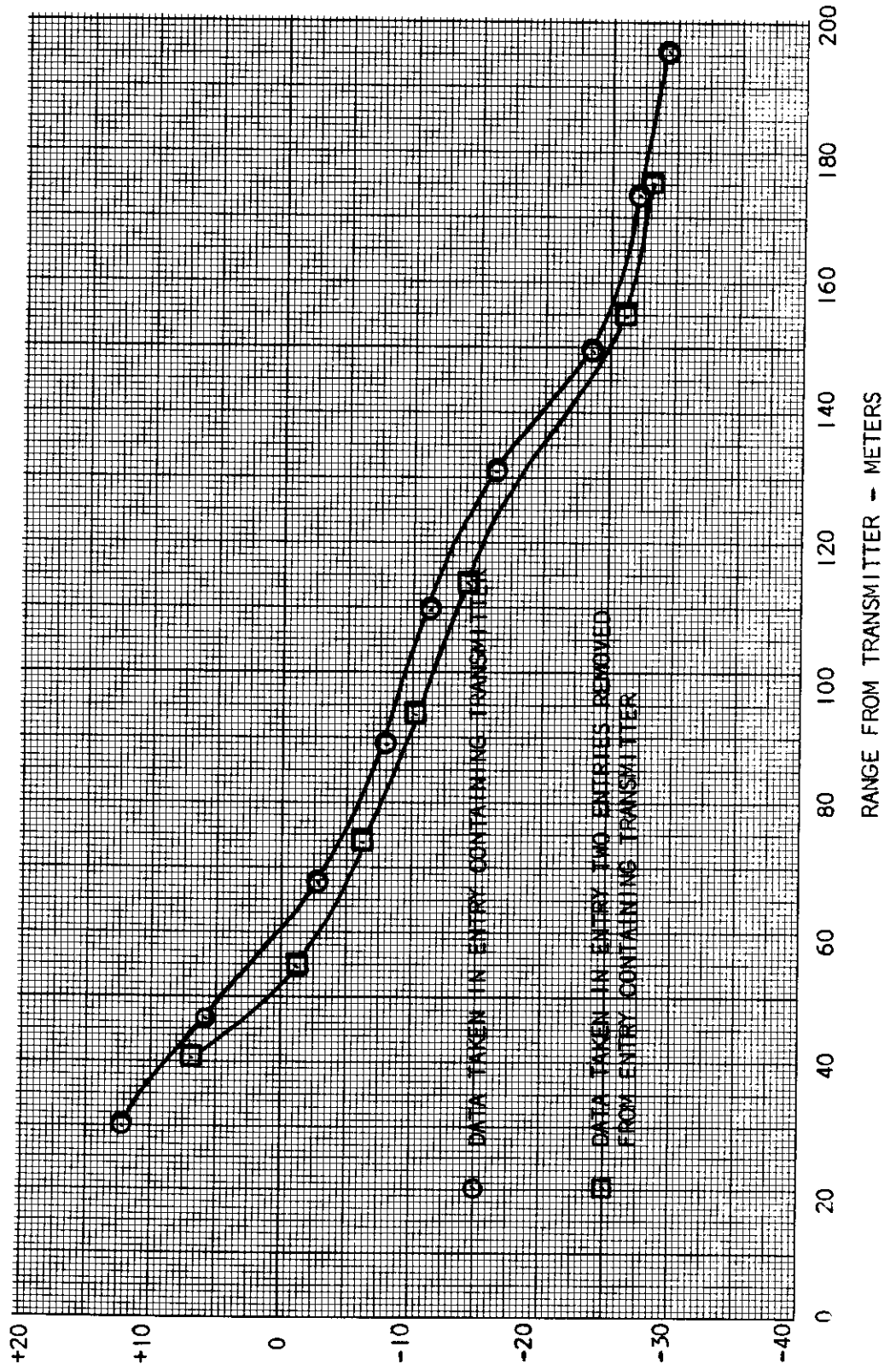
FIGURE A12

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
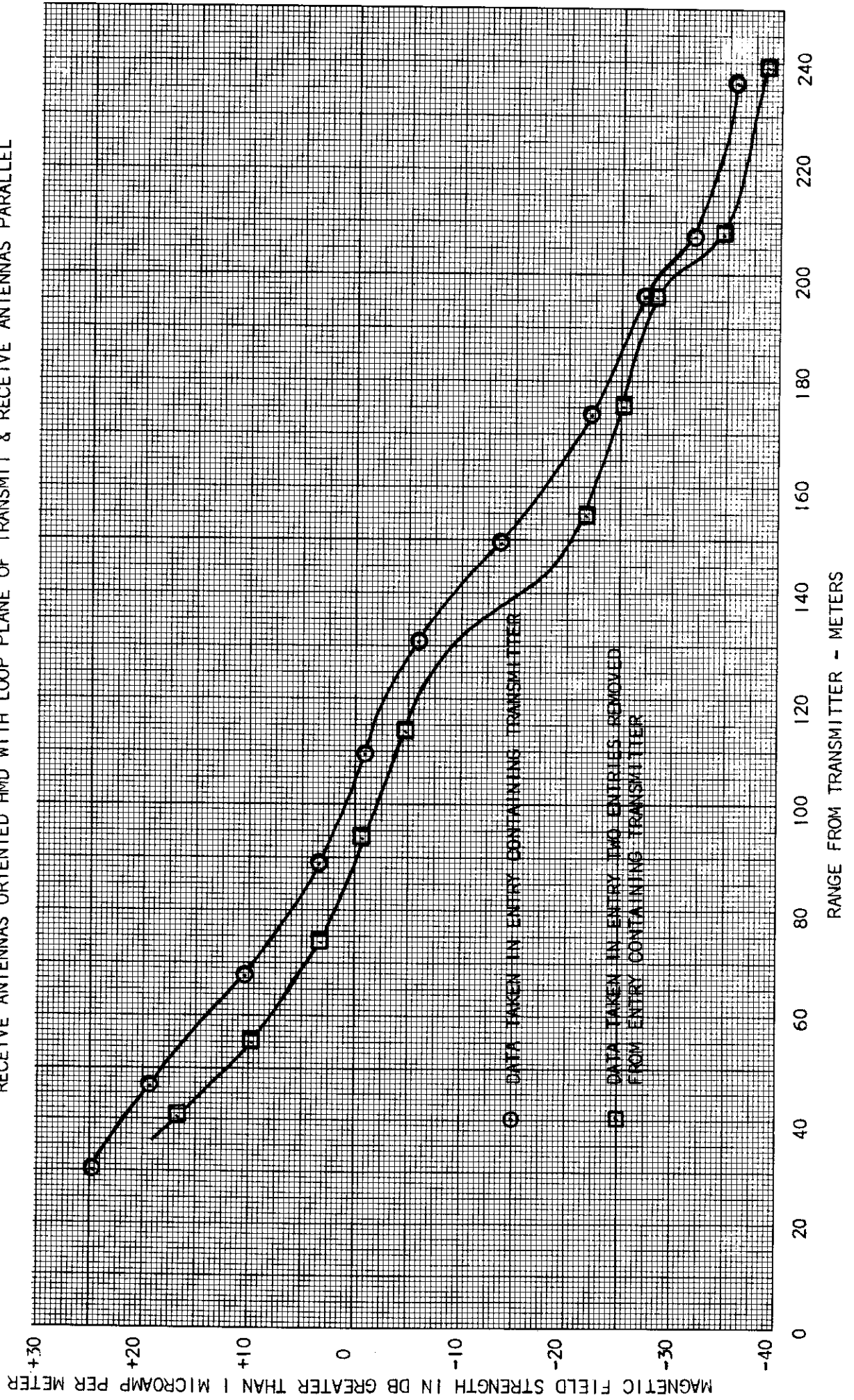
NANTY GLO #31 MINE TEST DATA AT MEDIUM FREQUENCY

TOWARD FACE

TRANSMITTER

BELT

4160 VAC CABLE
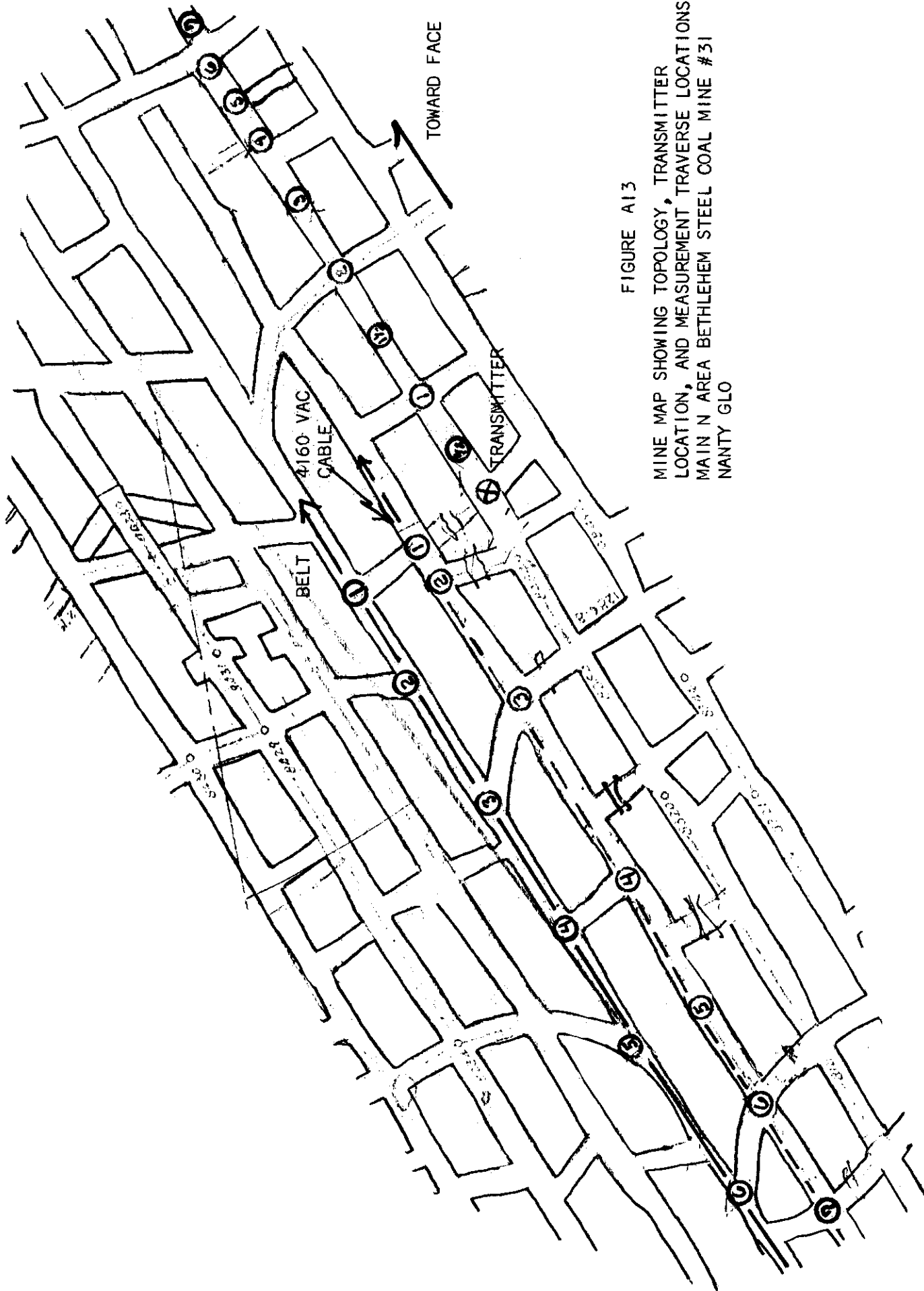
FIGURE A13

MINE MAP SHOWING TOPOLOGY, TRANSMITTER
LOCATION, AND MEASUREMENT TRAVERSE LOCATIONS
MAIN N AREA BETHLEHEM STEEL COAL MINE #31
NANTY GLO
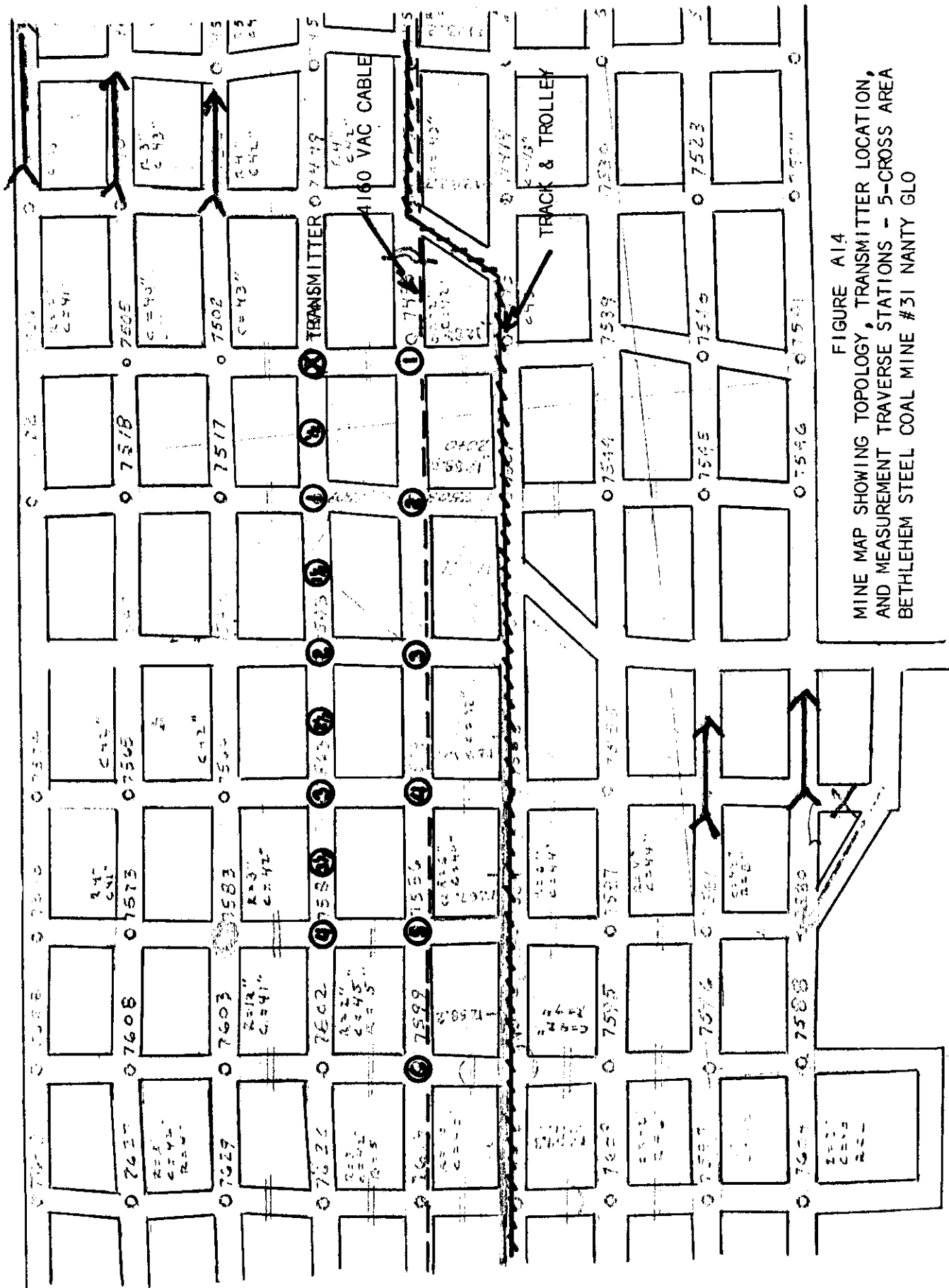
FIGURE A14

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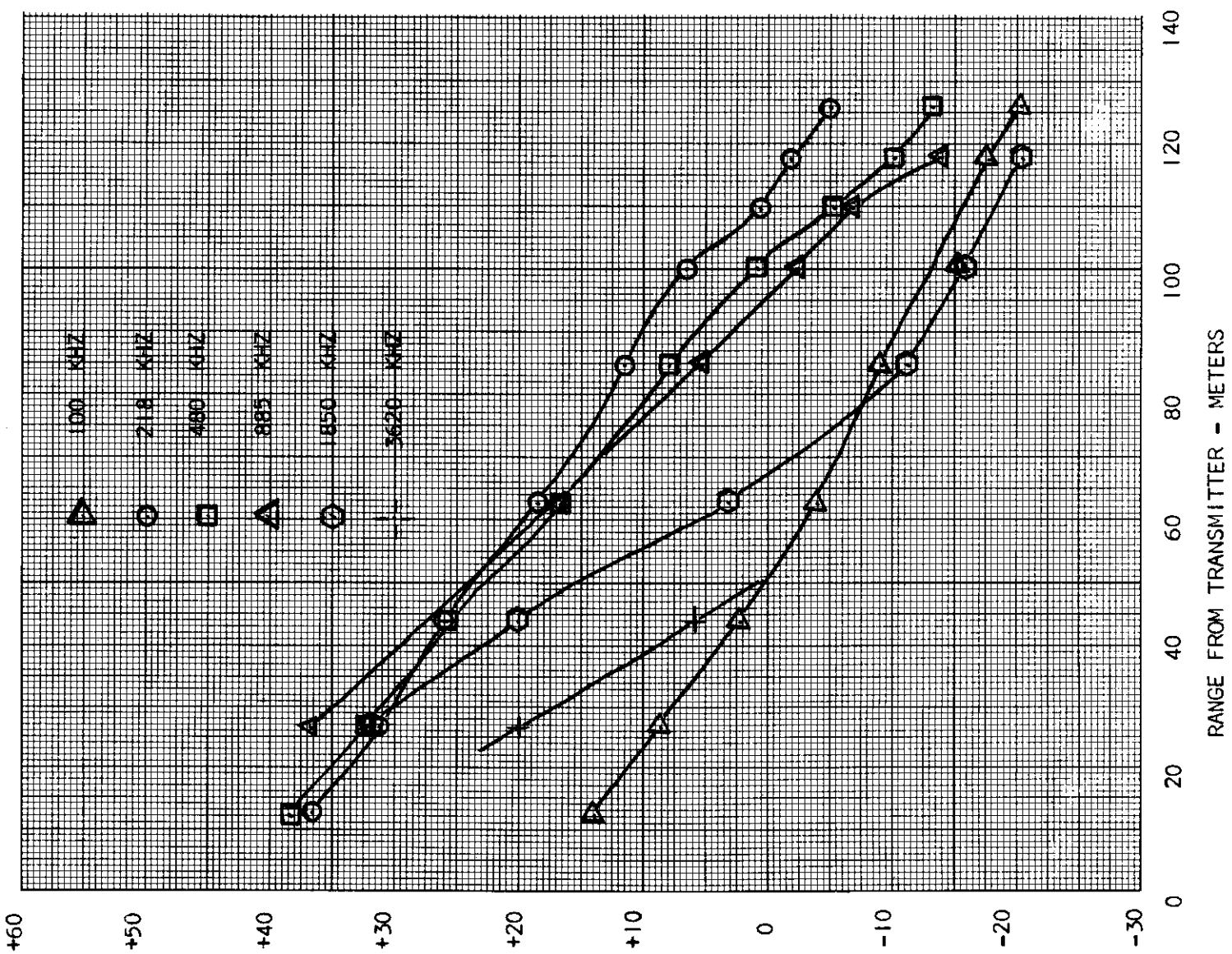BETHLEHEM STEEL COAL MINE #31 NANTY GLO

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

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

BETHLEHEM STEEL COAL MINE NANTY GLO #31   MAIN-N AREA

RECEIVE ANTENNA ORIENTED WITH LOOP PLANE HMD AND PARALLEL TO ENTRY DIRECTION
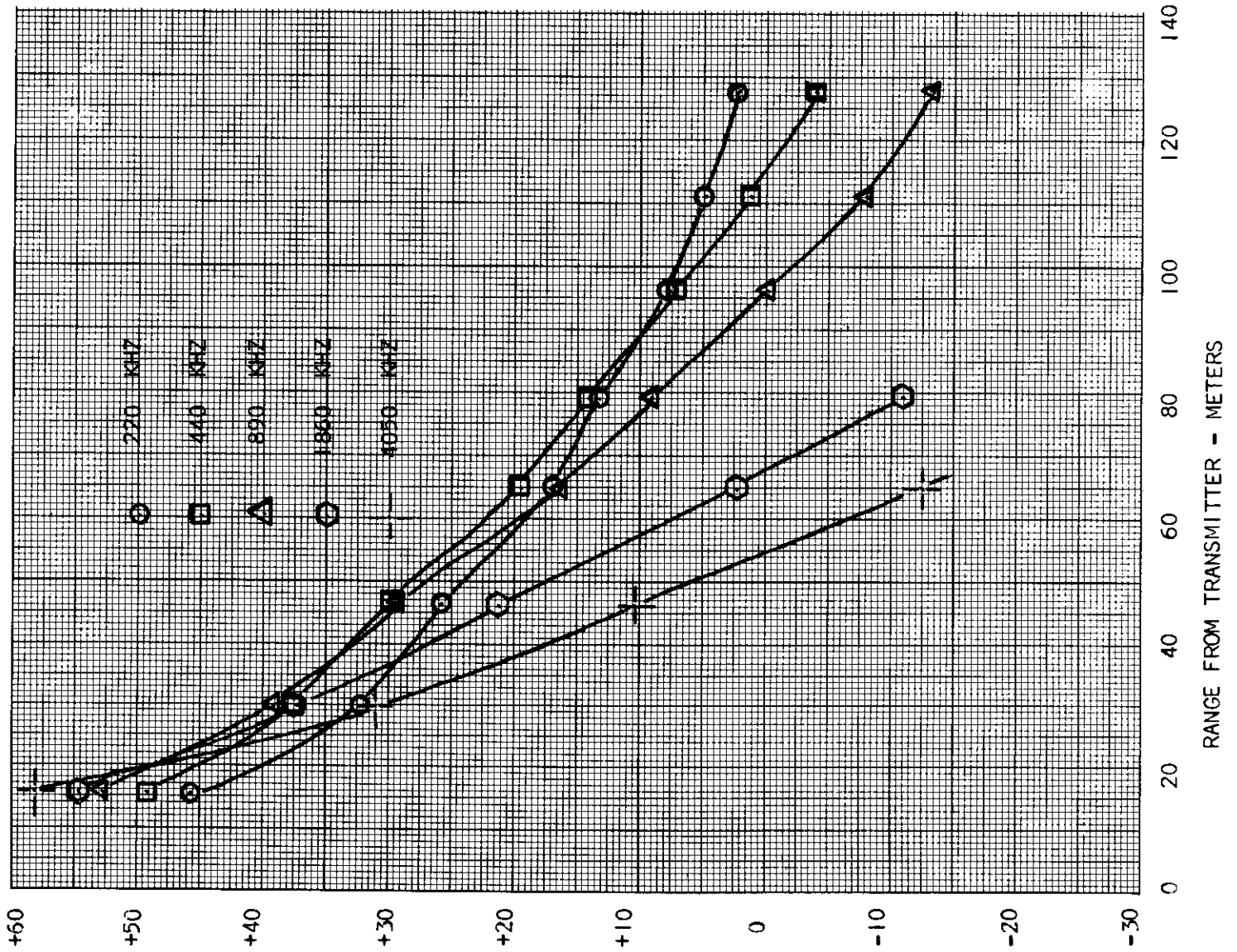

55
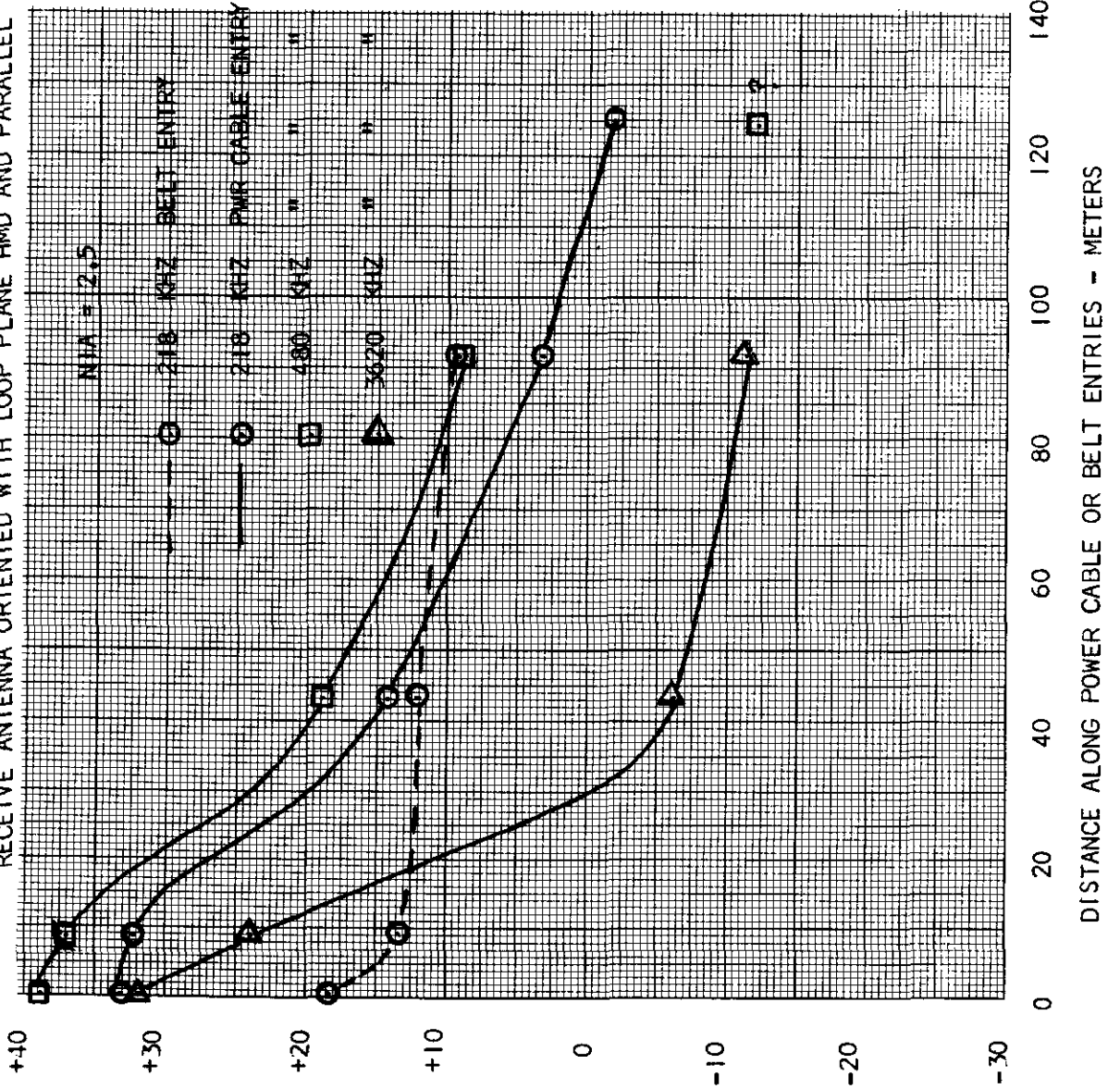
FIGURE A17

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

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

RECEIVE ANTENNA ORIENTED FOR MAXIMUM FIELD STRENGTH ADJACENT TO CABLE
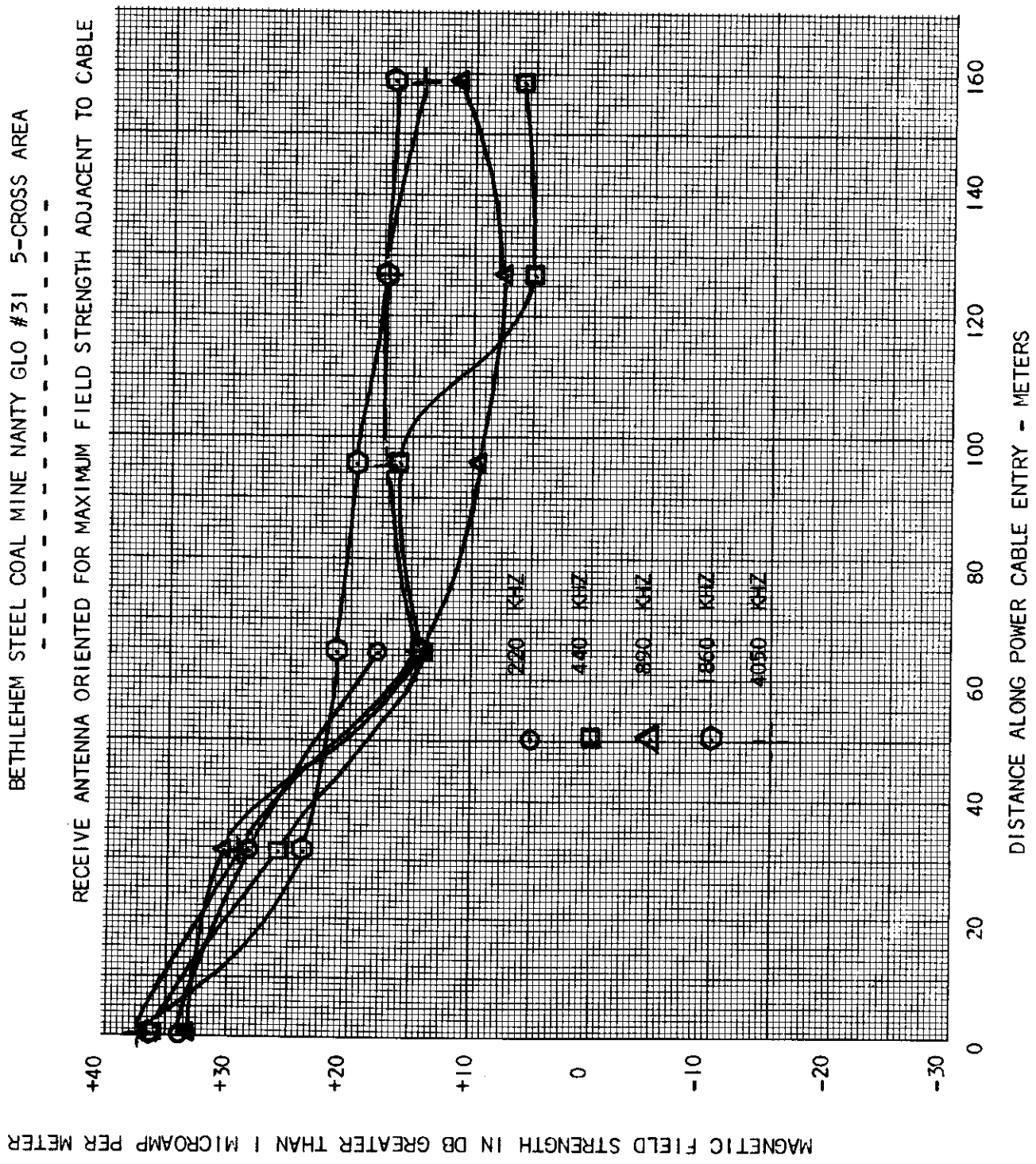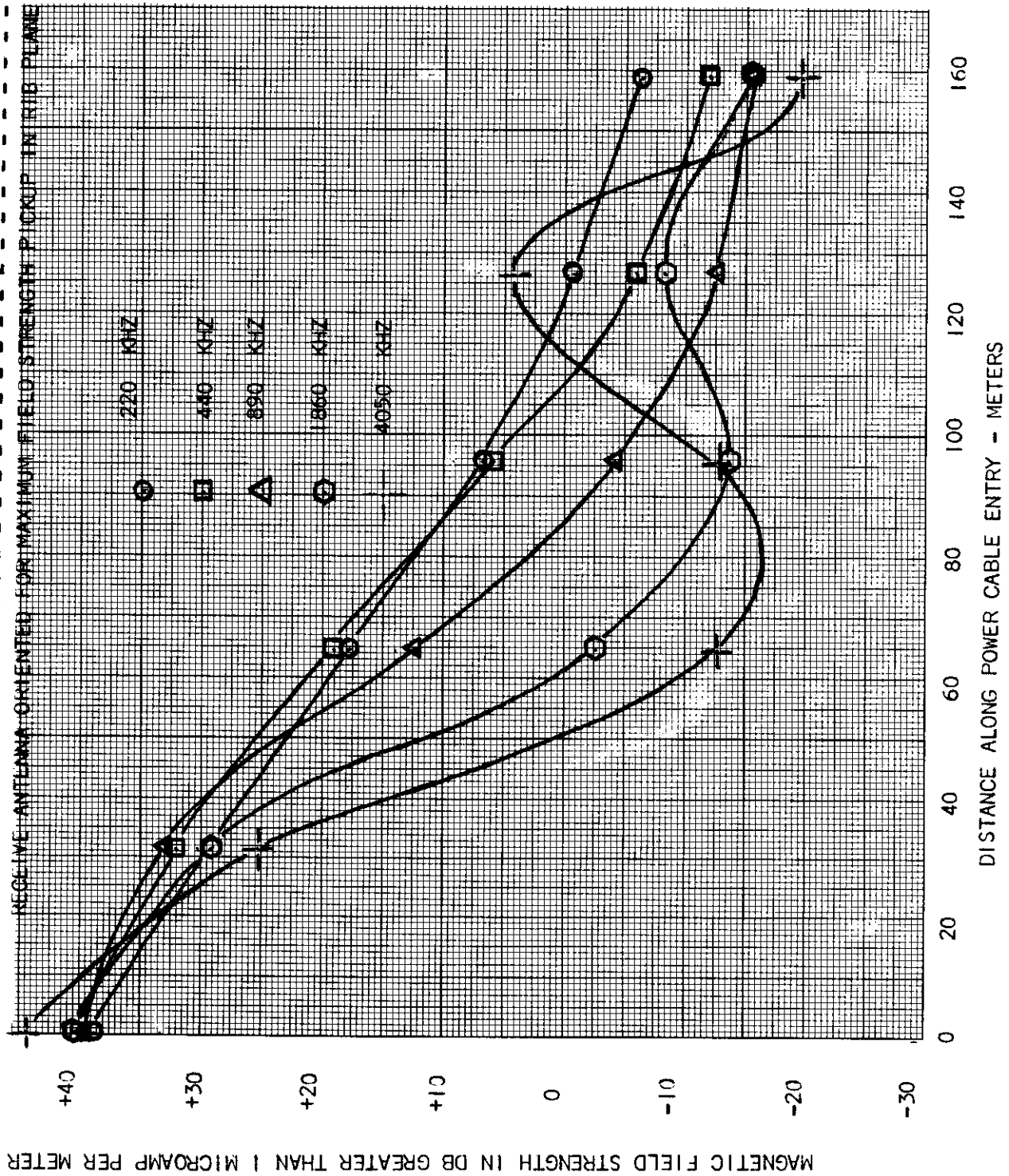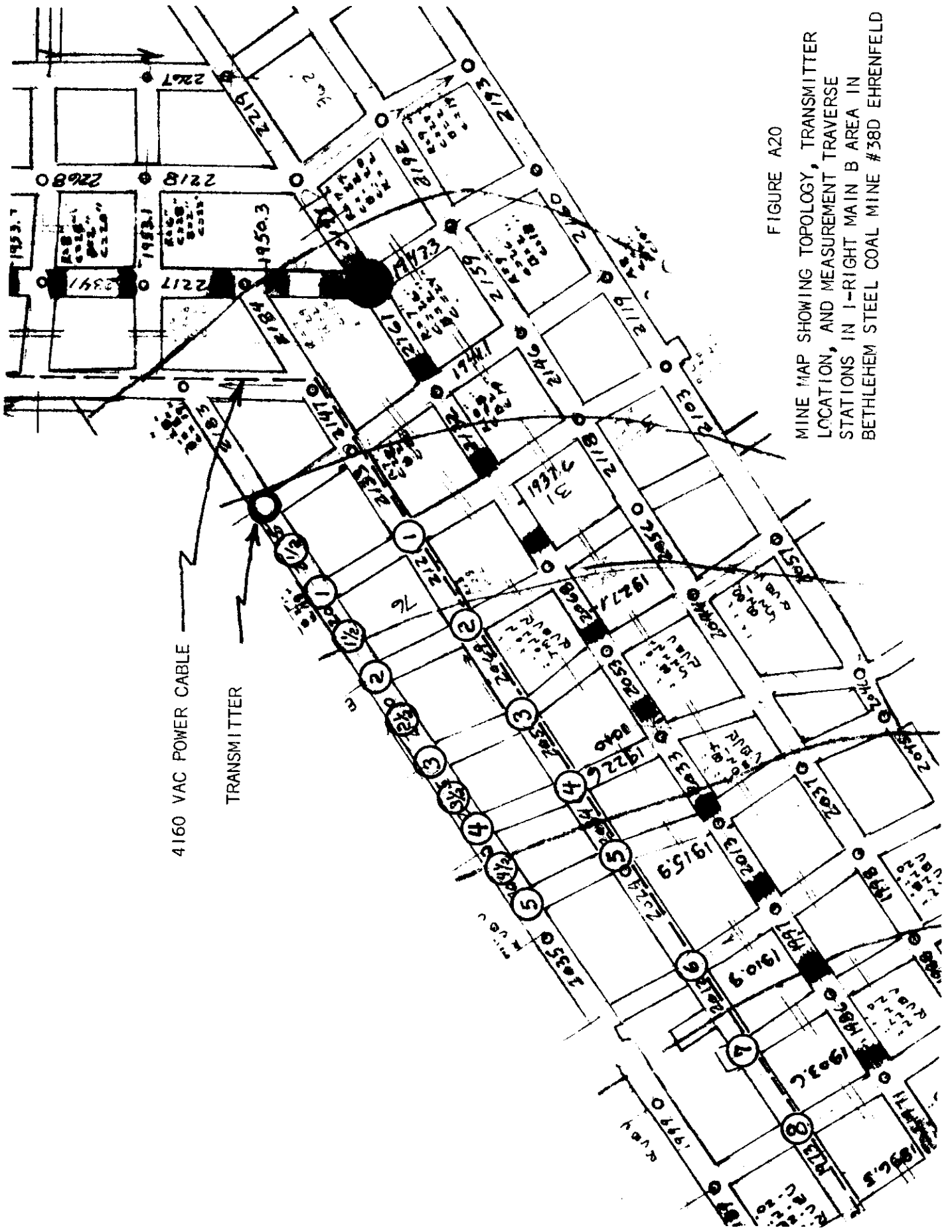
57

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

RECEIVE ANTENNA ORIENTED FOR MAXIMUM FIELD STRENGTH PICKUP IN RIB PLANE

220 KHZ

440 KHZ

890 KHZ

1860 KHZ

4050 KHZ

DISTANCE ALONG POWER CABLE ENTRY – METERS

MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICROAMP PER METER

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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

4160 VAC POWER CABLE

TRANSMITTER

60

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)

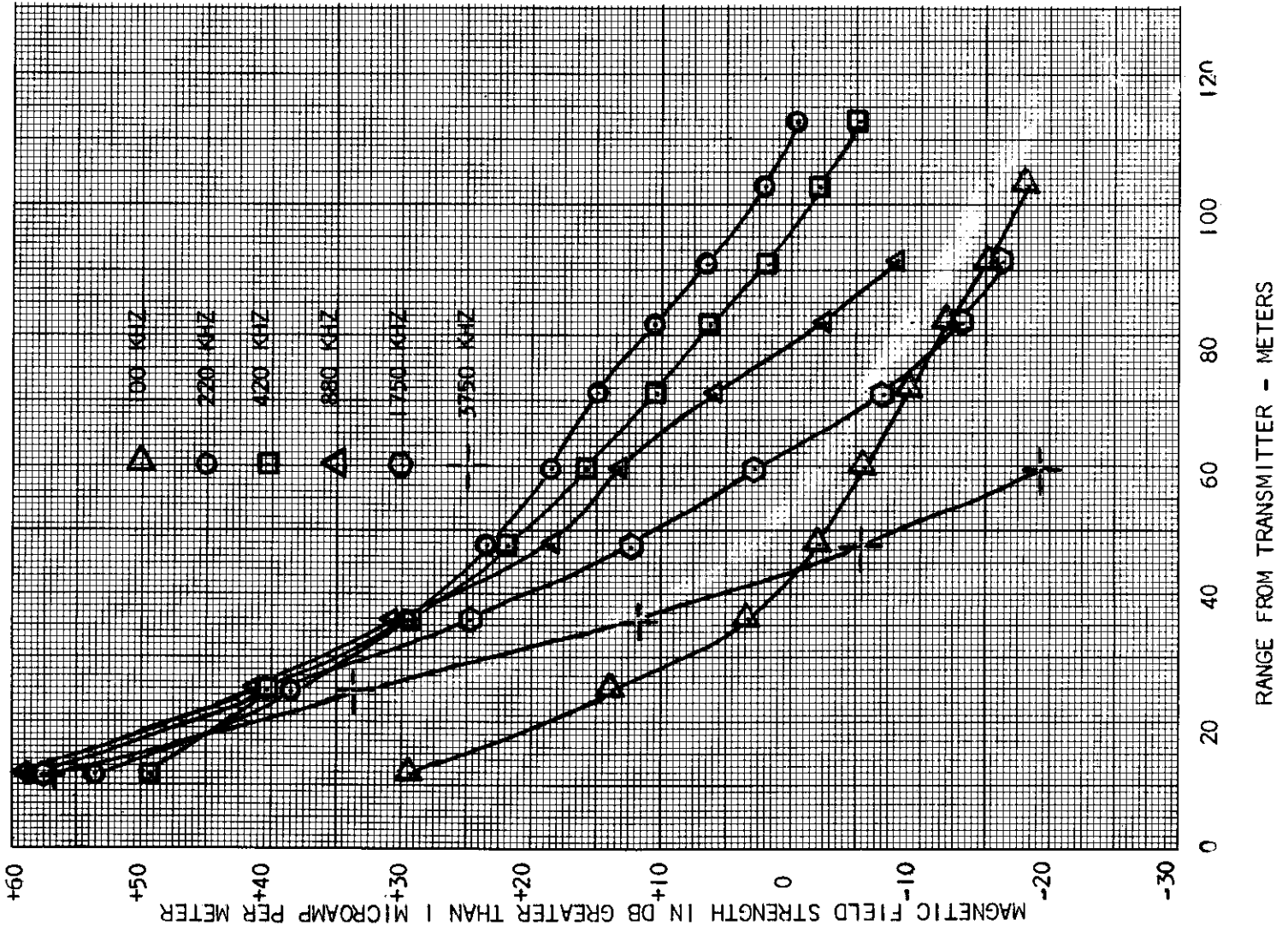NIA = 2.5

COPLANAR HMD ORIENTATION OF ANTENNAS

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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) I-RIGHT MAIN B

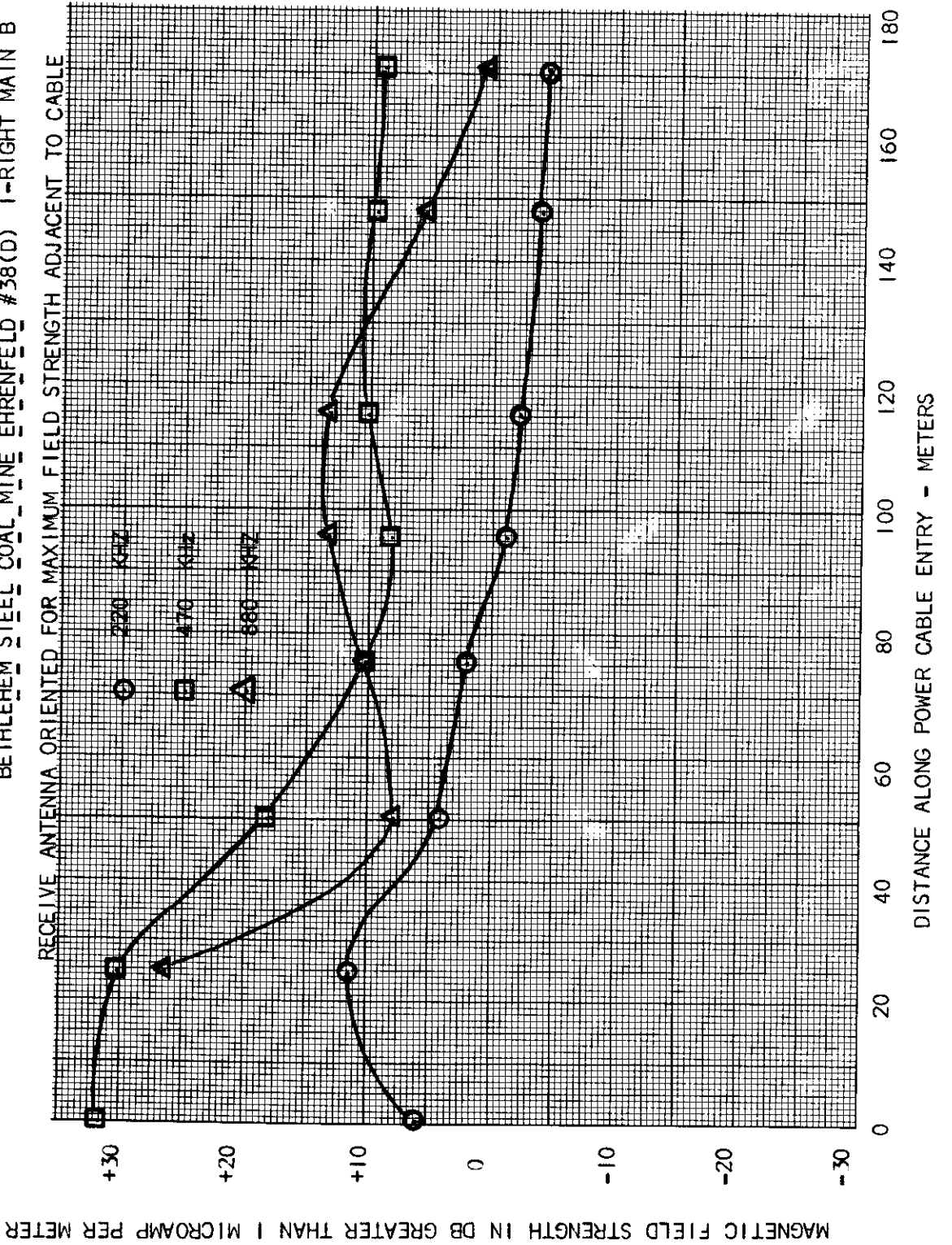RECEIVE ANTENNA ORIENTED FOR MAXIMUM FIELD STRENGTH ADJACENT TO CABLE

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

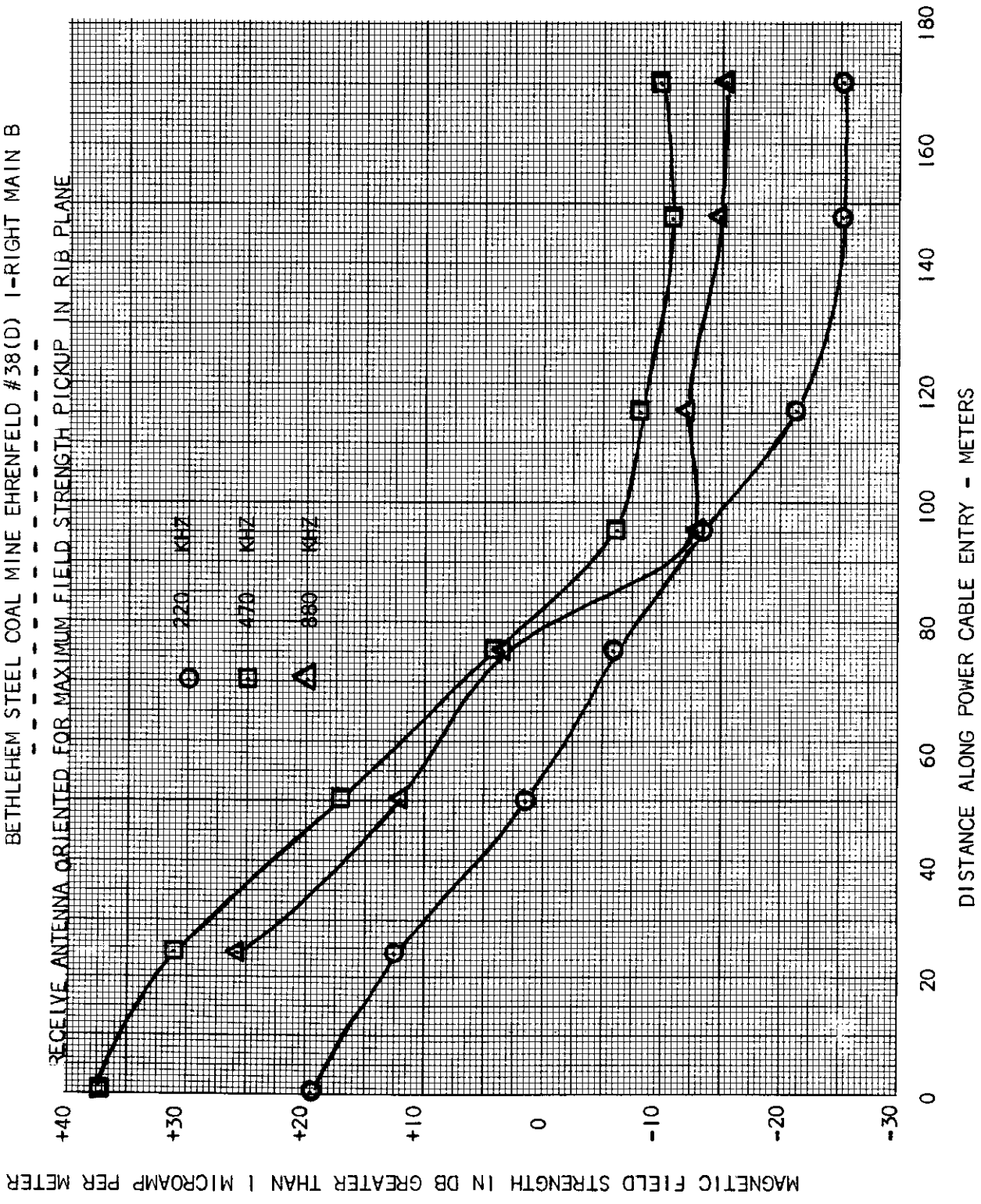RECEIVE ANTENNA ORIENTED FOR MAXIMUM FIELD STRENGTH PICKUP IN RIB PLANE

220 KHZ

470 KHZ

880 KHZ

DISTANCE ALONG POWER CABLE ENTRY - METERS

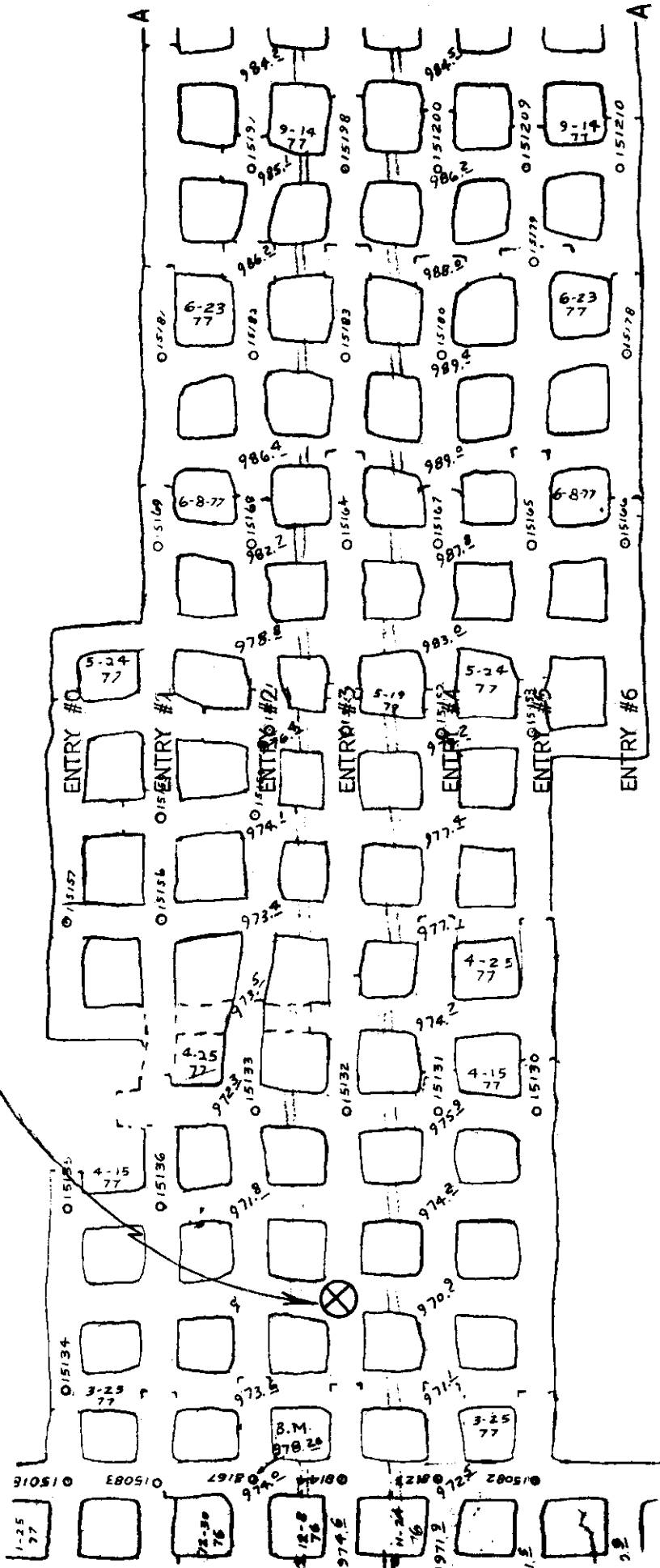MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICROAMP PER METER

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
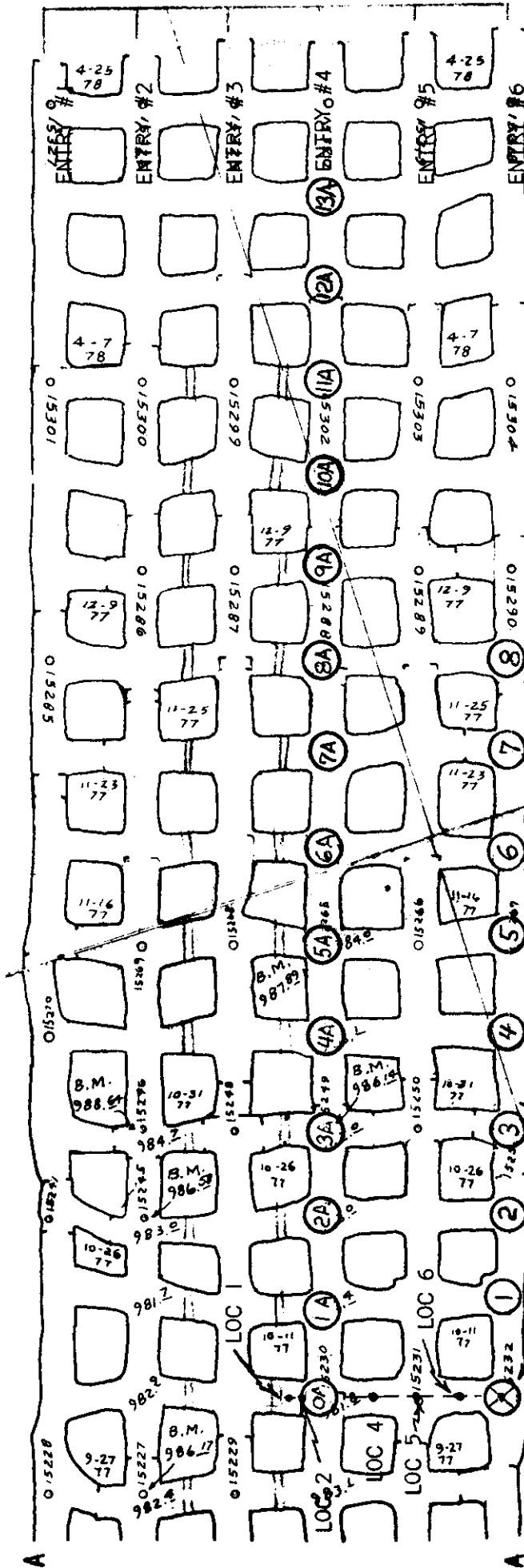
TRANSMITTER LOCATION FOR: QUASI-CONDUCTOR-FREE TESTS (STATIONS 1 - 8)
                          CONDUCTOR-PROXIMITY TESTS   (STATIONS 0A - 13A)
LOCATION 7 FOR CONDUCTOR PROXIMITY POLARIZATION TESTS(LOC 1 - 7)

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

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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

RANGE — METERS

MAGNETIC FIELD STRENGTH IN DB GREATER THAN 1 MICROAMP PER METER
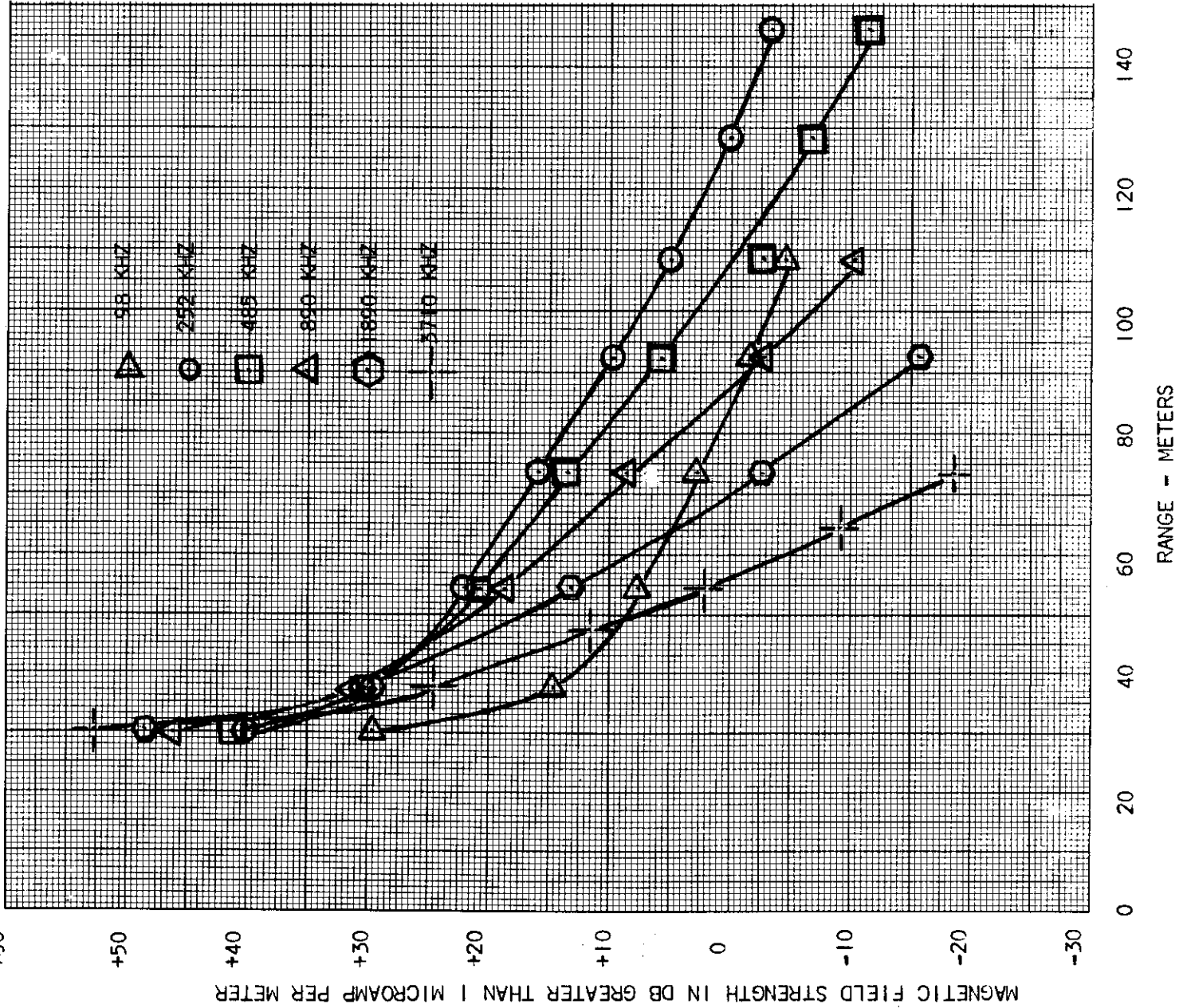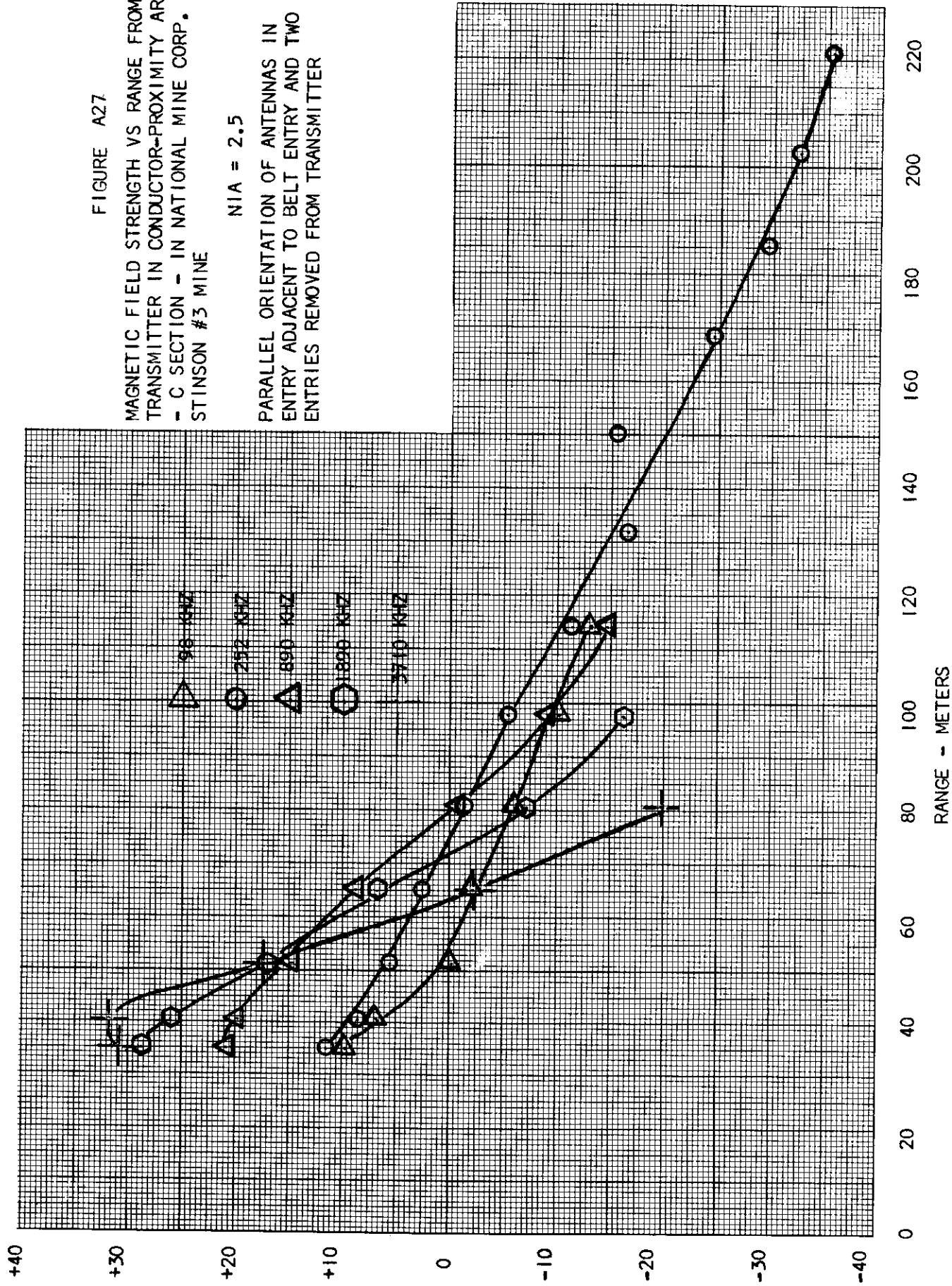
FIGURE A27

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 A28

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
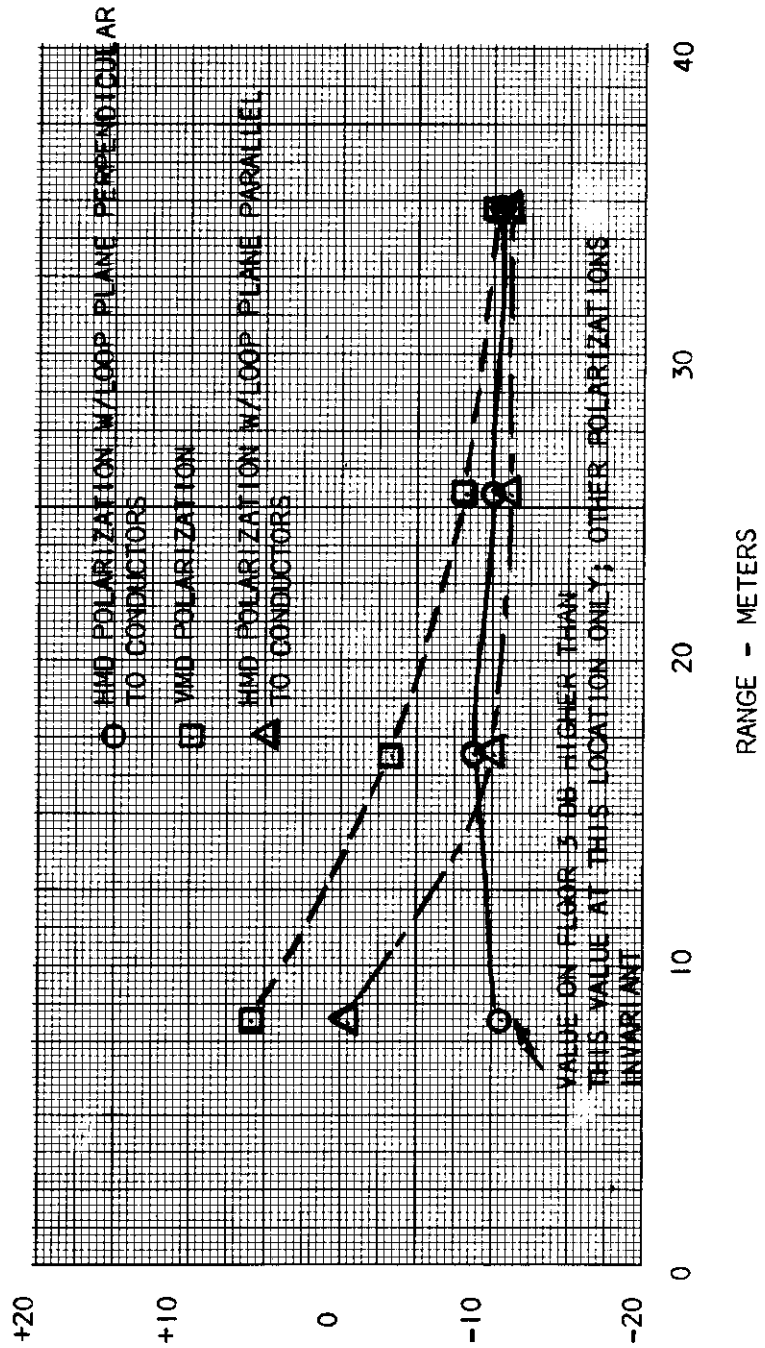
FIGURE A29

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

REFERENCES

(1) T.S. Cory, " Propagation of EM Signals in Underground Mines",
Collins Radio Group, Rockwell International Corporation,
Final Report, Bureau of Mines Contract H0366028, September 1977.

(2) T.S. Cory, "In-Situ Measurement of Coal Seam Conductivity Using
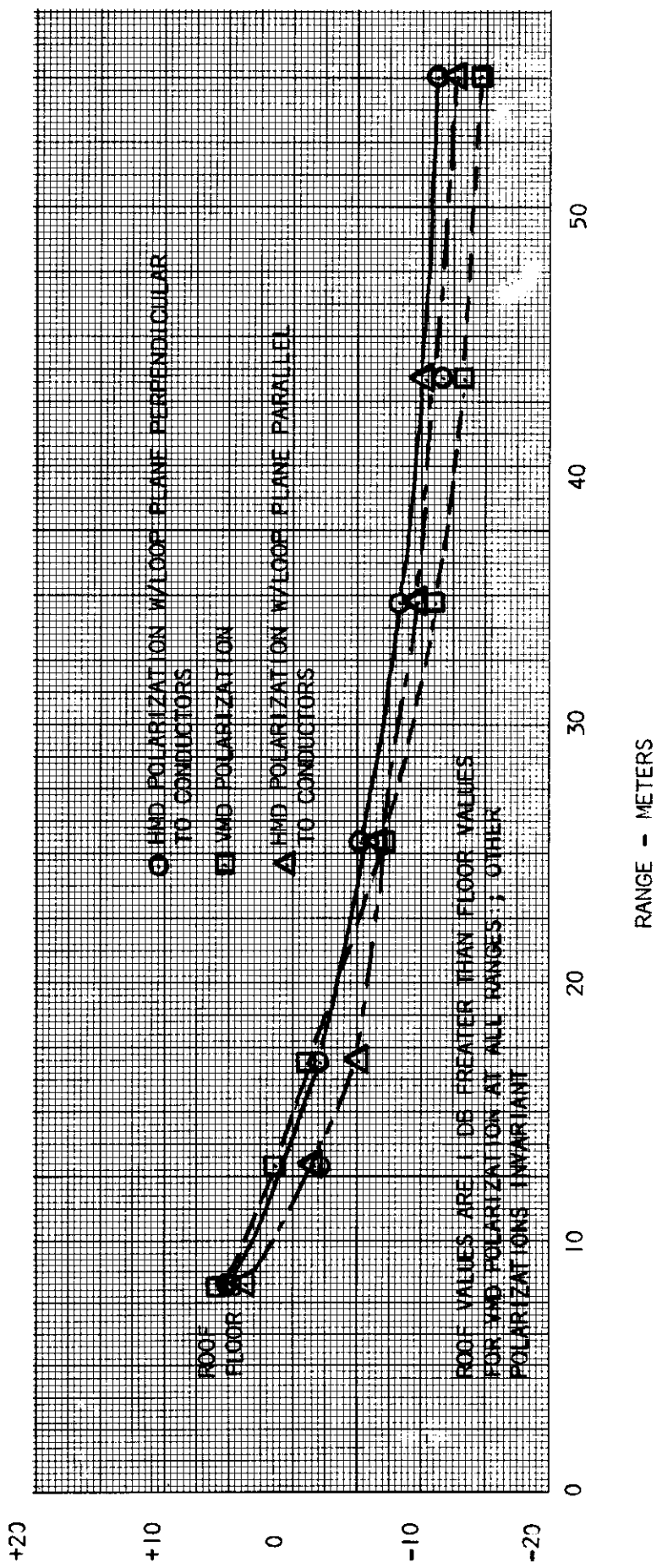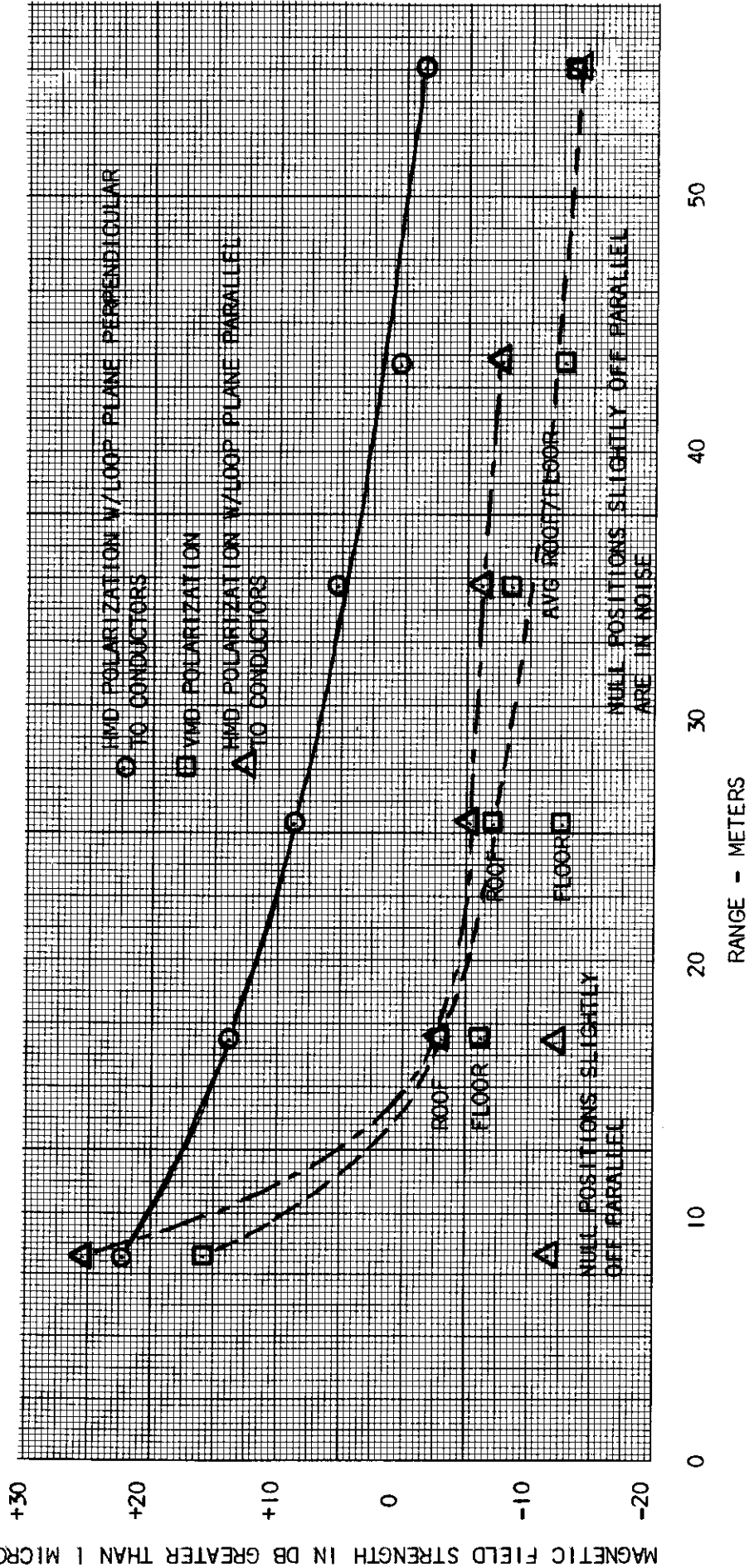a Parallel Wire Transmission Line Method", Collins Groups,
Rockwell International Corporation, Special Technical Report,
Bureau of Mines Contract H0377053, 18 May 1978.

(3) R.L. Lagace, A.G. Emslie, M.A. Grossman, "Modelling and Data
Analysis of In-Mine Electromagnetic Wave Propagation", Arthur
D. Little, Inc., Interim Report, Task Order #4, Bureau of Mines
Contract H0346045, May 1978.

(4) R.L. Lagace, A.G. Emslie, "Analysis of MF Propagation Data from
Margaret #11, Nanty Glo, Ehrenfeld, And Adrian Coal Mines",
Arthur D. Little, Inc., Working Memorandum, Task Order #4,
Bureau of Mines Contract H0346035, May 1978.

(5) R.P. Decker, "Research and Development Contract for Coal Mine
Communication System, Vol. 3 Theoretical Data Base", Collins
Radio Co., Final Report, Bureau of Mines Contract H0232056,
Section 6 pp 6-1 to 6-30, 15 November, 1974.

Summarizing:

(A) W. Bensema, M. Kanda, J.W. Adams, "Electromagnetic Noise
in Robena #4 Coal Mine, NBS Technical Note 654, April 1974,
(work performed under Bureau of Mines Contract H0133005).

(B) J.W. Adams, W.D. Bensema, M. Kanda, Electromagnetic Noise
in Grace Mine", NBSIR 74-388, June 1974, Bureau of Mines
Contract H0133005.

(C) M. Kanda, J.W. Adams, W.D. Bensema, "Electromagnetic Noise
in McElroy Mine", NBSIR 74-389, June 1974, Bureau of Mines
Contract H0133005.

(D) W.D. Bensema, M. Kanda, J.W. Adams, "Electromagnetic Noise
in Itmann Mine", NBSIR 74-390, June 1974, Bureau of Mines
Contract H0133005.

(E) W.W. Scott, J.W. Adams, W.D. Bensema, H. Dobroski,
"Electromagnetic Noise in Lucky Friday Mine", NBSIR 74-391,
October 1974, Bureau of Mines Contract H0133005.

(6) Loc. Cit. R.L. Lagace, A.G. Emslie, M.A. Grossman.

(7) Loc. Cit. R.L. Lagace, A.G. Emslie.

(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.

(9) Loc. Cit. A.G. Emslie, et.al.

(10)T.S. Cory, "Electromagnetic Noise & Propagation In Low-Coal Mines, Summary Data Report - 1, Helvetia Coal Co. Margaret #11 Mine", Collins Groups, Rockwell International Corporation, Bureau of Mines Contract H0377053.

(11)T.S. Cory, "Electromagnetic Noise & Propagation In Low-Coal Mines, Summary Data Report - 2, Upshur Coals Corporation Adrian Mine", Collins Groups, Rockwell International Corporation, Bureau of Mines Contract Ho377053.

(12)T.S. Cory, "Electromagnetic Noise & Propagation In Low-Coal Mines, Summary Data Report - 3, Bethlehem Steel Coal Mine #31 Nanty Glo", Collins Groups, Rockwell International Corporation, Bureau of Mines Contract H0377053.

(13)T.S. Cory, "Electromagnetic Noise & Propagation In Low-Coal Mines, Summary Data Report - 4,Bethlehem Steel Coal Mine #38D Ehrenfeld", Collins Groups, Rockwell International Corporation, Bureau of Mines Contract H0377053.

(14)T.S. Cory, "Electromagnetic Noise & Propagation In Low-Coal Mines, Summary Data Report - 5, National Mine Corp. Stinson #3 Mine", Collins Groups, Rockwell International Corporation, Bureau of Mines Contract H0377053.

SPECIAL TECHNICAL REPORT

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

Technique Development
Technique Application in Two Mines
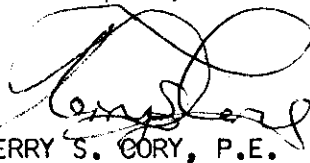
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18 May 1978

1.0 INTRODUCTION

The conductivity of coal seams greatly affects the ability to transmit
radio waves underground to any significant distance. Recent Fieldstrength
measurements and testing of two-way radios at medium frequency in coal
mines under Bu Mines sponsership 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 fieldstrength 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, $\sigma/\omega \epsilon_0$ (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 β/β_o with frequency would
    either be nearly linear (decade increase in conductivity
    for decade frequency increase) or exhibit a region of
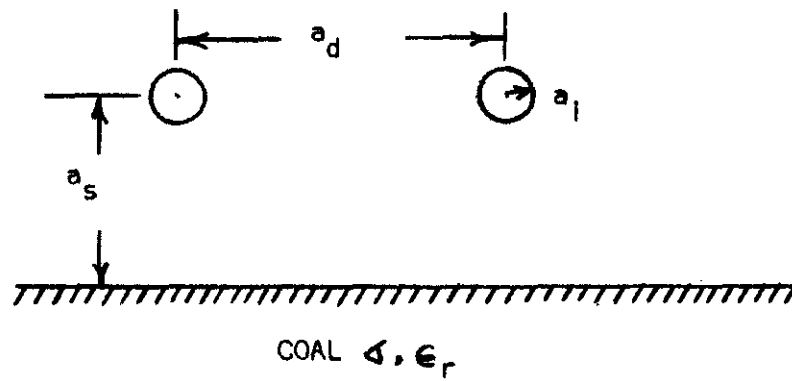   increased negative slope between regions of lesser negative
    slope.

COAL σ, ϵ_r

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 determinental 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, conputing the result explicitly, and
then adjusting the starting value each time until convergence was
obtained.

The expression for the normalized phase constant is;

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

where,

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

where,

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

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

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

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

$$R_{new} = \frac{\frac{\beta}{\beta_o} + R_{old}}{2} \qquad \text{until} \qquad \frac{\beta}{\beta_o} = R$$

within a specified degree of accuracy.

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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 attched 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_o 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

HP-204C SIGNAL GENERATOR
NOMINAL RANGE 20-1000 KHZ

600 OHM BALANCED OUTPUT

STODDARD CURRENT PROBE

PARALLEL WIRE TRANSMISSION LINE
200-300 FEET #14 WIRE SPACED 6 INCHES

LINE END EITHER SHORT CIRCUIT
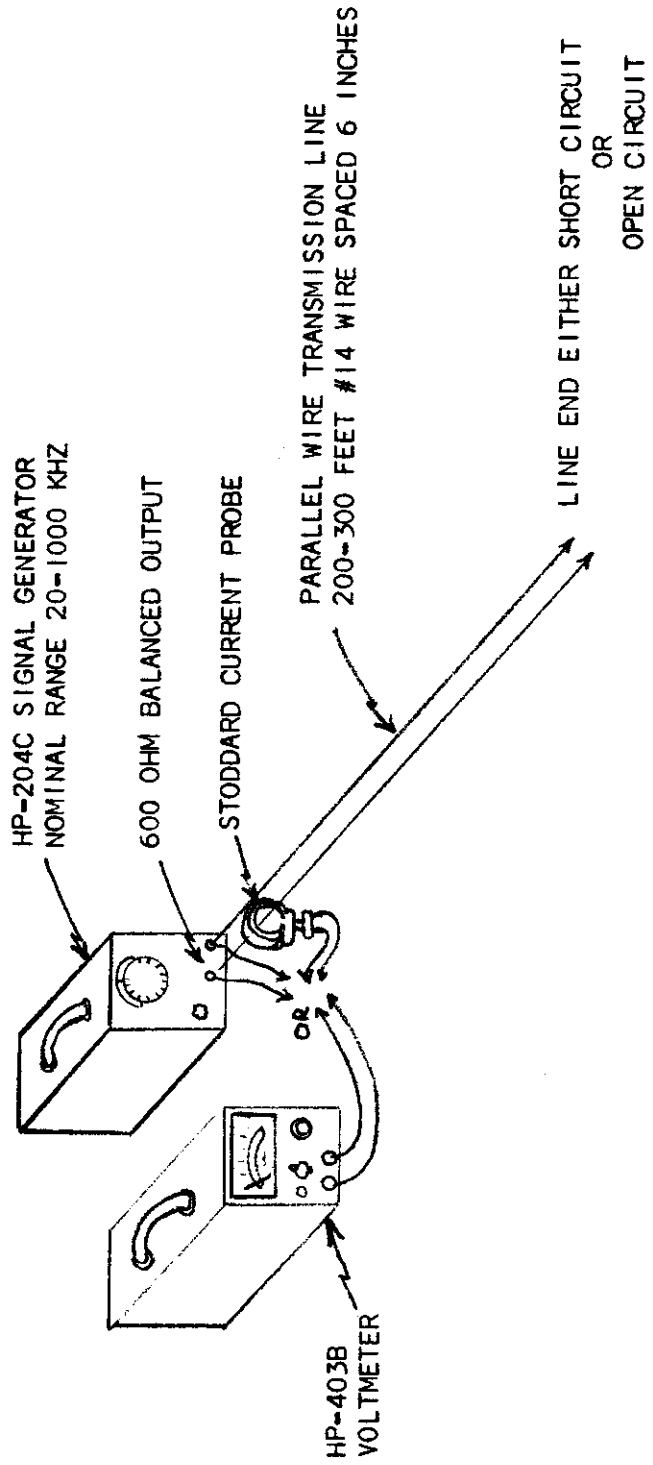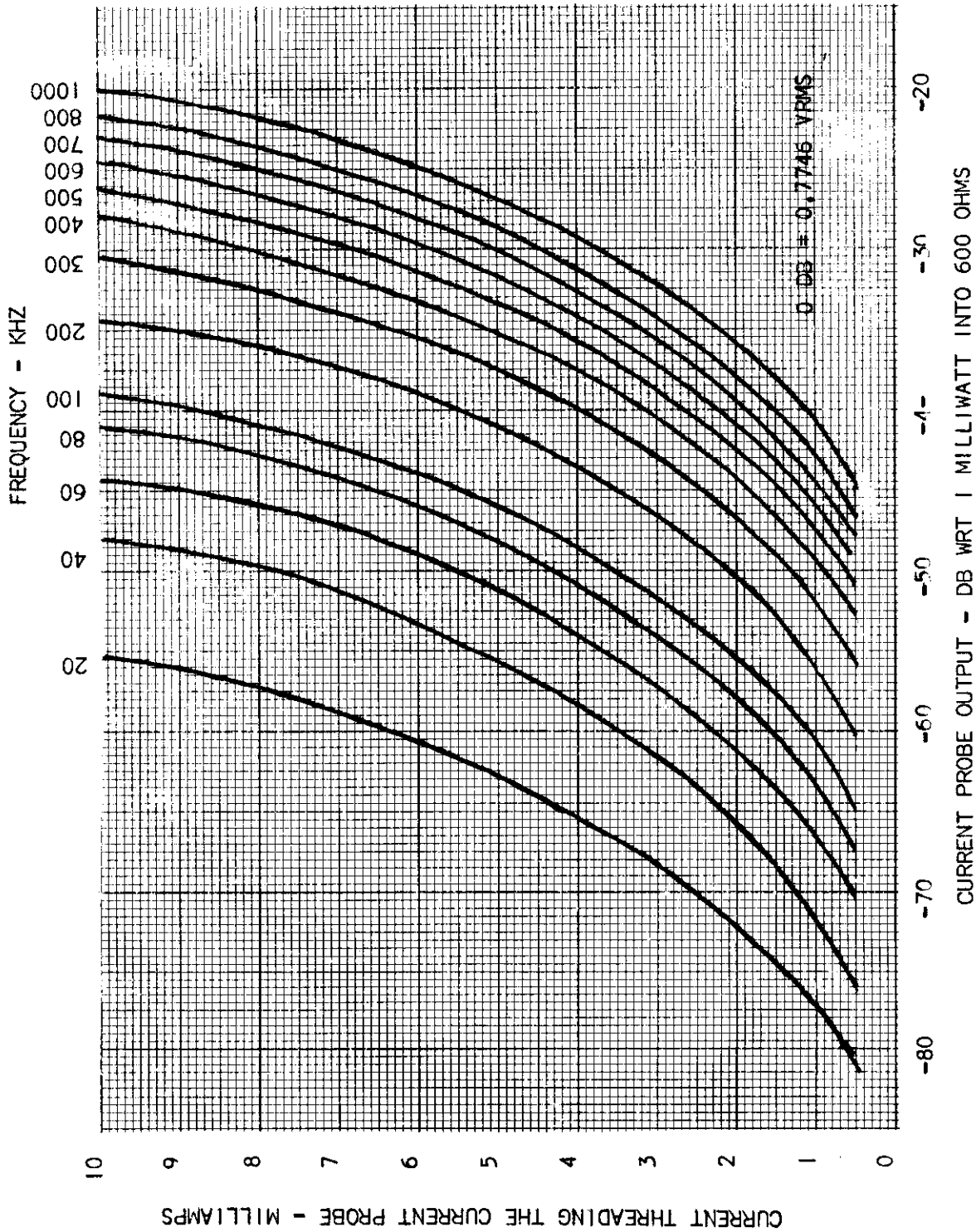OR
OPEN CIRCUIT

HP-403B
VOLTMETER

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.
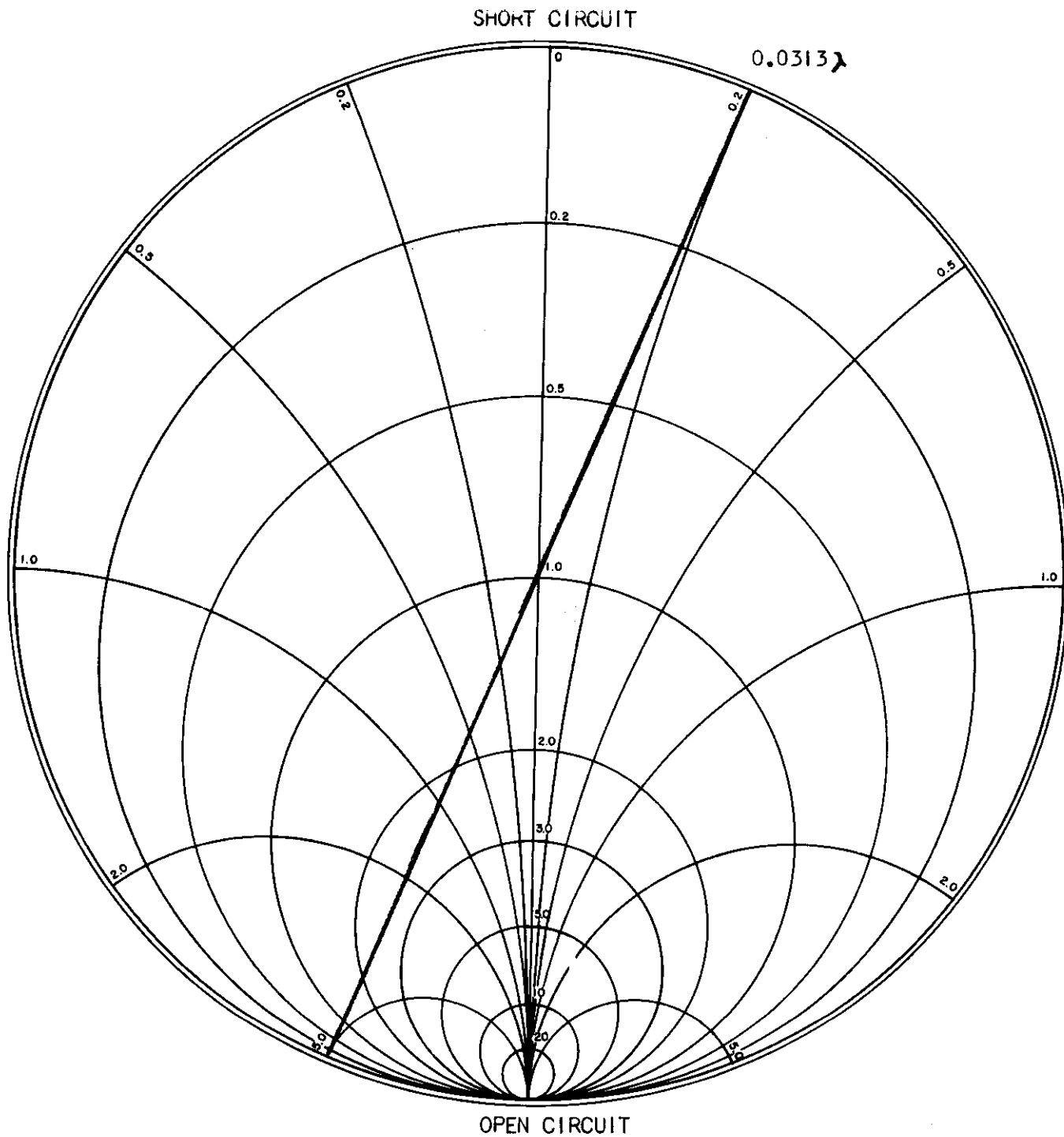
SHORT CIRCUIT

0.0313λ

OPEN CIRCUIT

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 I 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 x 10 and x 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 x 10
and x 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.

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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			$\left\lvert Z_{OC}/Z_{SC}\right\rvert$	B	B_0	B/B_0
	I(MA)	V(VOLTS)	$\lvert Z\rvert$	I(MA)	V(VOLTS)	$\lvert Z\rvert$				
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

FREQ(KHZ)	SHORT CIRCUIT			OPEN CIRCUIT			$|Z_{OC}/Z_{SC}|$	β	β_0	β/β_0
	I(MA)	V(VOLTS)	$|Z|$	I(MA)	V(VOLTS)	$|Z|$				
40	6.7	0.235	35.1	0.90	4.7	5222	148.8	0.0127	0.00817	1.554
60	6.5	0.36	55.4	1.30	4.9	3769	68.0	0.0190	0.01225	1.551
80	7.38	0.58	78.6	1.65	4.9	2970	37.8	0.0257	0.01634	1.545
100	7.10	0.70	98.6	1.42	3.5	2465	25.0	0.0313	0.0204	1.534
200	6.60	1.21	183.3	3.90	4.4	1128.2	6.15	0.0610	0.0408	1.494
300	8.85	2.60	293.8	4.85	3.61	744.3	2.533	0.0895	0.06126	1.461
400	6.65	2.85	428.6	3.76	2.00	531.9	1.241	0.1167	0.08169	1.428
500	5.75	3.15	547.8	5.75	2.22	386.1	0.705	0.1390	0.1021	1.361
600	4.90	3.70	755.1	4.85	1.25	257.7	0.341	0.1660	0.1225	1.355
700	2.37	2.55	1075.9	5.85	1.10	188.0	0.175	0.1870	0.14295	1.308
800	1.80	3.40	1889.0	6.70	0.73	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
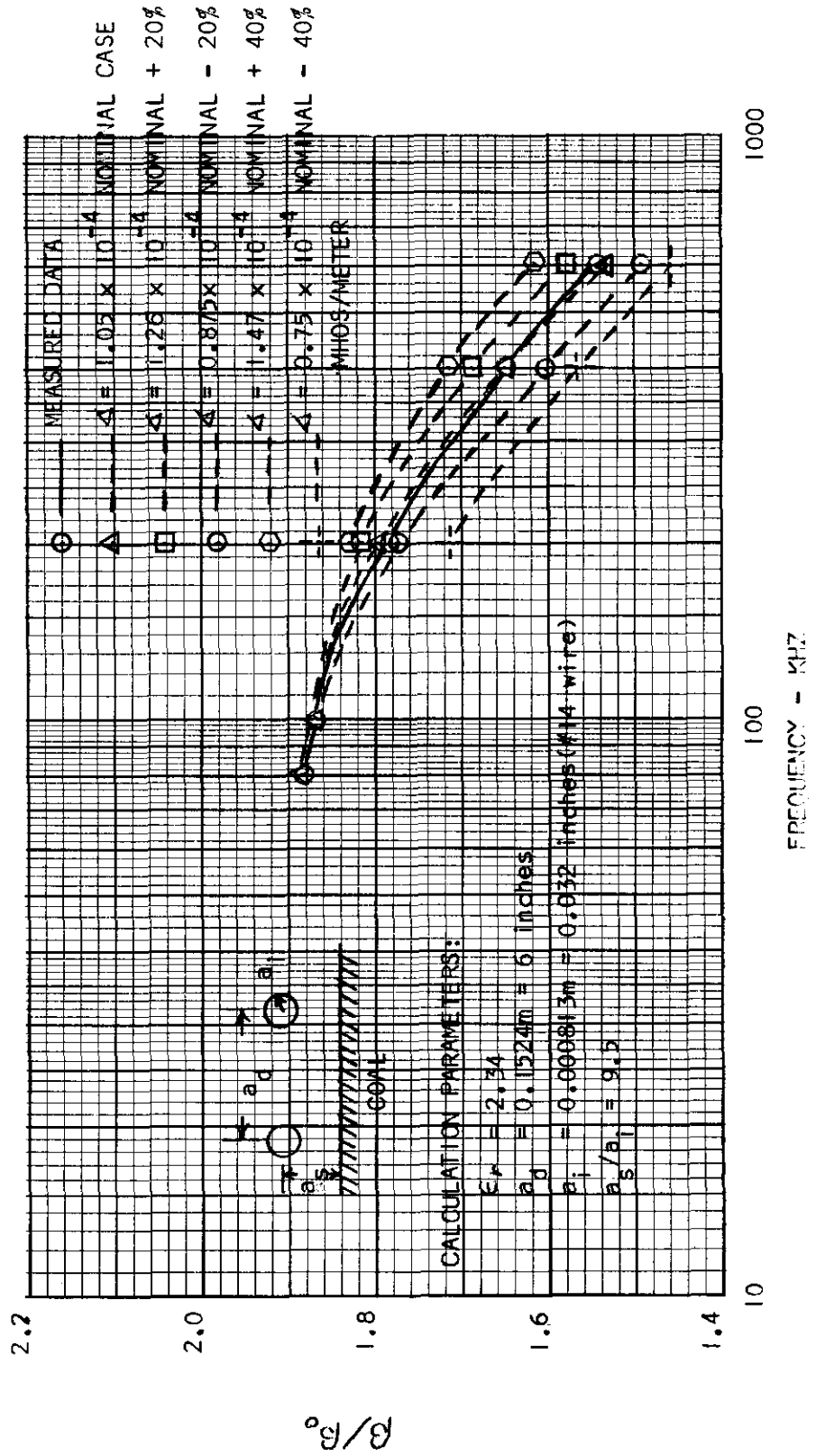
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FIGURE 6

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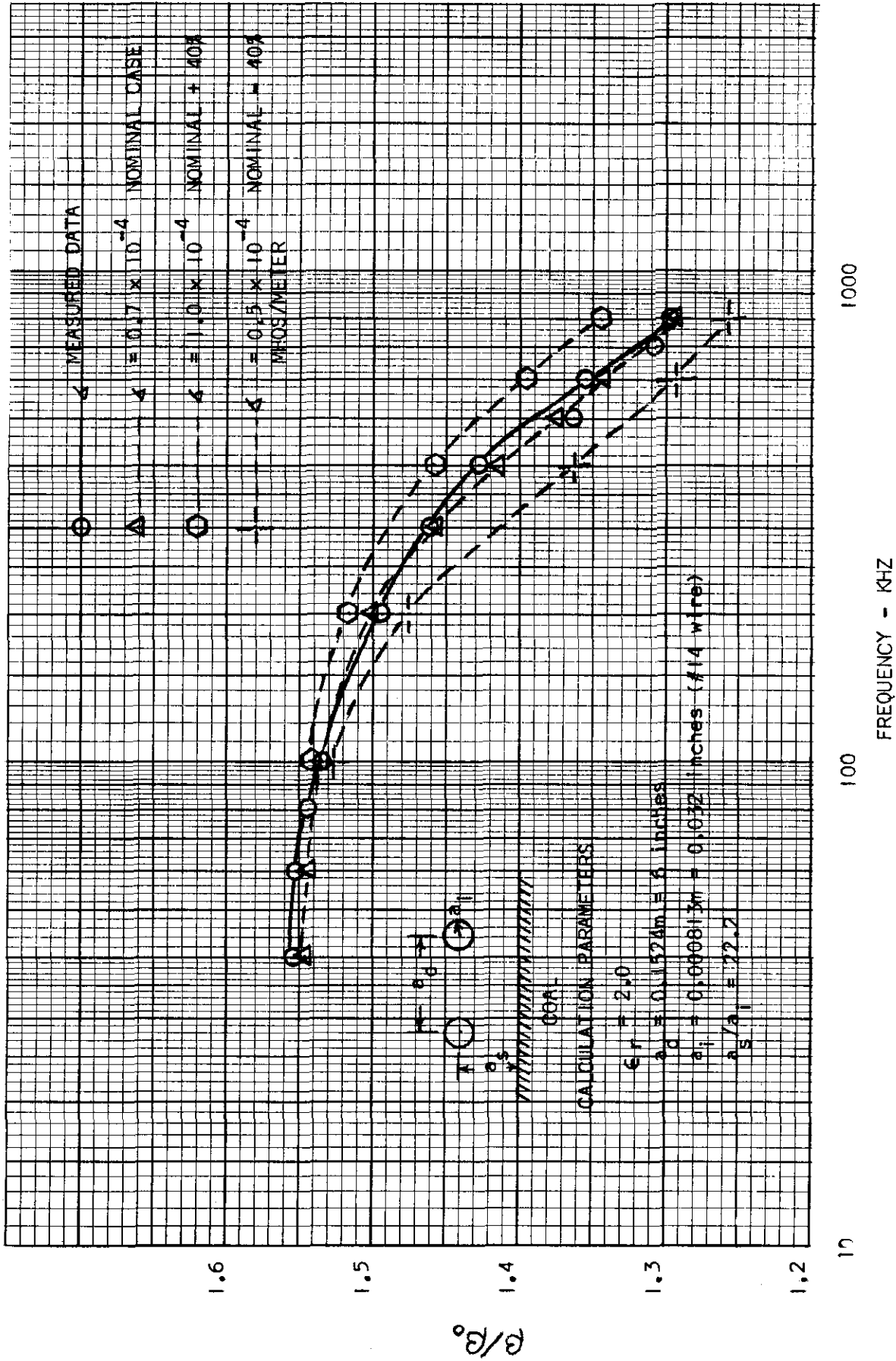VELOCITY CURVE FITTING TECHNIQUE ALONG A BALANCED PARALLEL WIRE LINE

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

Legend:

△ — $= 1.05 \times 10^{-4}$ NOMINAL CASE INVARIANT W/FREQUENCY

○ — — — LINEAR CONDUCTIVITY INCREASE W/FREQUENCY MATCHED TO NOMINAL CASE @ 219 KHZ ×10 INCREASE PER DECADE IN FREQUENCY

□ — · — · LINEAR CONDUCTIVITY INCREASE W/FREQUENCY MATCHED TO NOMINAL CASE @ 219 KHZ × 5 INCREASE PER DECADE IN FREQUENCY

CALCULATION PARAMETERS:

$f_r = 2.34$

$a_0 = 0.1524 m = 6$ inches

$a_i = 0.0008139 = 0.032$ inches

$a_0/a_i = 9.5$

ASSUMED CONDUCTIVITY VARIATION

FREQ(KHZ)	×10 INCREASE $\times 10^{-4}$	× 5 INCREASE $\times 10^{-4}$
80.0	0.383	0.542
132.4	0.634	0.897
219.1	1.05	1.05
362.6	1.738	1.229
600.0	2.876	2.033
	MHO/METER	

Y-axis: β/β_o
2.0 1.8 1.6 1.4 1.2

X-axis: FREQUEMCY – KHZ
10   100   1000

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– 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

FREQ(KHZ)	SHORT CIRCUIT HP-403B READING		OPEN CIRCUIT HP-403B READING	
	CURRENT PROBE	LINE VOLTAGE	CURRENT PROBE	LINE VOLTAGE
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

FREQ(KHZ)	SHORT CIRCUIT HP-403B READING		OPEN CIRCUIT HP-403B READING	
	CURRENT PROBE	LINE VOLTAGE	CURRENT PROBE	LINE VOLTAGE
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