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TECHNICAL SERVICES FOR MINE COMMUNICATIONS RESEARCH

MODELLING AND DATA ANALYSIS OF 50 to 5000 kHz RADIO WAVE PROPAGATION IN COAL MINES

SUPPLEMENT TO FINAL REPORT

Robert L. Lagace — Task Leader
Alfred G. Emslie, Michael A. Grossman

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

USBM CONTRACT HO346045
Task Order No. 4
FEBRUARY 1980

ARTHUR D. LITTLE, INC.
Cambridge, Massachusetts

Arthur D Little, Inc.

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PREFACE

This supplement to the final report is a collection of interim and monthly reports and working memoranda prepared during the course of this program to document the progress, methods and results of the work. The supplement is divided into the self-contained sections briefly described below.

I. SELECTED MONTHLY TECHNICAL LETTER REPORTS - This section is a collection of selected monthly technical letter reports that briefly summarizes the chronological development of the analyses and results, including the different concepts, theoretical approaches, and methods of data reduction and analysis explored, and the discoveries, insights and findings made along the way. More detailed treatments of the key developments and results are presented in the interim reports and working memoranda reproduced in subsequent sections of this supplementary report, and in the separately published final report.

II. BACKGROUND THEORY FOR MEASUREMENT PROGRAM ON MEDIUM AND HIGH FREQUENCY RADIO TRANSMISSION IN COAL SEAMS - Working Memorandum - This working memorandum gives the initial background theory needed to guide the planned measurements and data analyses of this program to describe the propagation of radio waves in coal seams for the frequency range of 50 to 5000 kHz.

III. MODELLING AND DATA ANALYSIS OF IN-MINE ELECTROMAGNETIC WAVE PROPAGATION - Interim Report - This interim report presents detailed treatments of the data analysis and modelling techniques used, and the associated results obtained from conductor-free area propagation data measured by T. Cory in the first set of six coal mines. The mines were located in three high-coal seams; the Pittsburgh seam in northern West Virginia, the Pocahontas No. 3 seam in Virginia, and the Herrin No. 6 seam in Illinois.

IV. ANALYSIS OF MF PROPAGATION DATA FROM MARGARET NO. 11, NANTY GLO, EHRENFELD, AND ADRIAN COAL MINES - Interim Report - This interim report presents detailed treatments of several improved data analysis and modelling methods applied to, and results obtained from, conductor-free area propagation data measured by T. Cory in the second set of four coal mines. These mines were located in three low-coal seams; the Upper Freeport seam in Pennsylvania and West Virginia and the Lower Freeport and Lower Kittaning seams in Pennsylvania. In addition, this report contains a reprint of two papers presented at a Bureau of Mines sponsored EM Guided Waves in Mine Environments Workshop held in Boulder Colorado. One paper describes the three-layer theoretical model and its application to the conductor-free data from the first six mines, while the second paper describes the theory developed for the coupling of loop antennas to a cable in a mine tunnel in a coal seam, and the model's application to data in the vicinity of cables taken at the Margaret No. 11 mine.

V. A METHOD FOR NONINTRUSIVE, IN-SITU MEASUREMENT OF COAL AND ROCK CONDUCTIVITIES IN A COAL MINE TUNNEL - Working Memorandum - This working memorandum briefly describes a possible direct method, and its potential advantages and shortcomings, for performing in-situ measurements of coal and rock conductivities.

VI. MODELLING AND DATA ANALYSIS OF IN-MINE ELECTROMAGNETIC WAVE PROPAGATION FROM 50 to 5000 kHz - Interim Report - This interim report presents a summary comparison of theoretical and experimental results for conductor-free areas in eleven coal mines located in seven coal seams. It also summarizes the findings and their implications for intrinsically-safe, portable radio communications between roving miners.

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I. SELECTED MONTHLY TECHNICAL LETTER REPORTS

SIXTH MONTHLY TECHNICAL LETTER REPORT
COVERING PERIOD FROM
4 OCTOBER TO 31 OCTOBER 1976
CONTRACT NO. HO346045
TASK ORDER NO. 4
C-78453

During this reporting period the following accomplishments were made in each of the individual task areas of Task Order No. 4.

Technical Support on the In-Mine Electromagnetic Wave Propagation Measurement Program

During this period we received the Spectra Associates field report prepared by Terry Cory describing the set of measurements and data taken on the field trip to Consol's Ireland mine, and we began analyzing the data taken in the quasi-conductor-free area. We plotted families of theoretical curves of H vs r with the phase constant, β, as a parameter for several expected values of the attenuation rate α, in the hope that estimates of both α and β could be obtained by noting which curves best matched the data. From α and β, σ_r (rock), σ_c (coal), and K_c (coal) are easily calculated. However, the curves were found to be not discriminating enough to determine β from the available data. Replotting the H vs r curves with α as a parameter for several values of β, allowed more convenient estimates of α to be made, but again not of β. Therefore, attempts to estimate β were abandoned and attention was focused on α only. Though the procedure is somewhat more involved, σ_c and σ_r estimates can be obtained. This method requires the use of an assumed value of the coal relative dielectric constant, K_c, and a systematic search for the combination of σ_r and σ_c values that produce a good fit of the theory to the data.

Preliminary analysis of the Ireland mine data in this manner revealed an attenuation rate α even lower than the very low one previously measured at Ireland in another area. In addition, the data at several frequencies did not behave in accordance with the theoretical model for a conductor-free area, particularly at extended ranges in the vicinity of 1000 ft from the transmitter. Something appeared to be preventing the signal level from decreasing at the attenuation rate expected. Examination of the mine map revealed the presence of a 7200 VAC cable on the floor in the adjacent entry. An approximate coupling analysis indicates that such a cable, even in an adjacent entry, is apparently capable of providing a lower loss alternate transmission path from the transmitter to a receiver located at an extended range in a mine such as this one in which the conductivity of the coal is low. This behavior will prove valuable for extending communication ranges in some mines. The coupling analysis took into consideration the effects of cable images in the roof and floor. Thus, to obtain accurate estimates of σ_r and σ_c, only data at positions closer to the source (where the data are less likely to be contaminated by the presence of the cable) will be usable. Preliminary examination of this close-in data reveals an attenuation rate and coal conductivity that is slightly higher than that found during the previous visit to Ireland. The analysis of these data should be completed during the next reporting period.

In addition, we remained in close contact with Terry Cory regarding the Ireland data reduction and regarding preparations and subsequent measurements made at the Inland Steel mine No. 1 in Sesser, Illinois. A simple substitution calibration measurement for determining the value of the transmit moment of the South African radios was recommended. A discrepancy in the behavior of the Ireland mine field strength levels with changing frequency was noted, which has since been traced to a simple calibration error at two of the frequencies. A simplified model geometry for examining the propagation behavior of MF radio waves along longwall coal faces was formulated for subsequent analysis by J. Wait of NOAA. Finally, we recommended two mines for the next Spectra Associates field trip, Consol's Robinson Run mine and Eastern Associated Coal's Federal No. 2 mine, both in the Pittsburgh seam in West Virginia, but south of Pittsburgh in contrast to the Ireland mine which is located west of Pittsburgh in the West Virginia panhandle.

During the next reporting period we plan to: continue our close communication with Terry Cory and PMSRC, analyze the Inland Steel mine data as well as complete the Ireland mine data analysis, perhaps start analyzing the Robinson Run and Federal mine data, and in the process try to devise better and simpler means of applying theoretical model results to explain the observed behavior of the data.

SEVENTH MONTHLY TECHNICAL LETTER REPORT
COVERING PERIOD FROM
1 NOVEMBER TO 28 NOVEMBER 1976
CONTRACT NO. HO346045
TASK ORDER NO. 4
C-78453

Technical Support on the In-Mine Electromagnetic Wave Propagation Measurement Program

During the November reporting period, major effort was devoted to analyzing the electromagnetic propagation data taken at the Inland Steel No. 1 mine in the Herrin No. 6 coal seam near Sesser, Illinois, and to a lesser extent the data taken at Consol's Ireland mine in the Pittsburgh coal seam near Moundsville, West Virginia. The analyses showed that the signal attenuation rates are about three times more severe (and the coal conductivities about ten times higher) in the Inland No. 1 mine than in the Ireland mine, thereby supporting the need to examine the propagation characteristics of mines in both different and similar coal seams and mining districts. Data from both mines required more analysis than originally anticipated; the Ireland mine data because they were contaminated by the presence of a cable in an adjacent entry, and the Inland No. 1 mine data because at frequencies above about 1 MHz they departed from the behavior expected from a simple three-layer model having frequency independent material characteristics.

The Inland mine data in particular were analyzed by a straight-forward method that provides a separate estimate of attenuation rate and coal/rock conductivities at each frequency based on the measured values of field strength versus distance in a conductor-free area of the mine. The analysis entails: removing the $1/\sqrt{r}$ cylindrical spreading factor from the data, replotting the modified data in the form dB/1μa/m versus meters on linear graph paper, fitting each set of replotted field strength versus distance data by a straight line having a slope α (attenuation rate) and a reference field strength level H_o at a mid-range distance, computing pairs of conductivity values (α_c, α_r) that satisfy a transmission-line-based attenuation rate equation $\alpha = f(\alpha_c, \alpha_r)$ for the graphically determined value of α, calculating field strengths by substituting these conductivity pairs into the theoretical field strength equation for the three-layer propagation model, and finally identifying that pair of conductivity values (α_c, α_r) for which the calculated theoretical field strength matches the data derived reference level at the prescribed mid-range distance.

Using this method of analysis it was shown that the Inland No. 1 mine can be well represented up to about 1 MHz by a simple three-layer model having $\alpha_c = 10^{-3}$ Mho/m and $\alpha_r = 0.2$ Mho/m. However, above 2 MHz the data exhibit increases in attenuation rate far in excess of that predicted by a model having the conductivities derived from the data below 1 MHz. In fact, further investigation revealed that the measured behavior can be closely approximated by a three-layer model having constant conductivity rock, but coal whose actual, apparent, or effective conductivity increases above 1 MHz, changing from about 10^{-3} Mho/m below 1 MHz to 1.8×10^{-3} Mho/m at 2 MHz and 3.5×10^{-3} Mho/m at 4.5 MHz.

Several possible causes for this behavior, which does not allow all the data to be fit with a single pair of constant conductivities, were hypothesized and analyzed in search of an explanation. Several standard references on the measured frequency dependence of the dielectric and conducting characteristics of materials did not include coal. Therefore we plan to contact potential sources of new or unpublished data on coal. Sensitivity analyses showed that even moderate-to-large errors in the values of "assumed" or "known" values of coal dielectric constant Kc, seam height h, and transmitter moment M would not account for the discrepancies. Potential resonance effects caused by coal pillars of dimensions in the vicinity of $\lambda/2$ and λ were considered and discounted. The source coupling factor was modified to include the dielectric constant of the rock K_r, to no avail. The scattering loss produced by the air/coal interfaces at crosscuts was also estimated and found to range from < 1 dB to about a maximum of 3 dB per crosscut instead of the approximately 10 dB per crosscut required at 4.5 MHz. The leaky waveguide mode of propagation (which predominates at UHF) was considered, but found to give excessively high attenuation rates. A periodic structure propagating mode was also postulated for the layout of parallel tunnels typically found along the mains and sub-mains in the coal seam, but was not extensively pursued at this time because of its anticipated low potential benefit to required effort ratio.

At present we do not yet fully understand the reason for the large increases in the signal attenuation rate and the apparent conductivity of the coal at frequencies above about 2 MHz in the Inland No. 1 mine. However, we believe that further detailed investigation of this behavior is of low priority at this time. Though scientifically interesting, it may not be of critical importance to the Bureau's present mine wireless communication program, because this behavior has not yet been encountered in more than one mine, and perhaps more importantly, even if it were understood, such a high attenuation rate at frequencies above 2-3 MHz would make these frequencies unsuitable for the intended application.

The more limited analysis of the Ireland data during this period was concentrated mainly on the 493 kHz and 1988 kHz data, and some 335 kHz SAR data, and was hampered by the presence of cables in the adjacent entry. The 1988 kHz data and 335 kHz SAR data allowed a good fit for the slopes (α) but not for the absolute levels. At 493 kHz, a fit for the slope and level was possible only for the three data points closest to the transmitter where the cable influence was negligible. The findings to date indicate that the coal conductivity σ_c is about 10^{-4} Mho/m at Ireland, as found before, but that the rock conductivity may be considerably lower than the 1 Mho/m estimated from previous data.

A telephone conference meeting was held between the Cory/Spectra/Collins team and PMSRC and ADL staff prior to the measurement team's visit to Consol's Robinson Run mine and Eastern's Federal No. 1 mine. Agreement was reached on the following points. Conductor free area data has the highest priority. Data will be taken down to 50 kHz and up to 4.5 MHz if possible, and at closer distance spacings if the attenuation rates are as high as at the Inland mine. The coplanar antenna orientation is the most important, perpendicular orientations the least, with some data samples of 40° rotations (about the vertical and horizontal axes) from coplanar desirable. If possible, coal samples will be taken, and measurements made through a large block of coal. A sequence of measurements parallel to an isolated cable for several systematically varied transmitter and receiver separations from each other and the cable will be performed if possible. Discussion of the Robinson Run mine measurements and data was also conducted between T. Cory and R. Lagace of ADL via telephone during the week of the above mentioned field trip.

During the December reporting period, we plan to complete the analysis of the data from the Ireland and Inland mines, and to receive and analyze the data from the Robinson Run and Federal No. 1 mines, in preparation for a results presentation and program review meeting scheduled for mid-December. We also plan to continue to look for simpler and better ways to analyze and explain the behavior of the data, and to continue close collaboration with T. Cory and PMSRC staff.

EIGHTH AND NINTH MONTHLY TECHNICAL LETTER REPORTS
COVERING PERIODS FROM
29 NOVEMBER TO 31 DECEMBER 1976
AND
1 JANUARY TO 30 JANUARY 1977
CONTRACT NO. HO346045
TASK ORDER NO. 4
C-78453

Technical Support on the In-Mine Electromagnetic
Wave Propagation Measurement Program

During the December and January reporting periods, substantial progress was made in analyzing the mine propagation data, in devising improved and simpler methods of analysis, and in documenting the results of this work. Analysis of the quasi-conductor-free area propagation data from both the Consolidation Coal Ireland mine and the Inland Steel No. 1 mine was completed. In addition, similar data were received and analyzed for Consolidation Coal's No. 95 mine (Robinson Run) and Eastern Associated Coal's Federal No. 1 mine. Both these latter mines are located in Northern West Virginia in the Pittsburgh coal seam. It was found that the signal propagation behavior in the second pair of mines was similar to the behavior in the Ireland mine which is also in the Pittsburgh seam. Namely, signal attenuation rates in the Pittsburgh seam mines were found to be lower by a factor of about three than the rates found in the Inland No. 1 mine in the Herrin No. 6 seam over the frequency range from about 100kHz to 2MHz. It now appears that plots of the attenuation rate, α, versus frequency may be one of the most easily obtainable and useful means of classifying and comparing the propagation characteristics of different mines and seams.

Tabulated below is a summary of the coal and rock conductivity estimates for each of the mines analyzed to date. Using these values of conductivity, corresponding estimates of magnetic field strength versus range can be computed, at frequencies of interest, from the three-layer model theoretical equations.

Conductivity Estimates

Mine	Seam	Seam Thickness h(m)	Coal σ_c (Mho/M)	Rock σ_r (Mho/m)
Robinson Run(#95)	Pittsburgh	1.5	0.3×10^{-4}	0.085
Federal No. 1	"	2	0.26×10^{-4}	0.084
Ireland (II)	"	2	1.0×10^{-4}	0.054
Ireland (I)	"	2	{1.4×10^{-4}	0.3 }
			2.0×10^{-4}	1.09
Inland No. 1	Herrin No. 6	3	10×10^{-4}	0.22

Ireland I and II refer to measurements taken in two different parts of the Ireland mine on two different occasions, the II data representing the most recent measurements. It should also be noted that sedimentary rock and coal typically exhibit anisotropic electrical properties; therefore in the strict sense, σ_c represents the vertical or transverse coal conductivity, whereas σ_r represents the horizontal or longitudinal rock conductivity. In general, longitudinal values for a material are higher than its transverse values.

As was the case for the first two mines analyzed, it was necessary to devise still another method to analyze the data from the latter two mines. The previous method (described in our November monthly report) using the data-derived attenuation rate, α , in concert with a reference field strength, H_o (r_o), was found to be too restrictive to be successfully applied to these new data. Thus, we replaced this method with another one which is not only simpler but appears to be more universally applicable to the analysis of mine propagation data.

This new data analysis method relies mainly on the behavior of the data-derived attenuation rate, α , a quantity that can be reliably obtained from the field strength versus distance data taken in conductor-free areas, and which is not dependent on the source/mode coupling factor. The attenuation rate α at each frequency is obtained as in the previous method, and a family of "constant α" curves are then plotted in the form σ_r versus σ_c. Each data-derived value of α is used to generate a σ_r versus σ_c curve from the transmission line attenuation rate equation $\alpha = F(\sigma_r, \sigma_c, f)$ A point $(\hat{\sigma}_r, \hat{\sigma}_c)$ representing a kind of "center of gravity" of the intersections of the family of curves is then chosen by visual inspection of the plot. This point $(\hat{\sigma}_r, \hat{\sigma}_c)$ defines the experimentally determined values of rock and coal conductivity for that mine. This method is applicable to mines in which the rock and coal conductivities can be treated as frequency independent quantities over the frequency range of interest. Theoretically, the family of constant α curves should intersect at a common point $(\hat{\sigma}_r, \hat{\sigma}_c)$ representing the unknown conductivities of the coal and rock. In practice, variations from the model, experimental errors, and graphical analysis errors smear this point into an intersection "region". Using these values $(\hat{\sigma}_r, \hat{\sigma}_c)$, the magnitude of the magnetic field strength versus range can then be computed at each frequency of interest. Comparison of theoretical and experimental field strength results for the Robinson Run and Federal #1 mines reveal a generally favorable overall agreement with regard to form and relative variations, with some differences in absolute level yet to be resolved.

The experimentally determined set of conductivities $(\hat{\sigma}_c, \hat{\sigma}_r)$ can also be substituted back into the attenuation rate equation $\alpha = F(\sigma_r, \sigma_c, f)$ to generate an "average" α versus f curve representing the attenuation rate variation with frequency for that mine. Comparison of such curves with the corresponding data-derived values of α at each measurement frequency in the Robinson Run and Federal No. 1 mines reveals these curves to be very reasonable "best fit" curves to the α data points, as it should be.

This good agreement provides yet a third method of estimating the rock and coal conductivities; namely, finding the pair of (σ_r, σ_c) values (by a constrained trial and error substitution procedure) that gives a reasonable "best fit" theoretical $\alpha = F(\sigma_r, \sigma_c, f)$ versus f curve to the data-derived values of α. This third method was used with success on the Ireland mine and Inland No. 1 mine data, data which did not produce a definitive intersection region in the method that uses the family of "constant α", σ_r vs σ_c curves.

All of these results and methods of analysis were presented at the scheduled program status review and planning meeting held at PMSRC, Bruceton, PA in mid-December. In attendance were R. Lagace and A. Emslie of ADL, T. Cory of Spectra Associates, W. Laubengayer and L. Wilson of Collins Radio, and H. Dobroski of PMSRC. A twenty-five page handout of results consisting of twenty-two graphs and three summary sheets was distributed to the attendees by ADL and discussed. Priorities were also established for the measurements at the next two mines. Namely, the primary objective will be to perform measurements in so-called "quasi-conductor-free" areas, and the secondary objective will be to perform measurements along selected paths parallel to simple-geometry mine conductor systems. Preference will be given to locations adjacent to or through large coal blocks in the quasi-conductor-free areas when possible. Section signal mapping measurements will not be performed at these mines.

As a result of discussions at this meeting and afterwards, the selection criteria for the next two mines were established and several candidates were identified. One mine will be selected in the Herrin No. 6 seam from candidates in several high production counties north of the county in which the Inland mine is located, to check the applicability of the Inland results to another mine in the Herrin No. 6 seam. The other mine (the first of the two to be visited) was selected from candidates in several high production counties in the Southern West Virginia - Eastern Virginia area, in a completely different seam, to obtain another sample of the propagation variability expected in different coal seams. The mine selected is the Island Creek VP #1 mine, in the Pocahontas #3 coal seam, in Buchanan County, Virginia and measurements were conducted there by the Spectra Associates/Collins Radio measurement team in mid-January.

During the rest of this reporting period our efforts were devoted mainly to documenting the theory, analysis techniques and results to date in the form of a draft interim report that will eventually be incorporated as part of the final report for this task. As part of this effort, we also derived a more general and complete theoretical expression for the source/mode coupling factor, and proved that the accuracy of the transmission line approximation to the wave mode solution is within 0.3% even at the lowest frequency of 57kHz. We expect the draft of the interim report to be completed in February. This report will also include plots showing the expected variations of signal strength with frequency at two communication ranges of present interest by the Bureau, 400m(1312ft) and 200m(656ft), for several values of rock and coal conductivity that span the values found in mines to date. Such plots, when compared with similar curves of receiver and mine noise levels versus frequency, will reveal which frequencies offer the most favorable performance at each range in mines having different propagation and noise characteristics, and the source strength required to achieve a specified level of performance at these frequencies.

Finally, summary notes from R. Decker of Spectra Associates describing results of his three-layer and five-layer model computer analyses of the mine data were also received and briefly reviewed during this period. A second set of summary notes was received at the end of this reporting period.

During the February reporting period we plan to complete the draft interim report on the first four mines, receive and analyze the data from the Island Creek VP #1 mine, and to continue close collaboration with T. Cory of Spectra Associates and H. Dobroski of PMSRC.

TENTH THROUGH SEVENTEENTH COMPOSITE MONTHLY
TECHNICAL LETTER REPORT
COVERING PERIOD FROM
31 JANUARY TO 30 SEPTEMBER 1977
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Technical Support on the In-Mine Electromagnetic
Wave Propagation Measurement Program

During the reporting period substantial progress was made both in the analysis of the in-mine EM wave propagation data and in the preparation of an interim summary report. The data from the remaining two mines were analyzed, and the consolidated results from all six high-coal mines have been plotted up in over 60 graphs which are being incorporated into an interim summary report which is near completion.

During February, the effort was concentrated mainly on: analysis of the in-mine data taken by Spectra Associates at the Island Creek Coal VP #1 mine in the Pocahontas No. 3 coal seam in Buchanan County, Virginia; collaboration with T. Cory of Spectra Associates regarding the data taken at the VP #1 mine and previous mines; and preparation of theoretical curves indicating the variation of field strength as a function of frequency with distance and coal/rock conductivities as parameters.

The VP #1 data indicated that the Pocahontas No. 3 seam has a lower signal attenuation rate than the Herrin No. 6 seam, but a higher attenuation rate than the Pittsburgh seam. Analysis showed that this occurred in spite of a coal conductivity less than that of the Pittsburgh seam, because the rock conductivity was also significantly lower than that of the Pittsburgh seam, thereby allowing more energy to escape from the coal seam waveguide. Generally favorable overall agreement was found between the theoretical and experimental magnetic field strength versus distance curves, both with regard to form and relative variation with frequency. However, there remain some discrepancies between theoretical and experimental absolute values over some frequency ranges, the theory generally predicting somewhat higher values than those measured, as was observed during the analysis of the Robinson Run and Federal No. 1 mine data. These discrepancies could be attributed to some limitations in the simple theoretical model used, and/or to some unaccounted for differences or variations in equipment calibration, experimental procedures, or equipment malfunction. As a result of telephone discussions with T. Cory of Spectra Associates regarding the latter, and further thought about the former, we conclude that both factors appear to be contributing to the differences observed between some of the predicted and measured absolute levels of field strength.

We also reviewed the second installment of Spectra Associates' three-layer model and five-layer model computer analyses and comparisons with data, and subsequently compared the theoretical results of R. Decker of Spectra Associates and those of the ADL model using Decker's derived values of conductivity. The ADL results were found to be generally higher than the Spectra results, but in closer agreement with the slopes of the data curves than the Spectra results.

Finally, the ADL theoretical model was used to generate plots of signal strength versus frequency for two ranges of interest, 400 m (1312 ft.) and 200 m (656 ft.) for the following ranges of coal and rock conductivity ($3 \times 10^{-5} \leq \sigma_c \leq 10^{-3}$ mho/m, $3 \times 10^{-2} \leq \sigma_r \leq 1$ mho/m). These plots were compared with a representative curve of rms mine noise versus frequency to illustrate the procedure of identifying the most favorable operating frequency as a function of range, mine conductivities, and noise conditions. These results will be presented in the interim summary report.

During March, the effort was concentrated mainly on the analysis of the data taken at the Peabody No. 1 mine in the Herrin No. 6 seam in Illinois, and the consolidation of signal attenuation rate results from all six mines in time for use in an Information Circular being prepared for a mine communications technology transfer seminar.

The data from the last of the six mines, the Peabody No. 10 mine, were analyzed and found to be better behaved than the data from both the VP No. 1 mine (Pocahontas No. 3 seam) and the Inland No. 1 mine (Herrin No. 6 seam). The results confirmed the high signal attenuation rate behavior experienced in the Inland No. 1 mine in the same seam. Furthermore, the analysis revealed Peabody No. 10 to be a mine with an even higher signal attenuation rate and a coal conductivity 2.5 to 4 times that of the Inland No. 1 mine. Generally favorable agreement was also found between theoretical and experimental field strength behavior with distance and frequency. Aspects of the measurements, data, and mine environments to date were discussed with T. Cory of Spectra Associates via telephone.

The signal attenuation rates, α, taken from all six mines expressed in dB/100 ft. and plotted versus frequency in a single graphic presentation as shown in Figure 1. (This data consolidation was completed in time for use in a more simplified form in the Mine Communications Technology Transfer IC on Section/Place Communications.) As suspected, the limited sample of data to date reveals that different seams appear to exhibit distinctly different signal attenuation rates, and with the present exception of the extremely high-loss Herrin No. 6 seam, the variation between mines within a seam is less than the variation between mines in different seams. If this property is further supported by tests in the remaining four mines to be measured, the easily obtainable attenuation rate may become the most convenient and useful predictor of expected MF mine wireless radio performance for mines in the major coal seams. Figure 1 also indicates that the important Pittsburgh seam is the most favorable seam investigated to date, and that the attenuation rate is so severe in the Herrin No. 6 seam that radio performance is likely to be acceptable only when in the vicinity of metallic mine conductors.

Table I presents the corresponding values of coal and rock conductivity derived for each of the mines measured. These values are used to generate the theoretical magnetic field strength versus range curves from the three-layer model field expressions. Figure 2 illustrates a set of theoretical curves generated for the VP No. 1 mine in the Pocahontas No. 3 seam while Figure 3 shows the similarity of the corresponding experimental data measured by Spectra Associates. Similar curves for all the mines have been included in the interim summary report.

Finally, initial consideration was given to obtaining a semi-empirical estimate of the mode coupling factor or the correction factor required as a function of frequency to provide a closer match to the absolute value of the data. Such a semi-empirical relationship might also suggest a simple physical explanation or relationship for the observed differences, and might also reveal a variation between coal seams similar to that exhibited by the attenuation rate.

During April, May and June, the effort was reduced to a low level consisting primarily of minor administrative matters and the preliminary formulation of ideas on other methods of mode coupling and data analysis, while awaiting a contract modification for additional technical support to PMSRC on this task order.

During July, August, and September effort resumed at a moderate pace, and was related primarily to simple semi-empirical methods for analyzing differences between theoretical and experimental results; revisions and additions to the interim summary report; interaction with other Bureau-sponsored investigators, and initial planning of an EM Guided Wave Workshop to be sponsored by the Bureau.

Several semi-empirical methods were examined for comparing theoretical and experimental absolute field values to identify systematic differences or trends in the effective coupling factor, effective source magnetic moment, or effective seam height and medium conductivities. The most promising approach appears to be one in which the differences between theoretical and experimental values of field strength expressed in dB are determined as a function of frequency at a fixed reference distance from the source. 100 meters was chosen as a representative distance that allowed most of the data from both low loss and high loss mines to be included, while avoiding most near field effects. The computed quantity $[H_{TH}(dB) - H_{EX}(dB)]$ can be considered a measure of the departure of the theoretical magnetic moment or coupling factor from that observed experimentally. Plots of these differences reveal that the simple three-layer model appears to apply best between about 200 and 1000 MHz, where it produces a relatively well-behaved overestimate of the field strength which is essentially independent of coal seam and less than about 7 dB. To get a more definitive and systematic measure of this observed behavior, we plan to analyze these differences statistically during the next reporting period.

Additions and revisions were also made to the interim summary report, incorporating the above results and new insights, together with adding to and completing the considerable amount of graphical artwork. We anticipate that this report will be completed and submitted to PMSRC during the November reporting period.

Finally, at the request of the technical project officer, R. Spencer and A. Emslie of ADL participated with J. Wait and D. Hill of NOAA and ITS and H. Dobroski, K. Sacks, R. Bartholomae, and J. Nagy of the Bureau of Mines and MESA in a meeting at PMSRC, Bruceton, PA., in July. The meeting was convened by PMSRC for the internal dissemination and transfer of information on related projects being sponsored by the Bureau, and for the initial planning of an EM Guided Wave Workshop to be held in Boulder, Colorado. Subsequent planning and coordination activities by R. Lagace and R. Spencer have been minor, consisting primarily of telephone discussions with K. Sacks of PMSRC and J. Wait of NOAA. Any significant effort required of ADL staff related to this Bureau-sponsored workshop will require additional funding, perhaps by means of a separate task order having its own statement of work and funding.

During the next reporting period, we plan to perform the statistical analysis described above and continue work on the interim summary report.

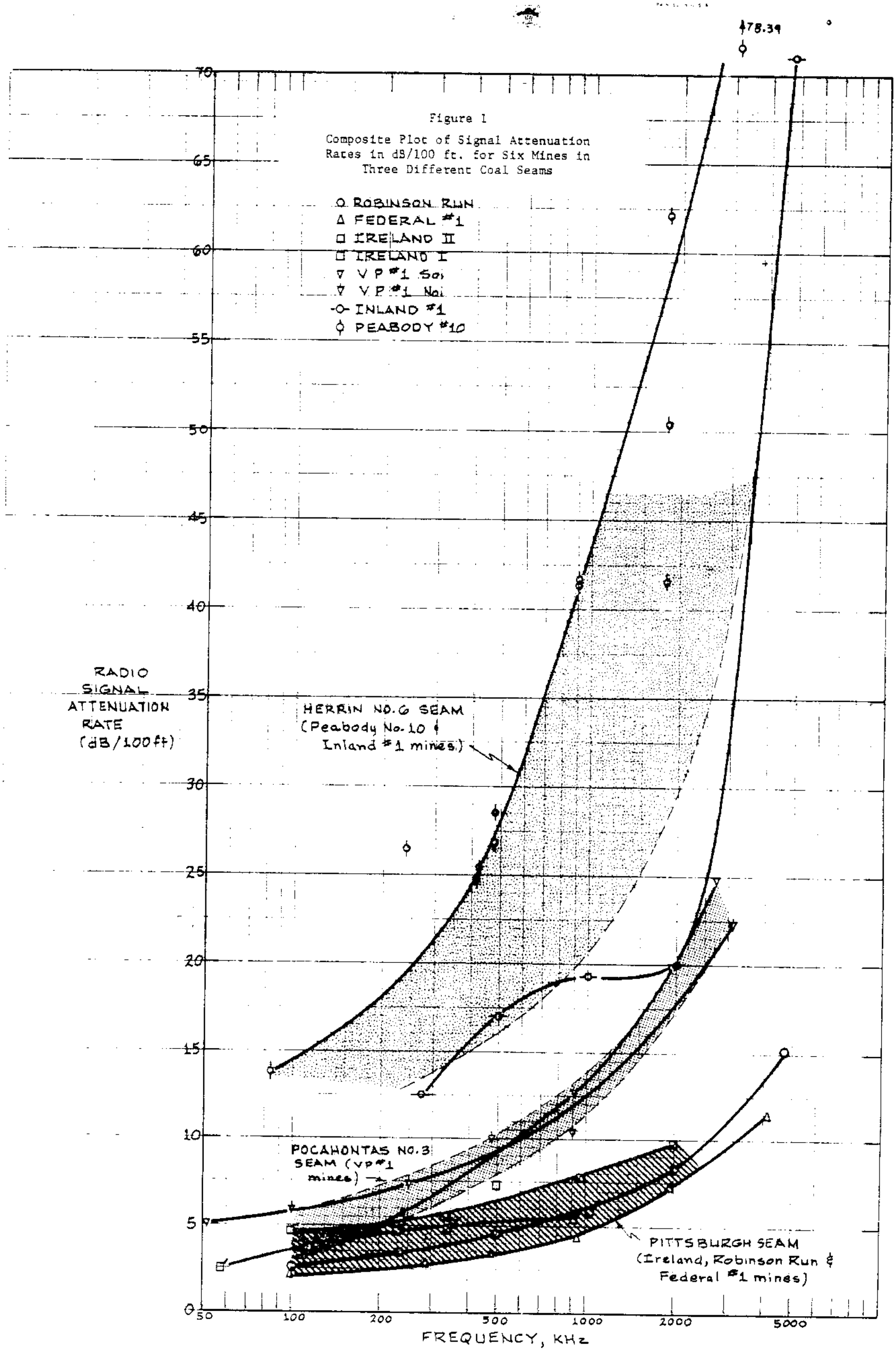

Figure 1
Composite Plot of Signal Attenuation Rates in dB/100 ft. for Six Mines in Three Different Coal Seams
O ROBINSON RUN
Δ FEDERAL #1
□ IRELAND II
□ IRELAND I
∇ VP #1 So.
∇ VP #1 No.
-O- INLAND #1
ϕ PEABODY #10
78.39
HERRIN NO. 6 SEAM (Peabody No. 10 & Inland #1 mines)
POCAHONTAS NO. 3 SEAM (VP #1 mines)
PITTSBURGH SEAM (Ireland, Robinson Run & Federal #1 mines)
RADIO SIGNAL ATTENUATION RATE (dB/100ft)
FREQUENCY, KHz
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
50
100
200
500
1000
2000
5000

TABLE I

CONDUCTIVITIES DERIVED FROM THE α VERSUS f PLOTS

Mine	h (m)	K_c	σ_c (Mho/m)	σ_r (Mho/m)	Seam
Robinson Run	1.5	6	0.3×10^{-4}	0.085	Pittsburgh
Federal No. 1	2	6	0.26×10^{-4}	0.084	Pittsburgh
Ireland II	2	6	1.0×10^{-4}	0.054	Pittsburgh
Ireland I	2	6	2.0×10^{-4} 1.4×10^{-4}	1.09 0.3	Pittsburgh Pittsburgh
Inland No. 1	3	6	1.0×10^{-3}	0.22	Herrin No. 6
Peabody No. 10					
1 Main South 1st West 2nd North	2	6	4×10^{-3}	0.3	Herrin No. 6
1 South 5-1/2 East/ 1 South Jct.	2	6	2.5×10^{-3}	0.3	Herrin No. 6
Pocahontas No. 1					
3 South Area Entry A	1.37	6	3×10^{-5}	0.01	Pocahontas No. 3
3 South Area Entry B	1.37	6	3×10^{-5}	0.0077	Pocahontas No. 3
2 North No. 1 (Plow Area)	1.19	6	6×10^{-5}	0.017	Pocahontas No. 3

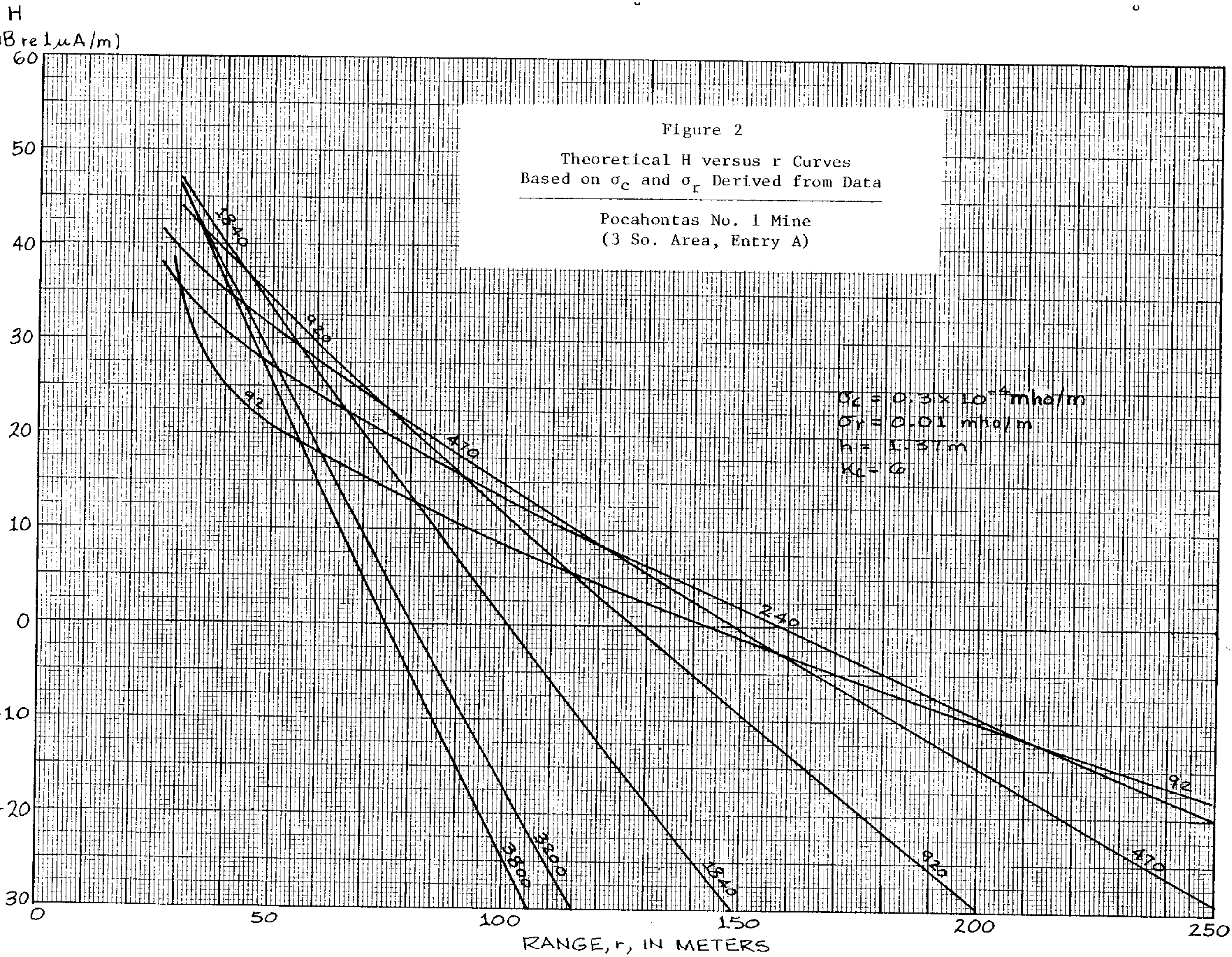

Figure 2

Theoretical H versus r Curves
Based on σ_c and σ_r Derived from Data

Pocahontas No. 1 Mine
(3 So. Area, Entry A)

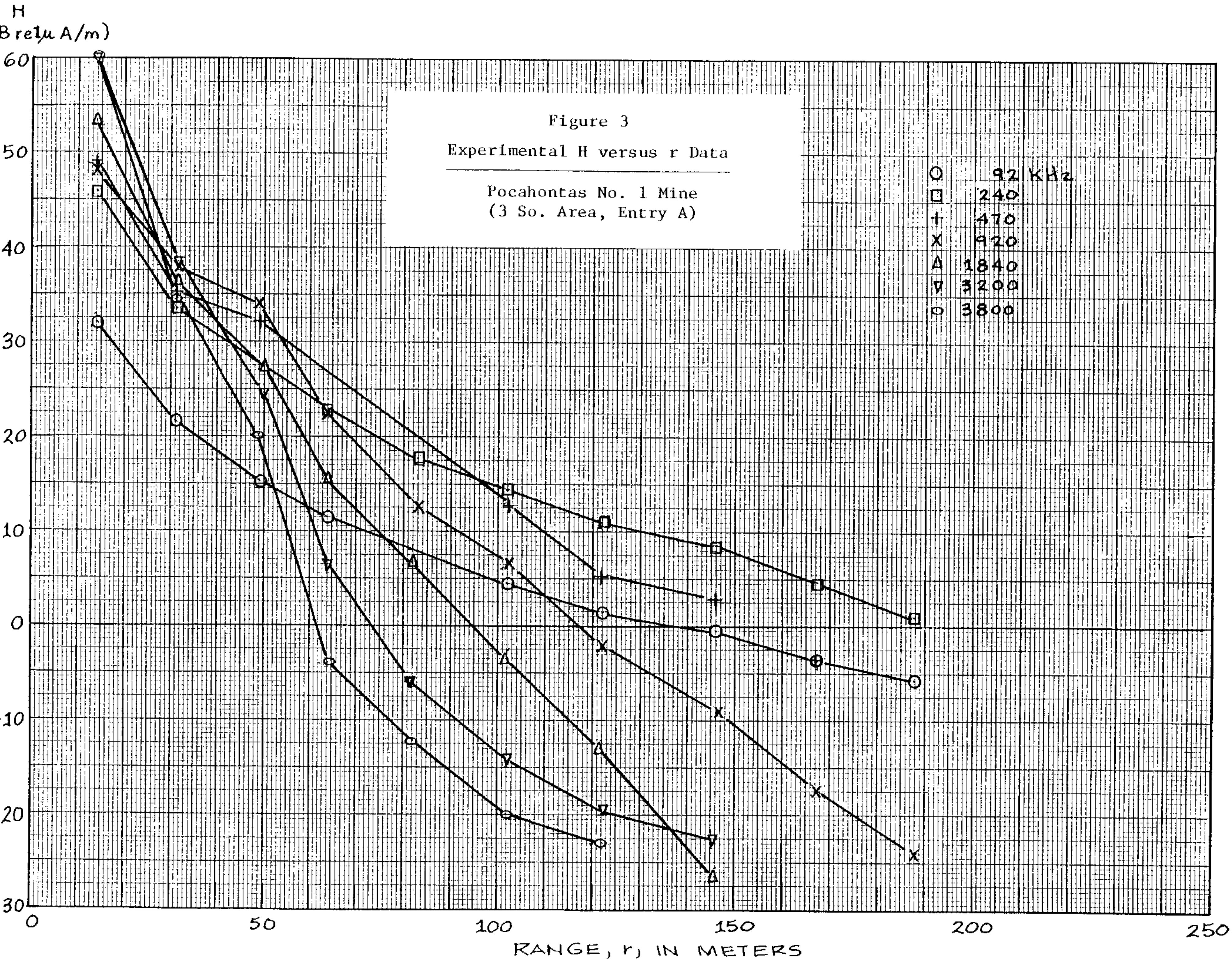

Figure 3
Experimental H versus r Data

Pocahontas No. 1 Mine
(3 So. Area, Entry A)

EIGHTEENTH MONTHLY TECHNICAL LETTER REPORT
COVERING PERIOD FROM
1 OCTOBER TO 30 OCTOBER 1977
CONTRACT NO. H0346045
TASK ORDER NO. 4
C-78453

Technical Support on the In-Mine Electromagnetic Wave Propagation Measurement Program

During this reporting period, effort was devoted primarily to the statistical analysis of the differences observed between the measured and theoretically predicted values of field strength, and secondarily to the interim summary report, and to telephone conferences with J. Wait of NOAA and K. Sacks of PMSRC related to: the upcoming Bureau-sponsored Guided Wave EM Workshop, reports of ADL and others on the propagation of radio waves in mines and near conductors, and planned Bureau radio propagation measurements and associated data analyses.

To statistically assess the goodness of fit of the simple three-layer theoretical model results to the measured data, the difference Δ = H(Theoretical) - H(Experimental) in dB was studied. The statistical analysis was restricted to data for the frequencies between 100 kHz and 1000 kHz at a reference distance of 100 meters. For frequencies outside the 100-1000 kHz range, the data indicated that the simple three-layer model was breaking down; i.e., H(Theoretical) was diverging from H(Experimental). One hundred meters was chosen as the reference distance because it allowed most of the data from both low and high loss mines to be included, while avoiding near field effects in most cases. The differences between theory and data were analyzed by:

- Computing the Sample Mean for all mines and 95% Confidence Intervals for both the population and sample mean at frequencies from 100-1000 kHz.
- Computing the Sample Mean for each seam (there were too few samples within each seam to compute a standard deviation on a seam basis).
- Plotting each of the characteristics found and analyzing the graphs.
- Testing the hypothesis that the theoretical model fit the data at the 95% level for the frequencies between 100 kHz and 1000 kHz.

From this analysis, the following observations and conclusions were made. The differences between the model and the experimentally recorded data were similar for all coal seams. The shapes of the curves for each seam average followed the same pattern and did not differ from one another by more than 1 or 2 dB, with the exception of the Herrin #6 seam at frequencies below 400 kHz. At these frequencies, data for only one mine in the Herrin #6 seam was available. However, at 400 kHz to 1000 kHz, the Herrin #6 seam average curve paralleled those of the other seams. This homogeneity implied that pooling all the data to compute a Grand Mean for all mines was a valid technique, and that the results from any analysis could be applied back to all the mines uniformly. Furthermore, it was shown that:

- Between the frequencies of 200 kHz to 900 kHz there is no significant difference between the model and the actual data readings.

- In this band of frequencies the average difference, $\bar{\Delta}$, ranged from 1.1 dB to 3.9 dB.

- The range from 200 kHz to 600 kHz appeared to be the best range for the model with both the variance and average difference between the model and actual data being smallest, and positive, within this frequency range.

In summary, based on the statistical analysis applied to the data available to date, it can be concluded that:

- The Grand Mean difference for all mines may be used in all analyses. Furthermore, it may be used to represent the individual seam averages;

- The simple three-layer model fits the experimental data in the 200 kHz to 900 kHz frequency range at the 100 meter reference distance. It does not fit the experimental data outside the range of those frequencies.

The details of this analysis and the tabulated and plotted results were also summarized in a memorandum entitled "Attenuation Rate for Radio Signals in Coal Mines: Model Goodness of Fit."

During the November reporting period we plan to complete the interim summary report, include the statistical analysis results in this report or in a separate working memorandum, continue earlier work on the analysis of coupling to conductors in mines, and collaborate via telephone with PMSRC staff, T. Cory of Spectra Associates, and J. Wait of NOAA related to the Bureau's in-mine measurement programs, as required.

TWENTY FIRST THROUGH TWENTY FIFTH COMPOSITE
MONTHLY TECHNICAL LETTER REPORT
COVERING PERIOD FROM 1 JANUARY THROUGH 28 MAY 1978
CONTRACT NO. H0346045
TASK ORDER NO. 4
C-78453

Technical Support on the In-Mine Electromagnetic Wave Propagation Measurement Program

During this reporting period substantial effort was expended and progress made in the analysis and understanding of experimental MF radio propagation data taken in conductor-free areas of U. S. coal mines, and in the development of a simple theoretical model for describing the coupling of loop antennas to a single cable installed in a tunnel in a coal seam. Data have now been analyzed from ten mines in six different seams, and have been summarized in a way that identifies the principal factors affecting MF radio wave propagation performance in different coal seams. In addition, two major reports were completed, and submitted to PMSRC, which summarize all of the theoretical modelling and data analysis completed to date. These reports are entitled "Modelling and Data Analysis of In-Mine Electromagnetic Wave Propagation" (Interim Report, May 1978) consisting of 105 pages and "Analysis of MF Propagation Data from Margaret No. 11, Nanty Glo, Ehrenfeld, and Adrian Coal Mines" (Working Memorandum, May 1978) consisting of 52 pages. During June we plan to complete all work on this Task Order and to submit the draft final report to PMSRC. We have reached the 75% expenditure point, and do not anticipate a significant overrun or underrun provided no unanticipated difficulties are experienced in the analysis of the data from the last mine. We have also discussed with the Technical Project Officer recommendations for a timely and moderate increase in scope of work related to analyzing the mine data in a new and improved way that has recently been developed that would make the results of this study more valuable and readily applicable to Bureau of Mines MF radio programs.

During January the effort was primarily related to the analysis of data taken by T. Cory in conductor-free areas and in the vicinity of cables in the Margaret No. 11 mine, and to the initial developments of a theoretical approach for the coupling of loop antennas to a cable installed in a tunnel in a coal seam waveguide. The conductivities of the coal and surrounding rock were computed by means of a more precise least square method involving a practical minimum search procedure. This Margaret No. 11 mine in low coal was found to have a conductor-free area attenuation versus frequency characteristic which lies between that of the Pocahontas No. 3 seam and that of the Herrin No. 6 seam.

The magnetic field strength behavior along cables in mine tunnels in the Margaret No. 11 mine was analyzed with respect to the longitudinal attenuation rate of the magnetic field signal along the cables. Three attenuation rate patterns are apparent. The first is noticed within an approximately 90° angular sector which is bisected by the perpendicular drawn from the loop to the cable. In this sector the field attenuation rate along the cable is on the order of 700 dB per kilometer, and represents the direct contribution of the coal seam mode field generated by the loop transmitter. Once beyond this region, the longitudinal attenuation rate reduces by one to two orders of magnitude, and is caused by a cable-guided mode excited by the transmit loop. In a tunnel containing only a single power cable, this cable guided mode was found to exhibit an attenuation rate of less than 10 dB per kilometer. However, in a tunnel containing a belt, pager phone line, and belt control lines a significantly greater longitudinal attenuation rate of 30 to 40 dB per kilometer occurs. We believe this higher attenuation rate in the beltway is due to shunt loading caused by the beltway supporting structure which is terminated into roof bolt anchors, and to the close coupling of the pager phone and control cable lines to this heavily shunt loaded beltway. This behavior resembles that of a shunt loaded trolley wire/rail line. The development of a theoretical model describing the degree of coupling between a transmit loop and a single cable installed in a coal seam waveguide centered on an integral approach for computing the current induced in the cable as a result of the summation of the infinitesimal emf's induced along the cable by the coal seam mode magnetic field generated by the transmit loop.

Communications were also maintained with T. Cory and H. Dobroski via telephone regarding the data taken at the Margaret No. 11 mine, T. Cory's transmission line approach for measuring the in situ conductivity of the coal, and the selection of coal mines to be visited.

During February the major effort was devoted to developing theoretical expressions for the coupling to a cable in a coal seam waveguide. Convergence problems were encountered in the integral approach used to derive an expression for the current induced in the cable by a transmit loop located at distance r away from the cable. The objective was to compute the value of cable current produced at a large distance down the cable from the location of the transmit loop. This approach was finally abandoned in favor of a different approach suggested by the principle of reciprocity. Namely, it was decided to derive the coupling expression by computing the open circuit voltage induced in the receive loop by the current-carrying cable. This approach was used with the method of images, to account for the effects of the roof and floor above and below the coal seam.

Expressions were first derived by having all the return current carried by only the first two images. Subsequently, the contributions from all images were included. Convergence problems were experienced with the infinite set of images method for both cases examined, namely by including and ignoring the presence of the coal. Even after solving the convergence problems, the computed theoretical values for the horizontal magnetic field in the coal seam were found to be significantly below those values measured experimentally. It was finally realized that the midpoint in the coal seam where the field was being computed was the location of a minimum or null in the horizontal magnetic field component perpendicular to the cable. In other words, the current carrying cable was not exciting the expected coal seam waveguide TEM mode. Ambiguities and other seeemingly unusual behavior of the plotted data were cleared up via telephone discussions with T. Cory, and suggestions were made for obtaining better experimental estimates of the low longitudinal rates experienced along the cable.

R. Lagace of Arthur D. Little, Inc., visited PMSRC twice during the month. The first visit was to make a progress report, and the second was to meet with representatives of Franklin Institute, PMSRC, and Motorola on problems associated with the coupling of electromagnetic radiation and waves to electrical blasting circuits in mines. The meeting on blasting circuits resulted in the identification of shortcomings in the theory and information that now exist, a preliminary agreement on the most important radio frequencies and applications for which definitive rulings may be possible in the near future, and the suggestion that this subject be treated at the March electromagnetic guided wave Workshop in Boulder, Colorado.

During the March reporting period the major effort was devoted to developing theoretical expressions for the coupling of loops to cables in coal seam waveguides and to refining the three-layer model for propagation in conductor-free areas. A major advance in understanding and simplicity was obtained by switching to a Fourier series representation for the cable current and its associated images in the rock, and by representing the wave generated by these currents as a bound guided wave propagating in the longitudinal cable direction and evanescent in the transverse direction to the cable. This allowed the contribution of each Fourier series harmonic to the resultant field at a radial distance r away from the cable to be simply computed. It also became readily apparent that only the first few harmonics made important contributions to the resultant field. The first and strongest harmonic produces only a vertical component of magnetic field at the seam midpoint; the horizontal component due to this harmonic passes through zero at that point. Thus, agreement with experimental horizontal H data taken at this point, would have to rely on an accidental rotational misalignment of the loop or a displacement of the loop from the midpoint. Unanticipated chance agreement could also occur if the roof and floor material had asymmetrical electrical properties. The contribution to the horizontal component at the midpoint due to the second harmonic contribution of the current, although present, was found to be insignificant. Consequently, the Margaret No. 11 mine data in the vicinity of cables are not adequate to prove or disprove the theoretical predictions, and a new set of measurements that examine the response to all polarizations has been defined for the last mine to be visited by T. Cory.

As a result of these analyses, the Fourier series approach was pursued and documented in the form of a paper presented at the electromagnetic guided wave Workshop in Boulder, Colorado, at the end of March. Curves were generated for loop-to-loop coupling via the cable, for the case in which both loops are separated from each other by a large longitudinal distance, and from the cable by radial distances of x_1 and x_2, and for the case where one of the loops is placed immediately underneath and adjacent to the cable.

The success of this Fourier series approach also led to its use in refining the derivation of the coal seam mode magnetic field produced by a vertical loop in the coal seam waveguide. Namely, the transmit loop and its images in the rock can also be represented by a Fourier series having in this case a DC term which couples to the quasi-TEM coal seam propagating mode.

The Fourier series approach to the coupling to cables in coal seam waveguides was also applied to the case of two or more cables located in a vertical plane within the coal seam waveguide. It was found that when a loop is located at large distances compared to the thickness of the coal seam, for example one pillar away in an adjacent tunnel, the loop couples more strongly to a common mode (monofilar) excitation of the cables in which the currents in all the cables travel in the same direction and the return current flows in the rock. However, when the loop is located close to the cable, at distances on the order of or less than the spacing of the cables, then better coupling will be made to a differential (bifilar) mode of excitation of the cables.

Assistance was also received from J. Wait, who was most cooperative in supplying us with values for the longitudinal phase constant for a wave propagating along a single cable located in a tunnel, values which were recently calculated for presentation at the electromagnetic guided wave Workshop in Boulder at the end of March.

During the electromagnetic guided wave Workshop, as a result of interactions with T. Cory, we conceived of a simple crossed loops method for making localized in situ measurements of the conductivity of coal and rock in mines, and derived theoretical expressions for the output signal as a function of conductivity of the medium to be measured.

During the April reporting period major effort was devoted to analyzing the data from the remaining three mines visited by T. Cory, to developing simpler methods of deriving the coal and rock conductivities by using the least square method, and to thinking of better ways to compare theoretical and experimental magnetic field strength behavior as a function of frequency and range.

At the beginning of April, technology transfer meetings were conducted at Arthur D. Little, Inc., between B. Austin of South Africa and R. Lagace and R. Spencer of Arthur D. Little, Inc. During two days of meetings, a considerable transfer of information and ideas on MF communications in mines was achieved. The subjects covered included system efficiency and intrinsic safety considerations in the design of antennas for personal MF radios; size and location of fixed station loops for wireless and cable coupled communications in mines; the coupling to mine AC power cables for the transmission of monitoring data to receiving stations; circuit design and fabrication considerations in the construction of mine worthy radios by South Africa; the effects of geological parameters on the polarization of MF waves in coal mines versus gold mines; hoist shaft communications to closed cages; coupling to and communications up a drill string and means to locate cutting heads sheared off from the drill string; and historical development and evolution of personal radio hardware for emergency communications in South African mines.

Several telephone discussions were also conducted with T. Cory, and H. Dobroski and K. Sacks of PMSRC. Discussions with Cory centered on detailed descriptions of the mine environments in which the measurements were taken at the most recent three mines, and with the types of measurements to be made in the last mine for verifying or disproving the ADL developed theory for coupling to cables in coal seams. Discussions with H. Dobroski centered on the types of measurements to be made in the final mine to be measured by T. Cory, and on upcoming mine tests planned for the new South African radios received by PMSRC. Discussions with K. Sacks centered on design problems and capabilities related to the fabrication of ferrite loaded loop antennas for use by miners as a substitute for air-core bandolier type loops.

Attenuation versus frequency plots for all four mines were determined and the associated conductivities were derived for rock and coal by using an improved version of the least square method for computing the conductivities. It is a method easily adapted to a pocket calculator, and it has been described in the working memorandum referred to at the beginning of this report. Plots of theoretical and experimental values of magnetic field strength at a reference distance of 100 m versus frequency were also compared for several of the latest mines measured.

During May the major effort was devoted to completing all data analyses of the quasi-conductor-free area data taken at the four low coal mines visited by T. Cory, and to documenting all the results to date in two major reports which were completed and submitted to the Bureau.

The experimentally derived α versus f results for all four low coal mines measured by T. Cory were converted to dB/100 ft. units and plotted upon the composite plot for all mines visited to date. It was found that these mines lie between those of the Herrin No. 6 and Pocahontas No. 3 seams, thereby making the favorable Pittsburgh seam behavior the exception rather than the rule so far. Two methods were also reviewed for the presentation and comparison of theoretical and experimental values of the magnetic field versus distance from the transmit antenna in conductor-free areas. One method involved the drawing of both theoretical and experimental H versus frequency curves at a standard range of 100 meters instead of the ratio of H_{Theor}/H_{Expt} previously used. The second method involved using the coupling factor, C, defined by the intercept of the $H\sqrt{r}$ versus r curve with the $H\sqrt{r}$ vertical axis. Experimentally determined values for this coupling factor were compared with theoretically derived ones from the coal seam mode three-layer model magnetic field expression.

Since the coupling factor intercept with the vertical axis is a more fundamental quantity than the magnetic field at a reference distance of 100 m, it was decided that subsequent comparisons of the theoretical and experimental absolute values of the magnetic field should be based on this coupling factor C. This coupling factor was shown to be relatively insensitive to the coal and rock conductivities. This theoretical coupling factor expression also generally overestimates the field strength value below about 1 MHz while underestimating it at frequencies above 1 MHz.

The dependence of coupling factor and attenuation rate on coal seam thickness, h, was also examined. The coupling factor C was found to be moderately dependent on the coal seam thickness, h, and the attenuation rate α more strongly dependent on it. Consequently, curves were drawn showing how the coupling factor versus frequency and attenuation rate versus frequency behavior was influenced by the coal seam height. Increasing seam thickness was found to shift the coupling factor curve downward by a relatively constant amount at all MF frequencies, and to shift the attenuation rate curve downward by an increasing amount with increasing frequency. This behavior indicates that longer communication ranges will be obtained in high coal seams than in low coal seams having the same rock and coal electrical properties.

All the results for the analysis of the conductor-free area data for the first six mines were documented in an interim report entitled "Modelling and Data Analysis of In-Mine Electromagnetic Wave Propagation" consisting of 105 pages. This report includes a section on the selecting of operating frequencies for MF systems designed for installation in different types of coal seams. The results and the analytical techniques developed and refined for the last four mines were also documented in a Working Memorandum entitled "Analysis of MF Propagation Data from Margaret No. 11, Nanty Glo, Ehrenfeld, and Adrian Coal Mines" consisting of 52 pages. This latter report includes a detailed description of the simplified procedure for deriving the coal and rock conductivities from the α versus f plots by the least square method.

R. Lagace visited PMSRC at the beginning of May to provide a progress report on the work completed to date. At the end of the May reporting period, another progress report was given to H. Dobroski of PMSRC at Arthur D. Little, Inc. Several discussions were also conducted by telephone and in person with PMSRC technical staff regarding MF radio installations for the Lucerne mine, the applicability of the Geonics conductivity measuring equipment in mines, and a crossed loop method for measuring coal and rock conductivity. Telephone collaboration was also maintained with T. Cory regarding measurements made at the last low coal mine. Arrangements have been made for the delivery of the data to ADL by the end of the first week in June.

During the next reporting period we plan to complete the analyses of the data from the last mine measured by T. Cory, and to compile and complete the draft final report for this Task Order for submission to PMSRC.

TWENTY SIXTH THROUGH TWENTY EIGHTH COMPOSITE
MONTHLY TECHNICAL LETTER REPORT
COVERING PERIOD FROM 29 MAY THROUGH 27 AUGUST 1978
CONTRACT NO. H0346045
TASK ORDER NO. 4
C-78453

Technical Support on the In-Mine Electromagnetic Wave Propagation Measurement Program

During this reporting period the conductor-free area data from the last low coal mine, the Stinson #3 mine, was analyzed and a highly satisfactory agreement obtained with the ADL three-layer model. Furthermore, the attenuation characteristic of this mine places it between that of the Pocahontas #3 seam and the Herrin #6 seam. After careful analysis the conductor proximity data were found to be unusable for comparison with the ADL cable-in-a-coal-seam model, and the data were found to exhibit some presently inexplicable behavior.

The attenuation versus frequency data from the first six mines were analyzed by the least square error method for deriving the rock and coal conductivities used for the last four mines. Coupling factor curves were generated for all mines measured to date, and analyzed statistically to determine goodness of fit of the coupling factor to the data. The model was found to be in extremely good agreement with the data in the 200 to 1000 kHz band of interest for mine wireless radio communications.

A Working Memorandum was completed and submitted to PMSRC documenting the crossed loop method for in situ measurement of coal or rock conductivity. Two reports received from T. Cory were also reviewed.

During this reporting period the Stinson #3 mine report was received from T. Cory, and the conductor-free area data were analyzed to obtain curves of attenuation rate α versus frequency, coupling factor C versus frequency, and the rock and coal conductivities. Very good agreement with the theoretical model was obtained for this mine, both with regard to α versus f, and C versus f behavior. The conductivities found for this mine are $\sigma_r = 4.1 \times 10^{-3}$ Mhos/m and $\sigma_c = 3.0 \times 10^{-5}$ Mhos/m. We also found that the Stinson data place this mine between the Pocahontas #3 seam and the Herrin #6 seam regarding attenuation versus frequency characteristics. Below 500 kHz the attenuation rate versus frequency curve falls within the range found for the Pocahontas #3 seam. Above 500 kHz the attenuation versus frequency characteristic rapidly moves up through the band occupied by the Lower Freeport, the Upper Freeport, and the Lower Kittanning seams reaching attenuation rate values near the lower limit of those found for the Herrin #6 seam at 3710 kHz.

Considerable time was spent examining the conductor proximity data taken at the Stinson #3 mine before concluding that they were not suitable for comparing with the single cable in a coal seam model previously formulated. The principal reason for this conclusion was that the tunnel contained four or five parallel conductors distributed over the tunnel cross-section instead of one, and the transmit loop was located at a position halfway betwen two of them instead of immediately adjacent to, and in the plane of, the conductor closest to the perpendicular path traversed by the receive antenna. This fact makes it very difficult to calculate a coupling factor, to compare with the signals measured, without introducing considerable ambiguity. A second measurement problem with respect to the data is the presence of a component of magnetic field parallel to the cables that also increases with increasing frequency. We cannot presently explain this behavior for a parallel set of conductors. However, such behavior could occur if a "spur" conductor was present running perpendicular to the main set of cables going perhaps to a pump or pager phone or other electrical device either within the main tunnel or down cross cuts adjacent to the cross cut in which the receive antenna was located. T. Cory is not certain whether such perpendicular spur conductors were present at the time of the measurements.

In an attempt to find some data that could be used to verify or contradict the single cable in a coal seam model derived by ADL, we reviewed and examined in detail the conductor proximity measurements made in the first mine ever visited by the Collins Radio/T. Cory measurement team, namely the Consolidation Coal Rose Valley Mine in West Virginia. It appears that these data will also be inappropriate for comparing with the ADL coupling to cable model. Examination of these data did uncover a situation in which a magnetic field component parallel to the main run of cables was also measured. However, the component was measured at a cross cut intersection just beyond the end of a pager phone line spur running into the cross cut perpendicular to the main run of cables. In this case the presence of this pager phone line perpendicular to the main run of cables offers a plausible explanation for the presence of the parallel magnetic field components.

We initiated and completed analyzing the attenuation versus frequency data from the first six mines using the improved least square error method of determining the coal and rock conductivities. The coupling factor, C, defined by the intercept of the straight line far field approximation of $H\sqrt{r}$ with the vertical axis ($r = 0$), was also computed and plotted for these mines. All the experimental and theoretical attenuation versus f, coupling factor versus f, and conductivity results form all mines were assembled, plotted up, and examined in considerable detail for reasonableness, consistency, and overall integrity prior to subjecting the coupling factor data to statistical analysis.

In some cases, mainly for some of the data taken at the Inland No. 1, Peabody No. 10, Pocahontas No. 3, Nanty Glo and Robinson Run mines, substantial time and effort were spent checking, recalculating and rethinking the data reduction methods, experimental procedures and data, analytical techniques, and overall veracity and applicability of the data. Telephone collaboration with T. Cory assisted this effort. As a result, errors were found and purged in some of our previous data reduction/analysis and in some of the data themselves. A small amount of the data, or the conditions under which they were taken, were also judged to be highly inconsistent or suspicious based on several criteria. These were justifiably excluded from the statistical analysis of goodness of fit of the simple coupling factor theory to the experimental data. These few deviant data have not been totally ostracized however; they will be included in the final report where they can receive further observation and possible diagnosis of the cause of their aberrant behavior by other practitioners.

The quantity $\Delta C = C_{THEOR} - C_{EXPER}$ (in dB) was analyzed statistically in seven frequency bands covering the range from 83 kHz to 4750 kHz, to determine the mean difference $\overline{\Delta C}$, the 95% confidence limits on the mean difference, and the 95% confidence limits on the differences for the sample population. The ADL simple three-layer model was found to fit the data extremely well over the frequency range from 200 to 1000 kHz which is of greatest interest for coal mine applications. In particular we found a mean difference of less than +1 dB, a 95% confidence interval of about ±2 dB for the mean, and a 95% confidence interval of about ±(7 - 10) dB for the population. The theory was found to overestimate the coupling factor above 1000 MHz and below 200 kHz, giving a mean difference of about +5 dB around 100 and 2000 kHz.

We also found a good way to visually present the derived conductivities; namely by characterizing each test location in each mine as a point on a graph where the coal conductivity is plotted along the ordinate and the rock conductivity along the abscissa. The results to date appear to reveal trends and clusterings that define the average, high, and low signal attenuation rate conditions.

A Working Memorandum was completed and submitted to PMSRC documenting the simple crossed loops method for making localized in-situ conductivity measurements. The Working Memorandum is entitled "A Method for Nonintrusive In Situ Measurement of Coal and Rock Conductivities in a Coal Mine Tunnel."

The Draft Final Report submitted to the Bureau by T. Cory was reviewed, as well as the special technical report issued by T. Cory entitled "In Situ Measurement of Coal Seam Conductivity Using a Parallel Wire Transmission Line Method." We note in this latter report that the values of coal conductivity derived by T. Cory from these measurements are within the same order of magnitude as derived by the ADL three-layer model, but that the values of T. Cory are approximately twice as high as the values obtained from the three-layer model. A relative dielectric constant of about 2 is also obtained by T. Cory as opposed to the value of 6 assumed in the ADL three-layer model. An unexpected benefit to the ADL low impedance line demonstration experiment also occurred. T. Cory's technique for determining β of the line was modified slightly and used to measure the wavelength along normal and low-Z lines at the McElroy mine.

During the next reporting period we plan to request from the mine companies the petrographic analyses of the coal in the vicinity of the measurement sites at all mines visited by T. Cory, in order to statistically analyze these data relative to their impact on the values obtained for the coal conductivity in each mine. From this analysis we hope to determine whether any correlation exists between the values of coal conductivity and any of the quantities routinely analyzed by mines to assess the marketability of its coal. We also plan to start writing sections of the draft final report, and to continue telephone collaboration between H. Dobroski of PMSRC; the measurement contractor, T. Cory; and J. Wait and D. Hill of ITS/NOAA as required. Preparation and submission of the draft final report for this task order was deferred to accommodate the additional analyses requested in Modification 4 to this Task Order.

TWENTY NINTH THROUGH FORTIETH COMPOSITE
MONTHLY TECHNICAL LETTER REPORT
COVERING PERIOD FROM 28 AUGUST 1978 TO 25 AUGUST 1979
CONTRACT NO. H0346045
TASK ORDER NO. 4
C-78453

Technical Support on the In-Mine Electromagnetic Wave Propagation Measurement Program

During this reporting period effort was spent primarily on examining the implications of the data analyses and associated theoretical models on the expected performance of MF radio systems in coal mines, and on preparing the draft final report.

"Average" values for coal and rock conductivities based on the processed propagation data to represent high, moderate and low loss coal seams were selected, and curves of coal seam coupling factor versus seam height and frequency were plotted. These representative values of conductivity were then applied to the theoretical coal seam propagation model, together with mine electromagnetic noise data, to generate curves of predicted maximum radio communication range versus frequency in high and low coal seams under "mine noise" and "receiver set noise" operating conditions.

Maximum radio communications range versus frequency in conductor-free areas was found to exhibit a broad peak centered between 300 and 700 kHz, a band well within the 200 to 1000 kHz frequency band over which the model is in extremely good agreement with the propagation data. Within the optimum frequency band of 300 to 700 kHz, maximum ranges were found to be highly dependent on attenuation rate, and thus on the electrical conductivities of the coal seam and its surrounding rock. Consequently, maximum communication ranges for portable, intrinsically safe radios can be expected to vary from low values of about 75 to 100 meters in a high-loss seam such as the Herrin No. 6, to high values of about 300 to 400 meters in a low-loss seam such as the Pittsburgh.

A significant part of the writing, editing, tables, and artwork were also completed on the draft final report. During the writing of the draft report, many final checks and searches were made regarding assumptions, methods of analysis and presentation, regions of model applicability, and plausible reasons for unexpected and/or unexplained data in both conductor-free areas and in the vicinity of mine cables. We are attempting to present the results of a large amount of data analysis and related propagation modelling in a comprehensive, but concise and easy to follow and use, format for the final report. The supplementary volume for limited distribution will include the working memoranda documenting many of the details, and preliminary steps, results, models, and analysis techniques for future reference by others.

During the next reporting period, we plan to receive coal petrographic/proximate analysis data from the test mines, analyze them to determine if any significant relationships exist between the proximate analysis data and the derived electrical conductivities, and incorporate the results in the draft final report. We also plan to complete the draft final report and submit it to PMSRC for approval.

II. BACKGROUND THEORY FOR MEASUREMENT PROGRAM ON MEDIUM AND HIGH FREQUENCY RADIO TRANSMISSION IN COAL SEAMS - Working Memorandum August 1976.

BACKGROUND THEORY FOR MEASUREMENT PROGRAM ON MEDIUM AND HIGH FREQUENCY RADIO TRANSMISSION IN COAL SEAMS

This memorandum gives the background theory needed to guide the forthcoming measurements on MF and HF radio wave propagation in coal seams and to reduce the data obtained in the measurement program.

In the frequency range of interest, namely, 50-1,000 kHz, the free-space wavelength is in the range of 6,000-300 m and is therefore very large compared with the thickness of a coal seam and with the transverse dimensions of a coal mine tunnel. Under these conditions, the only useful mode of propagation is an approximately TEM mode in the coal seam with the magnetic field horizontal and the electric field approximately vertical. This kind of mode can be launched and received by loop antennas placed in a tunnel with the two loops in the same vertical plane. Since the wavelength is so large compared with the tunnel dimensions, the transmission from one loop to the other is practically the same as if the loops were immersed in a virgin coal seam.

The magnetic field H at a distance r from the transmitting loop in the direction of the receiving loop is given by the formula[1,2]

$$H = \frac{iMk^2}{8b_e} H_1^{(2)'}(kr) \qquad (1)$$

where

$M = NIA$ is the magnetic dipole moment of the transmitting loop

$b_e = b + \frac{1}{2}\delta_r$ is the effective half-height of the coal seam

b = actual half height of the coal seam

δ_r = skin depth in the rock bounding the coal seam

$k = \beta - i\alpha$ is the complex propagation constant

$H_1^{(2)'}(z)$ = derivative of the first order Hankel function for an outgoing wave

The constant β is related to the actual wavelength λ in the medium by the relation $\beta = 2\pi/\lambda$. The wavelength depends on the electrical properties of both the coal and the rock strata above and below the seam, and on the frequency. It is generally much smaller than the free-space wavelength λ_o, partly due to the dielectric constant of the coal seam, but mostly due to the conductivities of the coal and the bounding media.

The constant α determines the propagation loss (dB/m) and depends on the same quantities as β, but in different ways.

To provide a complete understanding of the factors on which the wave propagation depends, the experimental program should therefore be arranged to measure both α and β at a number of frequencies. Determination of the phase constant β in addition to the attenuation constant α exactly doubles the amount of information available for constructing a good theoretical model of the electrical properties of the coal seam and the surrounding strata. The experimental equipment should therefore measure both the amplitude $|H|$ and the phase angle ϕ of the magnetic field H as functions of the distance r from transmitter to receiver.

From these measurements one can obtain both α and β from Eq (1), at each frequency separately. The procedure is as follows.

On substituting the asymptotic expansion for the Hankel function, we can express the magnetic field in the form

$$H = A \frac{e^{-ikr}}{\sqrt{kr}} (iR + S) \tag{2}$$

where

$$A = \frac{ie^{\frac{3\pi i}{4}} Mk^2}{\sqrt{32\pi}\ b_e} \tag{3}$$

and R and S are series[3] in inverse powers of kr. From these series we obtain for the real and imaginary parts of iR + S, up to inverse eighth powers,

$$\begin{aligned} Re(iR + S) = {} & \frac{0.87500 \cos \theta}{|kr|} + \frac{0.44531 \sin 2\theta}{|kr|^2} + \frac{0.19043 \cos 3\theta}{|kr|^3} \\ & - \frac{0.21469 \sin 4\theta}{|kr|^4} - \frac{0.37130 \cos 5\theta}{|kr|^5} + \frac{0.85008 \sin 6\theta}{|kr|^6} \\ & + \frac{2.40432 \cos 7\theta}{|kr|^7} - \frac{8.06757 \sin 8\theta}{|kr|^8} \end{aligned} \tag{4}$$

$$\begin{aligned} Im(iR + S) = 1 & + \frac{0.8700 \sin \theta}{|kr|} - \frac{0.44531 \cos 2\theta}{|kr|^2} + \frac{0.19043 \sin 3\theta}{|kr|^3} \\ & + \frac{0.21469 \cos 4\theta}{|kr|^4} - \frac{0.37130 \sin 5\theta}{|kr|^5} - \frac{0.85008 \cos 6\theta}{|kr|^6} \\ & + \frac{2.40432 \sin 7\theta}{|kr|^7} + \frac{8.06757 \cos 8\theta}{|kr|^8} \end{aligned} \tag{5}$$

where

$$\theta = \tan^{-1}\left(\frac{\alpha}{\beta}\right) \tag{6}$$

$$|k| = (\alpha^2 + \beta^2)^{\frac{1}{2}} \tag{7}$$

From (2) we obtain the relations,

$$\frac{d\phi}{dr} = \frac{d}{dr}(\text{Arg } H) = -\beta + \frac{d}{dr}\text{Arg}(iR + S) \tag{8}$$

$$\frac{d}{dr}\ln(|H|\sqrt{r}) = -\alpha + \frac{d}{dr}\ln|iR + S| \tag{9}$$

These equations can be rewritten in the form

$$\beta = -\frac{d\phi}{dr} + \frac{d}{dr}\text{Arg}(iR + S) \tag{10}$$

$$\alpha = -\frac{d}{dr}\ln(|H|\sqrt{r}) + \frac{d}{dr}\ln|iR + S| \tag{11}$$

where the terms containing $iR + S$ are small for large r, as can be seen from (4) and (5). This suggests that we determine β and α by a two-step iteration.

In the first step we omit the $iR + S$ terms and determine preliminary values of β and α from the first terms in (10) and (11), evaluated from the slopes of the experimental ϕ vs r and $\ln(|H|\sqrt{r})$ vs r curves at as large a value of r as possible, with due regard to the signal-to-noise ratio. In the second step we use the preliminary values of β and α to evaluate the $iR + S$ correction terms in (10) and (11), at the same value of r as used in the first step, and add the corrections to the preliminary values of β and α. Simulated tests of this procedure show that the final errors in β and α are within 1% at 20 kHz and within 0.3% at 1000 kHz.

The next problem, after β and α have been determined at a number of frequencies, is to use this information to obtain the electrical properties of the coal seam and the bounding layers of rock. To do this we use the transmission line formula

$$\alpha + i\beta = [(Z_s + i\omega L)(G + i\omega C)]^{\frac{1}{2}} \tag{12}$$

where

Z_s = sum of surface impedances of rock at upper and lower interfaces with coal seam (ohm/□)

$L = \mu_o h$ (Henry/m^2)

$h = 2b$ = height of coal seam (m)

$G = \frac{\sigma_c}{h}$ (Mho/m^2)

$C = \frac{\varepsilon_c}{h}$ (Farad/m^2)

σ_c = conductivity of coal (Mho/m)

ε_c = permittivity of coal (Farad/m)

A simple model, which we have used to interpret attenuation data for the Ireland Mine,[1] is (1) that only the rock adjacent to the coal seam is important and that its conductivity α_r is large compared with $\omega\varepsilon_r$, and (2) that the permittivity ε_c of the coal is known. Under these conditions there are only two unknown quantities, namely, α_r and α_c, on the right hand side of (12). Therefore, on separating real and imaginary parts of this equation, we can determine both α_r and α_c at each frequency.

For this model, surface impedance Z_s is given by the relation

$$Z_s = 2(1 + i)\left[\frac{\omega\mu_o}{2\sigma_r}\right]^{\frac{1}{2}} \tag{13}$$

On equating real and imaginary parts of (12) and solving for α_r and α_c we obtain the formulas

$$\sigma_c = \omega\varepsilon_c - \frac{2\varepsilon_c}{\mu_o h}\left(P + \sqrt{P^2 - Q}\right) \qquad (14)$$

Reference to other report or paper?

$$\sigma_r = 2\omega\mu_o \left[\frac{P + \sqrt{P^2 - Q}}{Q}\right]^2 \qquad (15)$$

where

$$P = \frac{h}{4\omega\varepsilon_c}\left(\alpha^2 - \beta^2 - 2\alpha\beta + 2\omega^2\mu_o\varepsilon_c\right) \qquad (16)$$

$$Q = \frac{\mu_o h^2}{2\varepsilon_c}\left(\alpha^2 - \beta^2 + \omega^2\mu_o\varepsilon_c\right) \qquad (17)$$

If the model is valid the values of α_r determined by (14) and (15) should be independent of frequency. This was found to be approximately true for the case of the Ireland mine except at the lower end of the frequency band at 57.5 kHz, for which the wave penetrated far enough into the rock above and below the coal seam to reach strata of lower conductivity.

Since virgin coal is readily accessible on the side walls of the mine tunnel, it would be very useful to measure α_c and ε_c directly in each mine visited. Then one could determine the surface impedance of the rock as a function of frequency by means of (12) written in the form

$$Z_s = h \left[\left(\frac{\sigma_c(\alpha^2 - \beta^2) + 2\omega\varepsilon_c\alpha\beta}{\sigma_c^2 + \omega^2\varepsilon_c^2} \right) - i \left(\frac{\omega\varepsilon_c(\alpha^2 - \beta^2) - 2\sigma_c\alpha\beta}{\sigma_c^2 + \omega^2\varepsilon_c^2} + \omega\mu_o \right) \right] \quad (18)$$

From Z_s vs ω one would be able to develop a more detailed model of the rock strata if the simple model discussed above were to show noticeable variation of α_r with ω.

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*Follow-up note: It was subsequently decided not to include a β measurement in this underground measurement program because of its complexity and impracticality for the anticipated experiments and its nonessential nature.

III. MODELLING AND DATA ANALYSIS OF IN-MINE ELECTROMAGNETIC WAVE PROPAGATION - Interim Report, May 1978

MODELLING AND DATA ANALYSIS OF
IN-MINE ELECTROMAGNETIC WAVE PROPAGATION

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INTERIM REPORT
On
Task Order No. 4
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Arthur D. Little, Inc.
Cambridge, Massachusetts

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I. INTRODUCTION

Initial propagation measurements by T. S. Cory in the Consolidation Coal Co. Ireland Mine in the Pittsburgh coal seam, and their subsequent analysis by ADL, revealed unexpectedly long communication ranges which could be attributed to exceptionally favorable geological conditions from an electromagnetic wave propagation standpoint. Namely, the waves in conductor-free areas of the mine were found to propagate in a parallel plane coal seam waveguide filled with coal having a conductivity near the low end of the range of coal conductivity values, and bounded top and bottom by rock having a conductivity near the high end of the range of rock conductivity values. Therefore, to determine whether these favorable propagation conditions were typical or exceptional for U. S. coal mines, additional measurements were performed in six coal mines having coal and rock geological characteristics both similar to and different from those found in the Ireland mine. The analysis and modelling of these additional data are the subject of this report.

The results show that significant variations in signal attenuation rates do occur between mines located in different coal seams. Of the three seams examined, the Pittsburgh seam measured in northern West Virginia has the most favorable attenuation rate, the Herrin No. 6 in Illinois is the worst with an order of magnitude higher attenuation rate than the Pittsburgh seam, while the Pocahontas No. 3 seam in western Virginia falls between them with a moderate attenuation rate. The simple three-layer model is seen to be a convenient and practical one which fits the experimental data best in the frequency band from 200 kHz to 900 kHz, the band which also promises to provide the most favorable performance for portable radio communications in coal mines. Simple and convenient methods are developed for calculating and characterizing a mine in terms of attenuation rate versus frequency, coal and rock conductivities, and a coupling factor. The methods are based on the three-layer model and a transmission line formulation for the propagation constant. The influences which the desired range of communication and the rock and coal conductivities exert on the choice of operating frequency are also examined.

The analysis of conductor-free area propagation data from an additional five mines, primarily in low-coal seams, is currently being performed, together with the analysis of data taken in the vicinity of electrical conductors found in mines. The results of these analyses will be included in the final report for this task order.

II. THE MODE OF PROPAGATION

At low and medium frequencies the only mode that propagates for useful distances in the stratified medium comprising the coal seam and the surrounding rock above and below the seam is the lowest mode, which is basically similar to the TEM mode for two infinite, parallel, horizontal metal plates. In both cases the mode can be either a plane wave or a cylindrical wave, with the H-field horizontal and the E-field approximately vertical. The cylindrical wave is of interest for the type of mobile communications desired within U. S. coal mines.

For simplicity, we consider only a three-layer model[1,2] in which the coal seam, of height h, has a conductivity σ_c and a dielectric constant K_c which we assume to have a fixed value of 6. The rock above and below the coal seam has a conductivity σ_r which is assumed to be much higher than $\omega\varepsilon_r$, and also much higher than σ_c.

When a vertical transmitting loop of magnetic moment M is placed at the center of a tunnel in the coal seam, the effect of the rock above and below the loop can be represented[3] by an infinite set of images of the loop, each with magnetic moment M, distributed along a vertical line with equal spacing given by the complex number

$$D = h + (1 - i)\delta_r \tag{1}$$

where h is the coal seam height and δ_r is the skin-depth in the rock, given by

$$\delta_r = \left(\frac{1}{\pi\mu_o f\sigma_r}\right)^{1/2} . \tag{2}$$

The set of images, including the transmitting loop itself, can be regarded as a periodic distribution m of magnetic dipole moment per unit spread along the vertical axis. The periodic function m can be represented by a Fourier series which has a constant term (zero-order harmonic)

$$m = \frac{M}{D} = \frac{M}{h + (1 - i)\delta_r} \tag{3}$$

This zero-order harmonic generates the TEM cylindrical wave of interest for communication purposes. The higher harmonics generate higher-order modes that are beyond cut-off for low and medium frequencies, and therefore die out very rapidly with range.

The uniform magnetic moment m distributed along the axis produces a cylindrical wave with magnetic field components

$$H_r = \frac{imk}{4}\sin\phi\cdot\frac{1}{r}\cdot H_1^{(2)}(kr) \tag{4}$$

$$H_\phi = \frac{imk}{4}\cos\phi H_1^{(2)'}(kr) \tag{5}$$

$$H_z = 0, \tag{6}$$

where $H_1^{(2)}$ is the first order Hankel function for an outgoing wave, and $H_1^{(2)'}$ is the derivative of the Hankel function. The complex propagation constant k is given by

$$k = \beta - i\alpha, \tag{7}$$

where α and β are the attenuation and phase constants which depend on the electrical properties of the strata and the frequency. The attenuation and phase constants are given by the mode condition derived from the boundary conditions of continuity of the tangential components of E and H at the interfaces between the coal and rock strata. More general analyses of the propagation waves within stratified media are given by Wait[4,5] and Gabillard.[6,7] In this report, however, we obtain both α and β from the simple transmission line formula

$$\alpha + i\beta = \sqrt{(R + i\omega L)(G + i\omega C)} \tag{8}$$

which, for the three-layer model, takes the form

$$\begin{aligned}\alpha + i\beta &= \sqrt{(2Z_s + i\omega\mu_o h)\left(\frac{\sigma_c}{h} + \frac{i\omega\varepsilon_c}{h}\right)} \\ &= \sqrt{\left[\frac{2(1+i)}{\sigma_r\delta_r} + i\omega\mu_o h\right]\left[\frac{\sigma_c}{h} + \frac{i\omega\varepsilon_c}{h}\right]}\end{aligned} \tag{9}$$

where $Z_s = (1 + i)/\left(\sigma_r \delta_r\right)$ is the surface impedance of the rock. We calculate α and β from the real and imaginary parts of the right hand side of (9).

At range r greater than about $1/\alpha$ from the transmitting loop in a direction in the plane of the loop, the magnetic field equation for $|H_\phi|$ is obtained by using the asymptotic form of the Hankel function in Eq. (5), setting $\phi = 0$, and substituting for m in Eq. (3), to give the formula

$$|H_\phi| = \frac{M\left(\alpha^2 + \beta^2\right)^{3/4}}{(8\pi)^{1/2}\left[\left(h + \delta_r\right)^2 + \delta_r^2\right]^{1/2}} \cdot \frac{e^{-\alpha r}}{\sqrt{r}} \qquad (10)$$

for $r \gtrsim 1/\alpha$.

Since this simple three-layer model describes the observed behavior in terms of a uniform, homogenous, surrounding rock medium having a conductivity σ_r, asymmetry in the electrical properties of the over- and underlying rock cannot be detected by analyzing the experimental data using this model. This shortcoming is not a serious one in the present application.

III. DERIVATION OF α VERSUS f CURVES FROM THE DATA

It is very desirable to find a simple way to characterize radio propagation in each coal mine. Curves of attenuation constant α versus frequency provide such a characterization and are readily obtained directly from the experimental data.[8]

Eq (10) shows that for ranges greater than about $1/\alpha$,

$$H \sqrt{r} \quad \propto \quad e^{-\alpha r} \quad . \tag{11}$$

From (11) we obtain the relation

$$\alpha \;=\; - \frac{1}{8.686} \; \frac{1}{dr} \left(20 \; \mathrm{Log} H + 10 \; \mathrm{Log} \frac{r}{r_o} \right) \; , \tag{12}$$

where r_o is any convenient range such as 100 m. Eq (12) indicates that if one adds 10 log (r/r_o) to the experimental values of H, expressed in dB, and replots the result as a function of r, the resulting graph should be a straight line, except at small values of r. The slope of the straight line (dB/m), divided by 8.686, gives α in m^{-1}.

Figure 1 shows an example of the technique applied to data from the Robinson Run mine at 228 kHz. It is seen that a good straight line is obtained, except for the expected departures at r = 30 m and 62 m. The slope is 54.4 dB/500 m which, when divided by 8.686 dB/Neper, gives $\alpha = 0.0125 \; m^{-1}$.

The same method has been applied to the data at all the frequencies used at Robinson Run. The results for α versus f are shown in Figure 2. Similar plots for other mines are given in Figures 3 to 8. In all the graphs but one, the values of α are based on straight line plots as unambiguous as the example in Figure 1.

The exception is the case of the Ireland "II" mine (Figure 5) where cables were present in entries adjacent to the entry in which the measurements were made. It appears that the TEM mode with which we are concerned couples to a guided type of mode involving a cable and the surrounding coal and rock. Since the guided mode has a smaller attenuation constant than the TEM mode, the effect is that the coupling back and forth between the two modes causes the signal to die off less rapidly beyond a certain range. The effect is shown in Figure 9, where the signal enhancement at 100 kHz sets in beyond about 180 m. In drawing the straight line to determine α, we disregard data points beyond this distance, and also the first data point for the reason previously mentioned. The line is therefore based on only the second and third data points. A similar selection of the data points is required at the other frequencies. The plot in Figure 5 is therefore less reliable than the other α versus f plots. It is seen, however, that the graph shows the same monotonic increase of α with f.

Figure 10 shows how the α versus f curves vary from mine to mine. Here α is given, for convenience, in dB/100 ft., and a log scale is used for f in order to give a better spread of the low frequency points. It is seen that the mines fall into three groups.

The mines in the Pittsburgh seam, comprising Ireland, Robinson Run, and Federal No. 1, have the lowest attenuation rates and, not surprisingly, are somewhat comparable with each other in attenuation. The Pocahontas No. 3 mine has an attenuation that overlaps that of the Pittsburgh seam mines at low frequencies but rises more rapidly with increasing frequency. The mines of the Herrin No. 6 seam, namely Peabody No. 10 and Inland No. 1, have considerably larger attenuation rates.

It is to be noted that all the attenuation curves when plotted as dB/100 ft. versus log f have similar concave-upward, monotonically-increasing shapes except for the Inland No. 1 curve, which is S-shaped. It is thought that the point at 2000 kHz is greatly in error and that the dotted line more nearly represents the correct trend for the Inland No. 1 mine.

IV. DEDUCTION OF CONDUCTIVITIES FROM α VERSUS f CURVES

The conductivities σ_c and σ_r can be derived from any α versus f curve by means of equation (9). On eliminating β from this equation, by separating the real and imaginary parts, we obtain the equation:

$$\sigma_r = \frac{\pi f \mu_o}{h^2} \left(\frac{a}{\sqrt{b^2 + ac} - b} \right)^2 \tag{13}$$

where

$$a = (\sigma_c + 2\pi f \varepsilon_c)^2 \tag{14}$$

$$b = \pi f \mu_o \sigma_o (\sigma_c + 2\pi f \varepsilon_c) + \alpha^2 (\sigma_c - 2\pi f \varepsilon_c) \tag{15}$$

$$c = \alpha^4 + (2\pi \alpha f)^2 \mu_o \varepsilon_c - (\pi f \mu_o \sigma_c)^2 \tag{16}$$

For a given point on the α versus f plot we calculate σ_r's from (13) for a sequence of values of σ_c, and plot σ_r versus σ_c. The curve obtained is a constant-α curve corresponding to the chosen point on the α versus f plot. The same procedure is applied to all points on the α versus f plot.

Figure 11 shows the set of constant-α curves corresponding to Figure 2 for Robinson Run. Ideally the constant-α curves would all intersect at a single point, corresponding to an unambiguous pair of values of σ_c, σ_r. However, owing to experimental error, non-uniformity of the coal seam, errors in computing the α's from the slope of the H $\sqrt{r}$ vs r curves, etc., the constant α curves fail to have a single intersection, but do neck down and then fan out again. The star on the graph represents a kind of center of gravity of the curves at the neck, and yields the values $\sigma_c = 0.3 \times 10^{-4}$ Mho/m, $\sigma_r = 0.085$ Mho/m. Figure 12 shows the set of ideal constant-α curves which all intersect at the point $\sigma_c = 0.3 \times 10^{-4}$, $\sigma_r = 0.085$.

Figure 13 shows the constant-α curves corresponding to the α vs f plot for Federal No. 1 mine (Figure 3). The best choice of the σ's in this case is $\sigma_c = 0.26 \times 10^{-4}$, $\sigma_r = 0.084$. In Figure 14 we compare the experimental α vs f plots for the two mines with theoretical α vs f graphs calculated by Eq (9) for the selected σ's. It is seen that quite good fits are obtained.

Unfortunately, the method does not work so well for the other mines, as seen, for example, in Figure 15 for Ireland I and Figure 16 for Inland No. 1. In both cases it is difficult to select the best pair of σ's. The values shown on the graphs are therefore very tentative. Under such conditions it is better to try to match the experimental α versus f plot directly by a theoretical curve based on Eq (9).

Figure 17 shows a set of theoretical curves made to pass through the 955 KHz point on the Inland No. 1 α vs f plot. It is seen that the theoretical curve C, with $\sigma_c = 10 \times 10^{-4}$ Mho/m, $\sigma_r = 0.22$ Mho/m gives a fair match to the data points.

Figure 18 shows similar plots for Ireland I, with all theoretical curves made to pass through the experimental point at 335 kHz. Curve D, with $\sigma_c = 2.0 \times 10^{-4}$ Mho/m, $\sigma_r = 1.092$ Mho/m appears to give the best fit to the experimental values. These values of the σ's are close to the values $\sigma_c = 1.4 \times 10^{-4}$ Mho/m, $\sigma_r = 1.0$ Mho/m determined previously[1] by matching H versus r curves. It is worth noting, however, that the value of σ_r is very sensitive to which theoretical curve is judged to be optimum. Curve C, for example, gives almost as good a fit as Curve D, but the value of σ_r is reduced to about 0.3 Mho/m, which is a more acceptable value for rock conductivity.

Figure 19 shows the case of Ireland II, with two theoretical curves arranged to pass through the experimental point at 950 kHz. Curve A seems to give the better overall fit, with $\sigma_r = 1.0 \times 10^{-4}$ Mho/m, $\sigma_r = 0.54$ Mho/m.

TABLE 1

CONDUCTIVITIES DERIVED FROM THE α VERSUS f PLOTS

Coal Mine	h (m)	K_c	σ_{coal} (Mho/m)	σ_{rock} (Mho/m)	Coal Seam
Robinson Run	1.5	6	0.3×10^{-4}	0.085	Pittsburgh
Federal No. 1	2	6	0.26×10^{-4}	0.084	Pittsburgh
Ireland "II"	2	6	1.0×10^{-4}	0.054	Pittsburgh
Ireland "I"	2	6	2.0×10^{-4}	1.09	Pittsburgh
			1.4×10^{-4}	0.3	Pittsburgh
Pocahontas No. 1					
3 South Area Entry A	1.37	6	3×10^{-5}	0.01	Pocahontas No. 3
3 South Area Entry B	1.37	6	3×10^{-5}	0.0077	Pocahontas No. 3
2 North No. 1 (Plow Area)	1.19	6	6×10^{-5}	0.017	Pocahontas No. 3
Inland No. 1	3	6	1.0×10^{-3}	0.22	Herrin No. 6
Peabody No. 10					
1 Main South 1st West 2nd North	2	6	4×10^{-3}	0.3	Herrin No. 6
1 South 5-1/2 East/ 1 South Jct.	2	6	2.5×10^{-3}	0.3	Herrin No. 6

V. MAGNETIC FIELD CALCULATED FROM THE CONDUCTIVITIES

From the conductivities given in Table I one can calculate α and β from Eq (9), δ_r from Eq (2), and H versus r from Eq (10). The results are shown in Figures 25-46 in comparison with the experimental H versus r plots. It is seen that the theoretical curves correspond qualitatively with the experimental data. The agreement is best for Robinson Run (Figures 25 and 26) and Federal No. 1 (Figures 27 and 28). This is not surprising since for these mines the derivation of σ_c and σ_r from the α versus f plots is quite unambiguous. It may be concluded that the three-layer model is valid for these two mines and also that the theoretical formulas (10) and (9) are correct. However, in spite of the generally favorable overall agreement with regard to form and relative variations with frequency, there remain some annoying differences in absolute level between the theory and data to be resolved. Namely, the theoretical curves for the Robinson Run mine are about 4 dB too high for the frequencies up to 500 kHz and about 14 dB too high above 500 kHz; while the Federal No. 1 theoretical curves are all about 10 dB too high. The nature of these differences strongly suggests a systematic irregularity in either the theory or measurements.

The comparison for Inland No. 1 (Figures 29 and 30) shows good agreement for the frequencies up to 955 kHz but wide divergence for 2000 and 4750 kHz, as was to be expected from the peculiar behavior of the α versus f plot (Figure 6). The agreement at the lower frequencies, where scattering and resonance effects would be unlikely, indicates that the three layer model is valid at least for these frequencies.

In the case of Ireland "II" (Figures 31 and 32) the agreement is surprisingly good, considering the uncertainties due to the presence of electrical cables in adjacent entries. Again the three-layer model seems to be justified.

Figures 33, 34, and 35 show theoretical H vs r curves corresponding, respectively, to the σ's for curves B, C, and D for Ireland "I" in Figure 18. Comparison with the experimental data (Figure 37) shows that the theoretical curves do not reproduce the wide spread in level of the experimental curves. Figure 33, with $\sigma_c = 1.0 \times 10^{-4}$ Mho/m and σ_r = 0.1172 Mho/m seems to give the best fit. The slopes of the theoretical curves are about right but the spread in level is too small and the average level is too low.

Figure 36 shows earlier calculations made by a cut-and-try procedure aimed at getting the best fit at 920, 350, and 230 KHz. It is seen that when this is done the 115 and 57.5 KHz curves turn out to be much too high compared with the experimental curves. It is to be noted that σ_c is about the same for Figures 33 and 36, while σ_r is 0.1172 Mho/m for Figure 33 and 1.0 Mho/m for Figure 36. It seems therefore that the slopes can be matched approximately to the experimental values for $\sigma_c \approx 1 \times 10^{-4}$ Mho/m but that matching the level requires a value of σ_r of about 1 Mho/m for the highest frequency and about 0.1 Mho/m for the lowest frequency.

As pointed out in our earlier report, this means that a three-layer model with frequency independent constitutive properties (σ_r, σ_c, K_r, K_c) is not quite adequate for the Ireland "I" mine for frequencies below about 200 KHz. Since the skin depth increases with decreasing frequency, rock material farther removed from the coal seam will be sampled by the wave at lower frequencies. If this material is of significantly lower conductivity than the rock material adjacent to the coal seam, it will present to the lower frequency a lower effective rock conductivity than that observed at higher frequencies. Thus an even larger skin depth results, which in turn increases the loss and reduces the coupling to the mode as shown by the $\left[h + (1 - i)\delta_r\right]^{-1}$ factor in Eq (3). Such considerations suggest that a five-layer model like the one examined by R. Decker of Spectra Associates might be useful to represent the behavior of the Ireland "I" mine location.

Figures 38 and 39 for the 3 South area, Entry A of Pocahontas No. 1 mine show that the theory is in fair agreement with the experimental results except at the highest frequencies of 3200 and 3800 kHz, for which the experimental results show a decrease in attenuation rate at ranges beyond about 70 meters. This trend is very probably due to the presence of conductors in the form of an air line in the adjacent entry and a track and trolley wire two entries away.

Figure 41 for Entry B in the same area of the Pocahontas mine, but one entry farther away from the conductors, still seems to show some effect from the conductors at 920 and 2720 kHz but agrees qualitatively with the theoretical curves in Figure 40. The experimental curve for 51 kHz in Figure 41 gives only relative values.

Figures 42 and 43 refer to the 2 North No. 1 Plow area of the Pocahontas No. 1 mine. The measurements were made along an entry adjacent to an entry containing a track and trolley wire, with the transmitter located in the adjacent entry two entries away from the track and trolley wire. Again the effect of the conductors is clearly seen in the difference between the theoretical and experimental curves for 3100 kHz.

Figures 44 to 47 show comparisons of theoretical and experimental results for two areas in the Peabody No. 10 mine. There is good qualitative agreement between theory and experiment at all frequencies, with no evident effect of conductors.

VI. DETERMINATION OF THE CONDUCTIVITIES AT EACH FREQUENCY SEPARATELY

In principle one should be able to determine σ_c and σ_r from the $H\sqrt{r}$ versus r plot at a single frequency by taking into account the vertical position of the $H\sqrt{r}$ versus r straight line as well as its slope, i.e., by noting the value of H on the line at some selected point r_o. For example, the 255 KHz data for the Inland No. 1 mine, shown in Figure 48, give a slope $\alpha = 0.0468\ m^{-1}$, and a field level H (80 m) = 12 dB re 1 μA/m. Knowing α and taking a trial value of σ_c, we calculate σ_r and β from Eq (9), δ_r from Eq (2), and H (80 m) from Eq (10). This procedure is repeated for a succession of values of σ_c until the target value H (80 m) = 12 dB re 1 μA/m is reached, as shown in Table II.

TABLE II

H (80 m) VERSUS σ_c

(for $\alpha = 0.0468\ m^{-1}$)

σ_c (Mho/m)	σ_r (Mho/m)	β (m^{-1})	δ_r (m)	H (80 m) (dB re 1 μA/m)
6×10^{-4}	0.0675	0.0320	3.844	9.7
7×10^{-4}	0.1024	0.0328	3.103	10.8
8×10^{-4}	0.1517	0.0336	2.250	11.7
9×10^{-4}	0.2195	0.0346	2.120	12.5
10×10^{-4}	0.3131	0.0356	1.775	13.2

It is seen that the target value of H is reached for σ_c between 8×10^{-4} and 9×10^{-4} Mho/m. On interpolating linearly we find that $\sigma_c = 0.85 \times 10^{-4}$ Mho/m, $\sigma_r = 0.20$ Mho/m, $\beta = 0.0341\ m^{-1}$ and $\delta_r = 2.335$ m. The final step is to calculate H (r) by Eq (10) and compare the result with the original experimental data, as in Figure 49, where it is seen that the fit is quite good.

The same procedure applied to the data for 335, 495, and 955 KHz gives approximately the same value of σ_r. We therefore assume that σ_r = 0.2 Mho/m for all frequencies, and then determine the value of σ_c that gives the best theoretical fit to the experimental H versus r plot at each frequency. The values of σ_c so obtained and the degree of fit are shown in Figures 49-54. The values of σ_c at 2000 and 4750 KHz are to be regarded as effective values that allow for whatever mechanism causes the abnormal values of α at these frequencies, as seen in Figure 6.

It turns out that the method illustrated in Table II, although successful for the Inland No. 1 mine, does not work in most other cases. The reason is that the range of the calculated values of $H(r_o)$, which may differ by less than only 1 dB for a large variation of σ_c, usually does not overlap the experimental value $H(r_o)$.

VII. STATISTICAL ANALYSIS OF THEORETICAL AND EXPERIMENTAL DATA VERSUS FREQUENCY

Figures 55-63 show plots of H_{THEOR}/H_{EXPT}, expressed in dB, versus frequency, at a standard range of 100 m which was chosen to be beyond the longitudinal skin depth $1/\alpha$ but within the range of most of the data. H_{EXPT} at a given frequency is the value determined from the $H\sqrt{r}$ versus r plot at 100 m, while H_{THEOR} is the theoretical value determined from the coal and rock conductivities derived from the α versus f curve.

For the mines of the Pittsburgh and Pocahontas seams, Figures 55-60, H_{THEOR}/H_{EXPT} is greater than 0 dB on the average and does not seem to have any systematic trend with increasing frequency. On the other hand, the mines of the Illinois seam (Figures 61-63) appear to show that H_{THEOR}/H_{EXPT} is about 0 dB on the average but tends to increase with frequency.

These differences in behavior can be attributed, as pointed out previously, to departures of the geological structure of the mines from the three-layer model assumed in the theory and to some extent random uncertainties in the measurements. If the overburden and underburden are not uniform in conductivity, as supposed, the surface impedances of the over- and underburdens no longer have a phase angle of 45° as in the case of a medium of uniform high conductivity. This alters the form of the transmission line equation, (9), and the effective magnetic moment equation (3). Therefore, it changes the way in which the attenuation constant α varies with frequency and the coupling to the coal seam TEM mode.

To determine the goodness of fit between the simple three-layer model predicted results and the measured data, the theoretical and experimental values have also been compared on a statistical basis. The ratio $\Delta = H_{THEOR}/H_{EXPT}$ expressed in dB was analyzed statistically as a result of trends shown by the Figures 55-63 plots of Δ versus frequency, at the standard range of 100 meters, for data taken from each of the mines. The Δ plots showed a small and relatively uniform disagreement, mainly on the high side, between about 100 and 1000 kHz, and progressively increasing disagreement, again on the high side, below 100 kHz and above 1000 kHz. The data at the higher frequencies also demonstrated considerable scatter relative to the predicted results.

The statistical analysis of Δ was restricted to data for the frequencies between 100 kHz and 1000 kHz at the reference distance of 100 meters. For frequencies outside the 100 to 1000 kHz range, the Δ plots indicated that the applicability of the simple three-layer model was breaking down. One hundred meters was chosen as the reference distance because it allowed most of the data from six mines in both low and high loss coal seams to be included, while avoiding near field effects in most cases. The ratio Δ in dB between theory and data in the 100 to 1000 kHz band was analyzed by:

- Computing the Sample Mean $\bar{\Delta} = \frac{\Sigma\Delta}{n}$ for each seam and the variance of Δ for the total sample population as a function of frequency (there were too few samples within each seam to compute a standard deviation on a seam basis).
- Computing the Sample Grand Mean for all mines in all three seams, and 95% Confidence Intervals for both the population and Sample Grand Mean as a function of frequency. These results are plotted in Figure 64.
- Testing the hypothesis that the theoretical model fits the data at the 95% Confidence Level for the frequencies between 100 kHz and 1000 kHz.

A detailed description of the statistical analysis is presented in the Appendix. From this analysis, the following observations and conclusions were made. The differences between the model and the experimental data were similar for all coal seams. The shapes of the curves for each seam average followed the same pattern and did not differ from one another by more than 1 or 2 dB, with the exception of the Herrin #6 seam at frequencies below 400 kHz. (At these frequencies, data for only one mine in the Herrin #6 seam was available.) This homogeneity implies that pooling all the data to compute a Grand Sample Mean for all mines is a valid technique, and that the results from any analysis can be applied back to all the mines uniformly.

The plot of the sample $\bar{\Delta}$ and its 95% Confidence Intervals in Figure 64 is a visual hypothesis test (t-test) that the model fits the experimental data, against the alternative hypothesis that the model does not fit the data. The analysis showed that between the frequencies of 200 kHz to 900 kHz, there is <u>no significant</u> difference between the model and the actual data, i.e., the Confidence Interval includes zero. In this band of frequencies the average ratio, Δ, ranges from 1.1 dB to 3.9 dB. The range from 200 kHz to 600 kHz appears to be the best range for the model; both the variance and the average Δ between the model and actual data being smallest, and positive, within this frequency range.

VIII. SELECTION OF OPERATING FREQUENCIES

The data analysis and theoretical modelling of coal seam waveguide radio wave propagation presented above provide a firmer foundation, than previously available, on which to base the selection of operating frequencies for wireless mine communication in the MF band. Large variations in signal attenuation rate have been found between the three coal seams investigated, seams widely separated geographically. The Pittsburgh seam, measured in northern West Virginia was found to be the most favorable, while the Herrin No. 6 seam measured in southern Illinois was found to exhibit extremely high loss.

In this section we briefly examine the behavior of the signal field strength in conductor-free areas versus frequency at two ranges of interest, 400 m (1312 ft.) and 200 m (656 ft.), as a function of the spread of coal and rock conductivity values, σ_c and σ_r, found in the mines and seams listed in Table I. The magnetic field strengths H in dB re 1 μA/m were calculated based on the three-layer model equations (10) and (9), without applying the statistically determined correction $\bar{\Delta}$ of Figure 64. The results are plotted in Figures 65 to 68 for the range of 200 m, and in Figures 69 to 72 for the range of 400 m. For each range, a series of four figures is used to illustrate the change in signal behavior as the coal conductivity is increased through the values 3×10^{-5}, 10^{-4}, 3×10^{-4}, and 10^{-3} Mho/m, while the rock conductivity is allowed to take on values from 3×10^{-2} to 1.0 Mho/m in each case. To reduce the number of variables for this comparative analysis, we have assumed a $K_c = 6$, a seam thickness of $h = 2$ m, and a transmit magnetic moment of 2.5 A-m^2.

Also plotted on these figures for comparison are magnetic field noise levels versus frequency. These noise levels represent the upper bound envelope of average rms values found in active areas of coal mines, and a lower bound noise level representing the intrinsic receiver noise for a narrowband FM radio receiver having an IF bandwidth B = 12 kHz, noise figure F = 6 dB, and loop antenna effective turns area NA = 1 m^2. The active mine noise levels were taken from Figures 73 and 74, which in turn were derived from the sample of magnetic field, time-averaged, rms noise levels measured at spot frequenices in three coal mines by Bensema, Kanda, and Adams[9,10,11] of the National Bureau of Standards.

Examination of Figures 65 to 72 reveals that performance is best for the combination of lowest coal conductivity and highest rock conductivity. Increasing coal conductivity increases the shunt loss in the coal seam waveguide, while decreasing the rock conductivity increases the series loss, both of which increase the signal attenuation rate. Furthermore, as this attenuation rate increases, the frequency behavior changes from a broad bandpass filter type of characteristic centered around 1 MHz for low attenuation rates like those found in the Pittsburgh seam, to an increasingly attenuated low pass filter characteristic having a steadily decreasing cutoff frequency as the attenuation rate increases to values like those found in the Herrin No. 6 seam. This trend toward the attenuated low pass filter behavior is of course more accentuated for the longer communication ranges, i.e., 400 m vs. 200 m.

The most favorable frequencies for communicating to these ranges can be estimated by comparing the signal level curves with the noise level curves plotted on each Figure. The most favorable operating bands are seen to be those where the slopes of the signal and noise curves are equal or nearly equal. Since the signal curves also represent levels for the largest, intrinsically-safe transmit moment, an absolute measure of performance can also be estimated by noting the number of dB that the signal level curve lies above the noise level curve at the frequency of interest. For example, a radio service performance level of Circuit Merit Figure No. 3 (occasional message repetitions required) requires that the average rms carrier-to-noise ratio at an FM receiver be at least 10 dB or better for the mine noise condition prevailing during the message transmission.

The equivalent receiver noise curve is probably the most representative for communication in conductor-free areas that are located at least one or two entries (i.e., separated by one or two pillar widths) away from mine electrical conductors carrying high noise currents. On the other hand, the active mine upper bound noise curves most likely give an overly pessimistic view. In this latter instance, these levels occur in the immediate vicinity of high power machinery and electrical conductors, locations where the signal will also be enhanced by the presence of the conductors. Thus an active area noise curve approximately half way between the two noise extremes is probably more indicative of worst case "conductor-free area" noise levels. These levels are likely to occur in transition regions between conductor-free and conductor-present locations.

Examination of Figures 69 to 72 reveals that conductor-free area portable-to-portable radio ranges on the order of 400 m will be attainable only in highly favorable, low attenuation seams like the Pittsburgh seam. Furthermore, the performance will occur only at operating frequencies between about 900 kHz to 2 MHz, and under noise conditions approaching the receiver noise limited case. Furthermore, Figures 64 to 68 illustrate that conductor-free ranges of 200 m will not be attainable in high loss seams such as the Herrin No. 6 seam, even at frequencies below 100 kHz and under receiver noise limited conditions. The outlook is somewhat improved, but not much, for moderate-to-high loss seams like the Pocahontas No. 3 seam, where 200 m ranges should be possible over a broad band of operating frequencies between about 150 kHz to 1.5 MHz under receiver noise limited conditions.

On a more positive note, the in-mine measurements of Cory and others have also shown that greatly improved radio communication ranges are obtainable in coal mines when the portable units are located in a tunnel having electrical conductors such as a power cable, pager phone line or trolley wire/rail line. Significant range improvements have even been experienced with one and sometimes both of the units located in a tunnel separated by a coal-pillar width from the tunnel with the conductors. In some cases, improvements have also occurred with one of the units located in a tunnel separated by two coal pillars from the tunnel having the electrical conductors. Since these conductors are generally located in haulageways and working sections where miners requiring communications are also located, this propagation condition is an important one. Moreover, it is one that may allow the desired radio communication ranges to be achieved and exceeded even in coal seams having high signal propagation attenuation rates. Therefore, additional data are presently being taken in the vicinity of mine electrical conductors by Cory, and being analyzed by ADL to quantitatively model and assess the impact of such conductors on the attainable radio communication range.

IX. CONCLUSIONS

Based on the physical and statistical analyses applied to the data available to date, it can be concluded that:

- MF band radio wave attenuation rates experienced in coal mine conductor-free areas are highly dependent on the coal seam in which a mine is located; and that this attenuation rate versus frequency can be determined in a simple way from measurements of H vs r.

- The simple three-layer model fits the experimental data in the 200 kHz to 900 kHz frequency band at the 100 meter reference distance, with the best agreement occurring between 200 and 600 kHz. This is the band that also promises to provide the most favorable performance for portable radio communications in coal mines.[1,2] The attenuation rates become unacceptably high above 1 MHz.

- The Sample Grand Mean, $\bar{\Delta}$, of the ratio H_{THEOR}/H_{EXPT} expressed in dB may be used to represent the Means for individual coal seams. Unlike the attenuation rate, the mode coupling factor appears to be independent of the coal seam in which a mine is located.

- Practical MF system performance estimates may be made in the 200 to 900 kHz band by applying the simple three-layer model to seams in which the attenuation rates have been measured, and using the appropriate $\bar{\Delta}$ to correct the predicted field values.

Data to date have come primarily from high-coal seams. Data from four additional mines in low-coal seams will be analyzed in the near future to assess the applicability of the model in thinner coal seams, and as a more rigorous test of the theory.

X. REFERENCES

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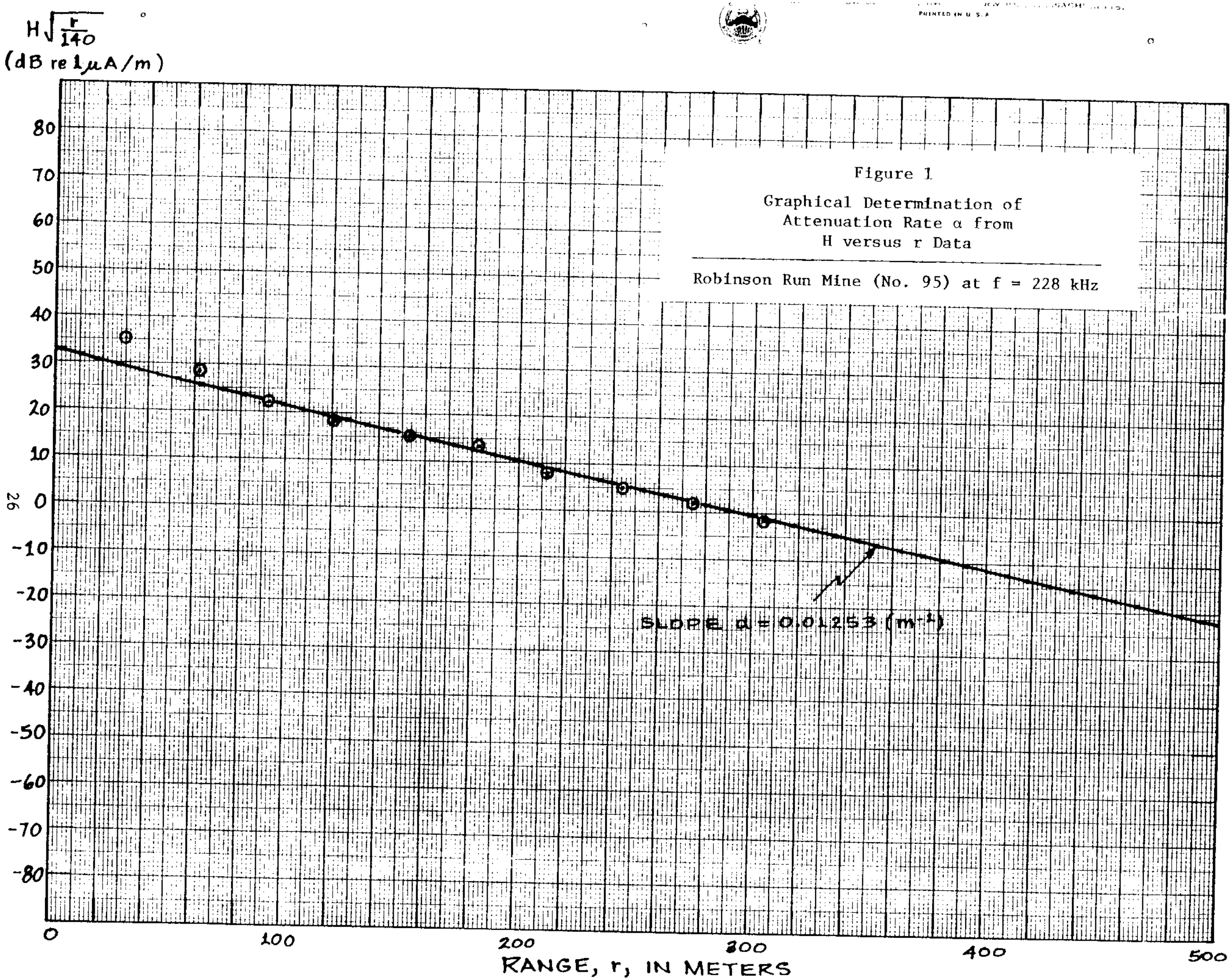


Figure 1

Graphical Determination of Attenuation Rate α from H versus r Data

Robinson Run Mine (No. 95) at f = 228 kHz

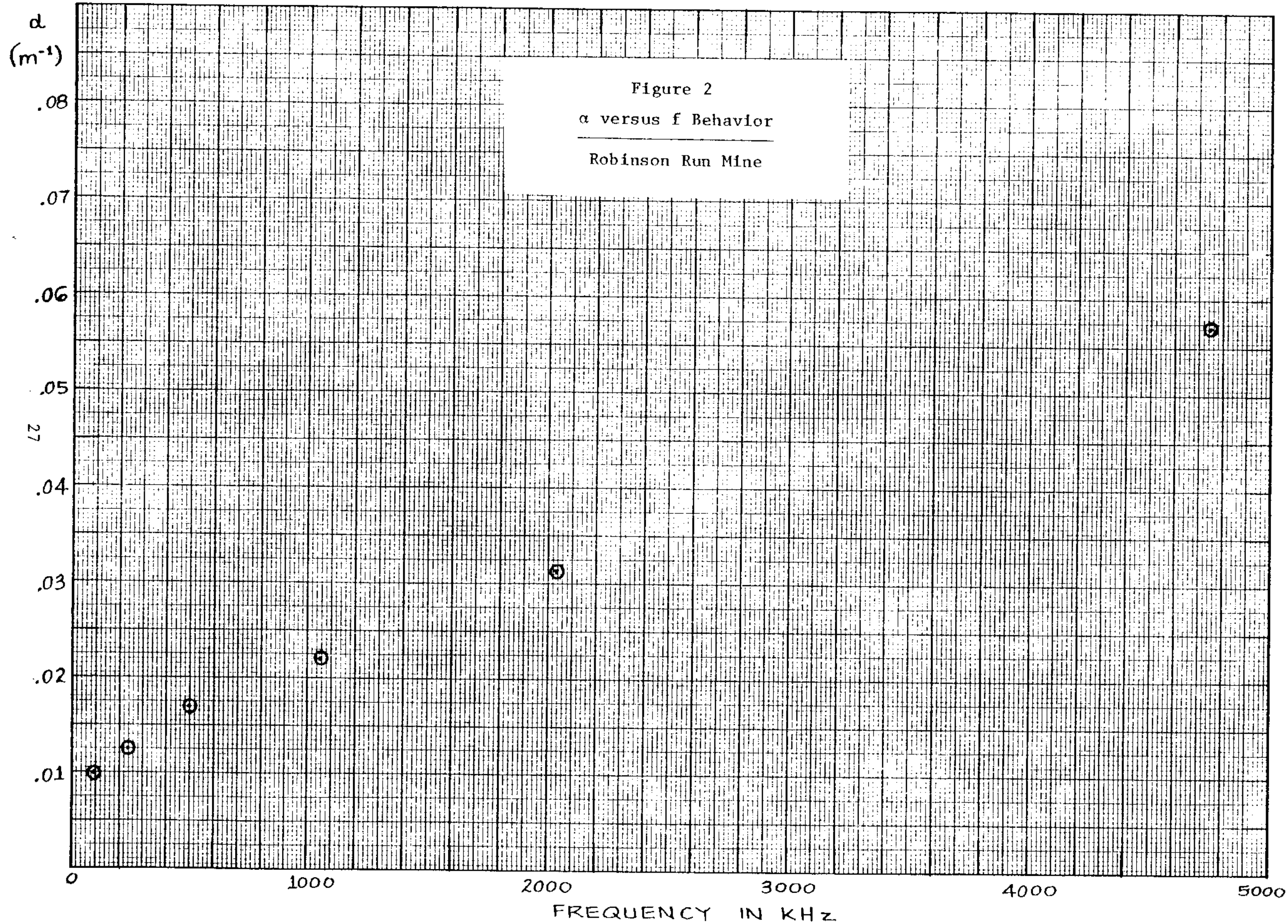


Figure 2
α versus f Behavior
Robinson Run Mine

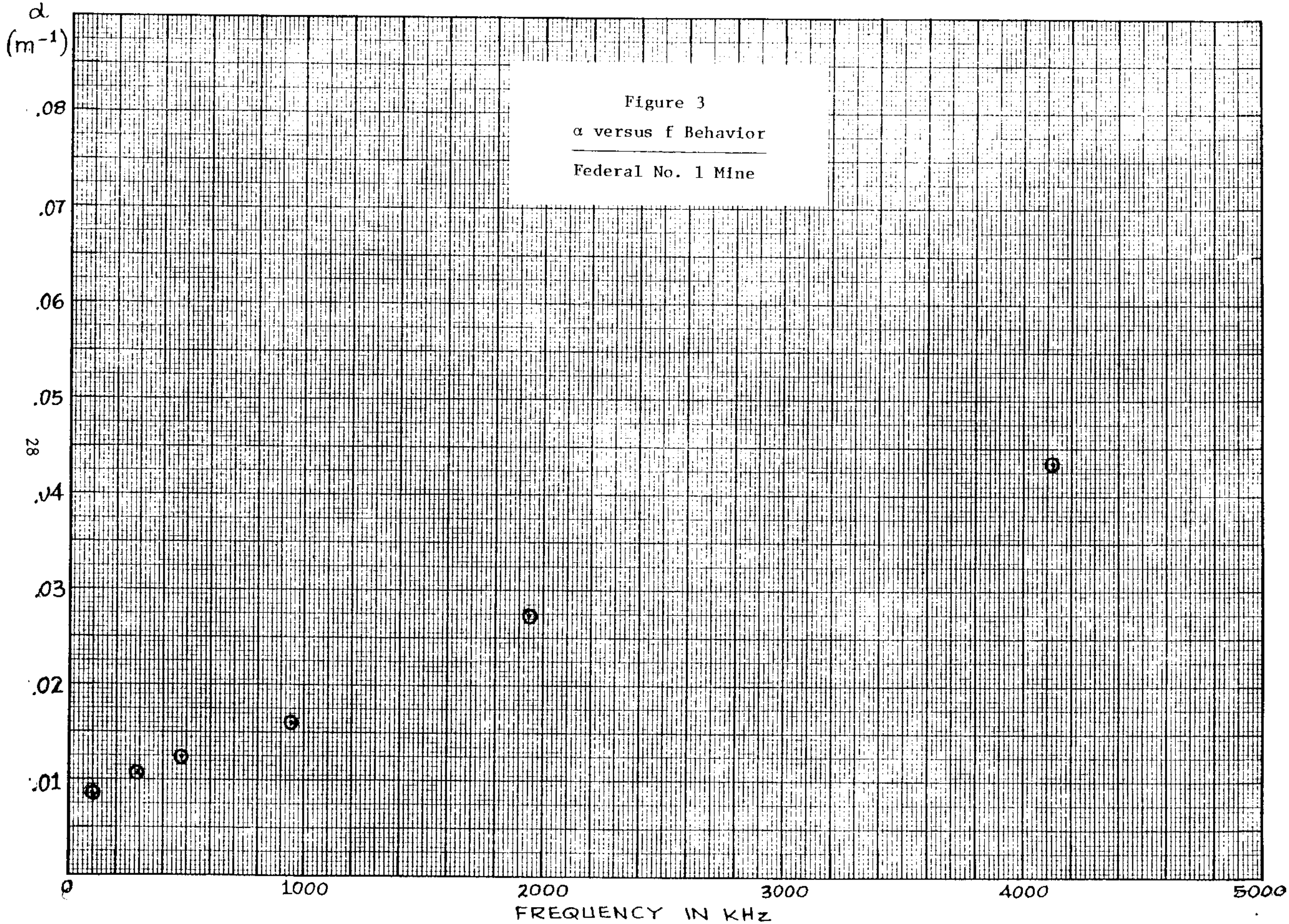


Figure 3

α versus f Behavior

Federal No. 1 Mine

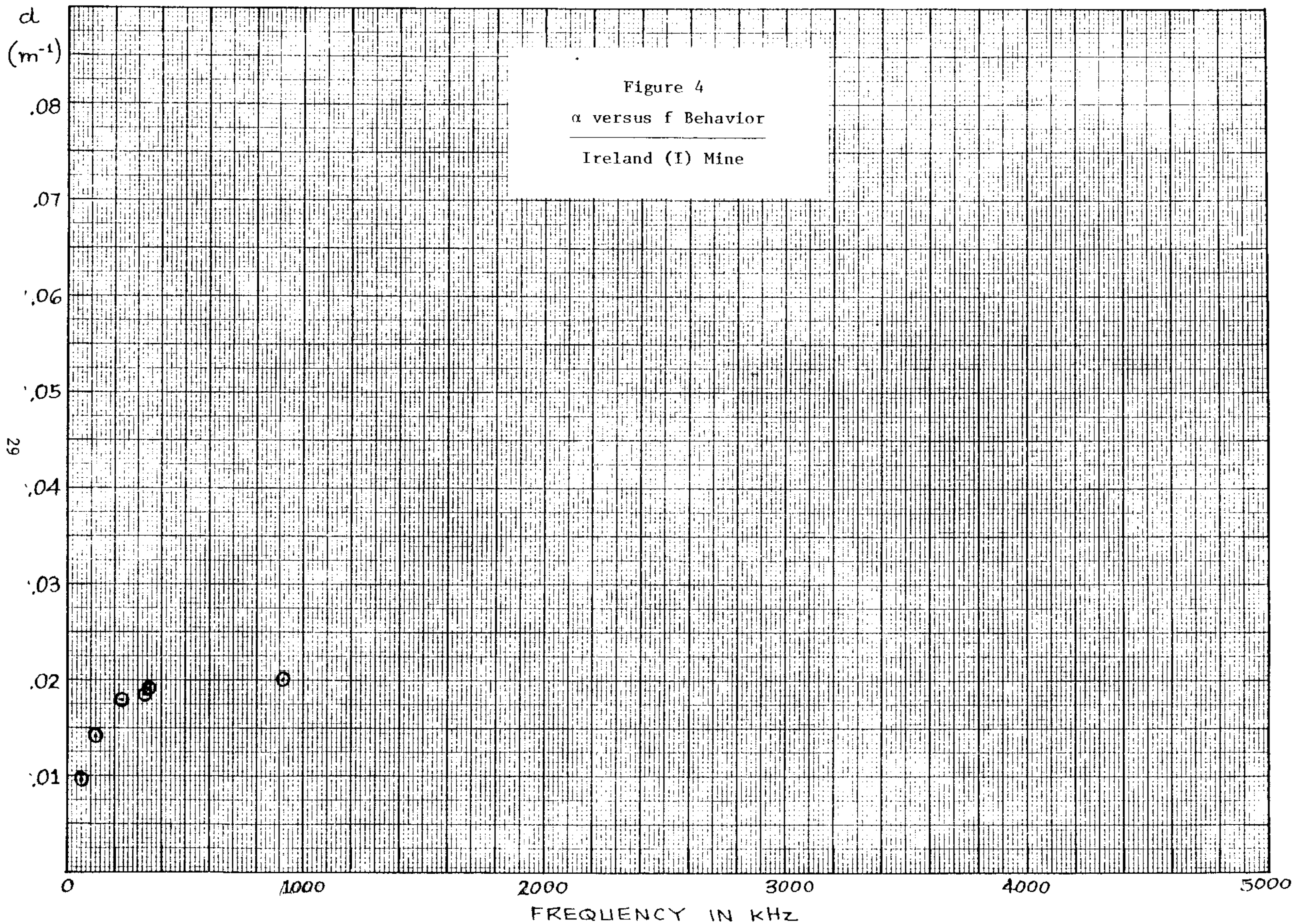


Figure 4
α versus f Behavior
Ireland (I) Mine

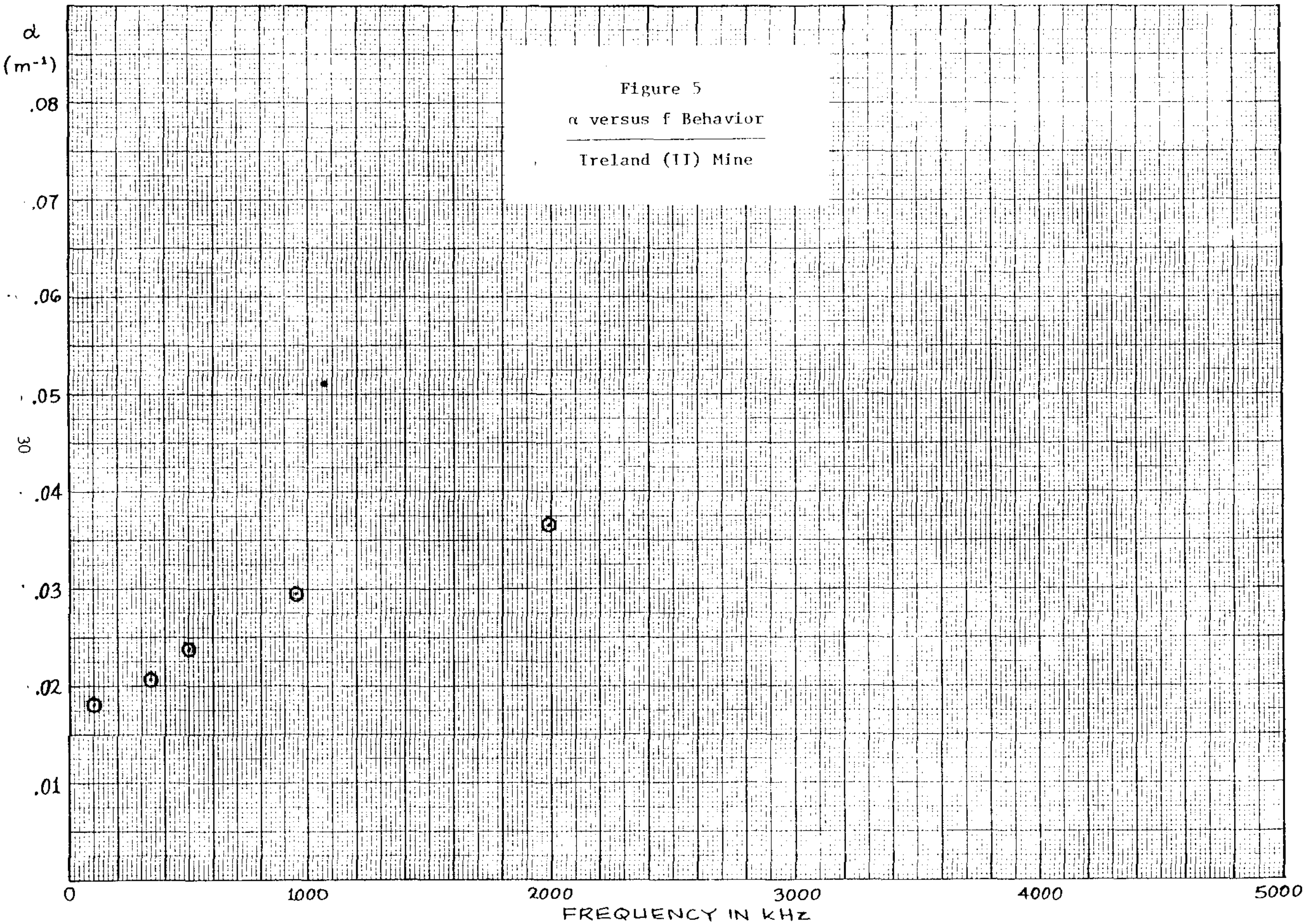


Figure 5
α versus f Behavior
Ireland (II) Mine
α
(m⁻¹)
.08
.07
.06
.05
.04
.03
.02
.01
0
1000
2000
3000
4000
5000
FREQUENCY IN kHz

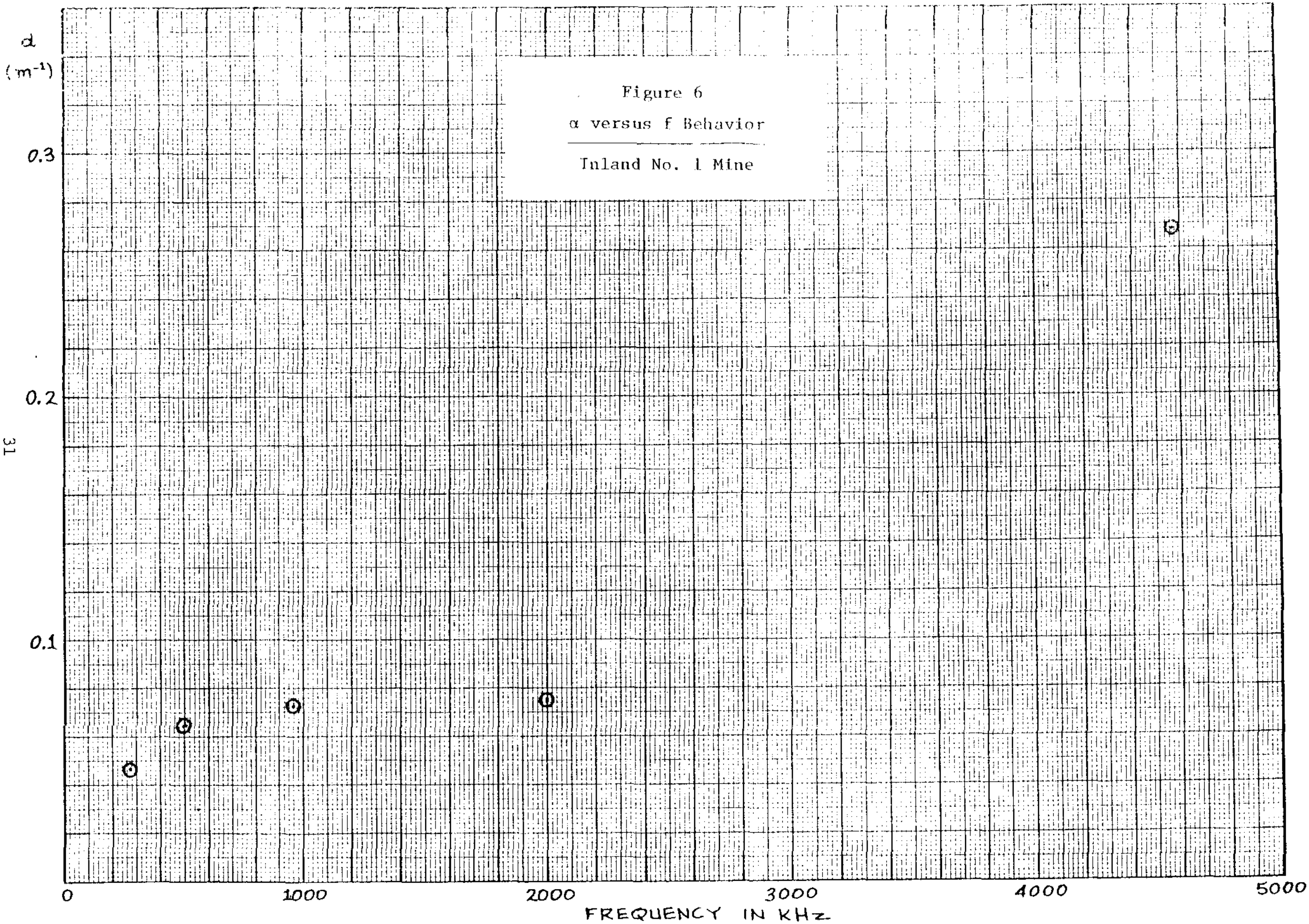


Figure 6

α versus f Behavior

Inland No. 1 Mine

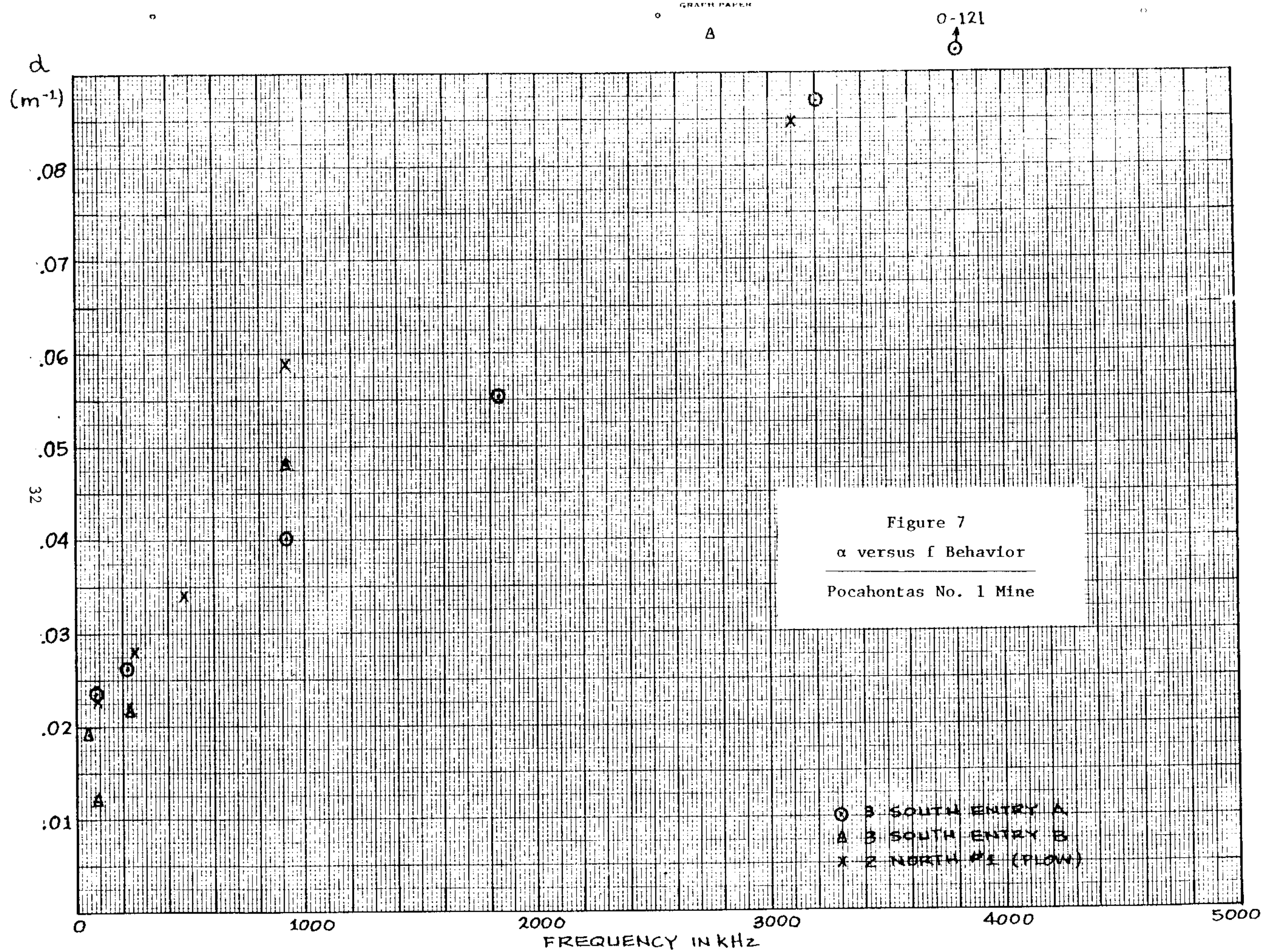


Figure 7
α versus f Behavior
Pocahontas No. 1 Mine

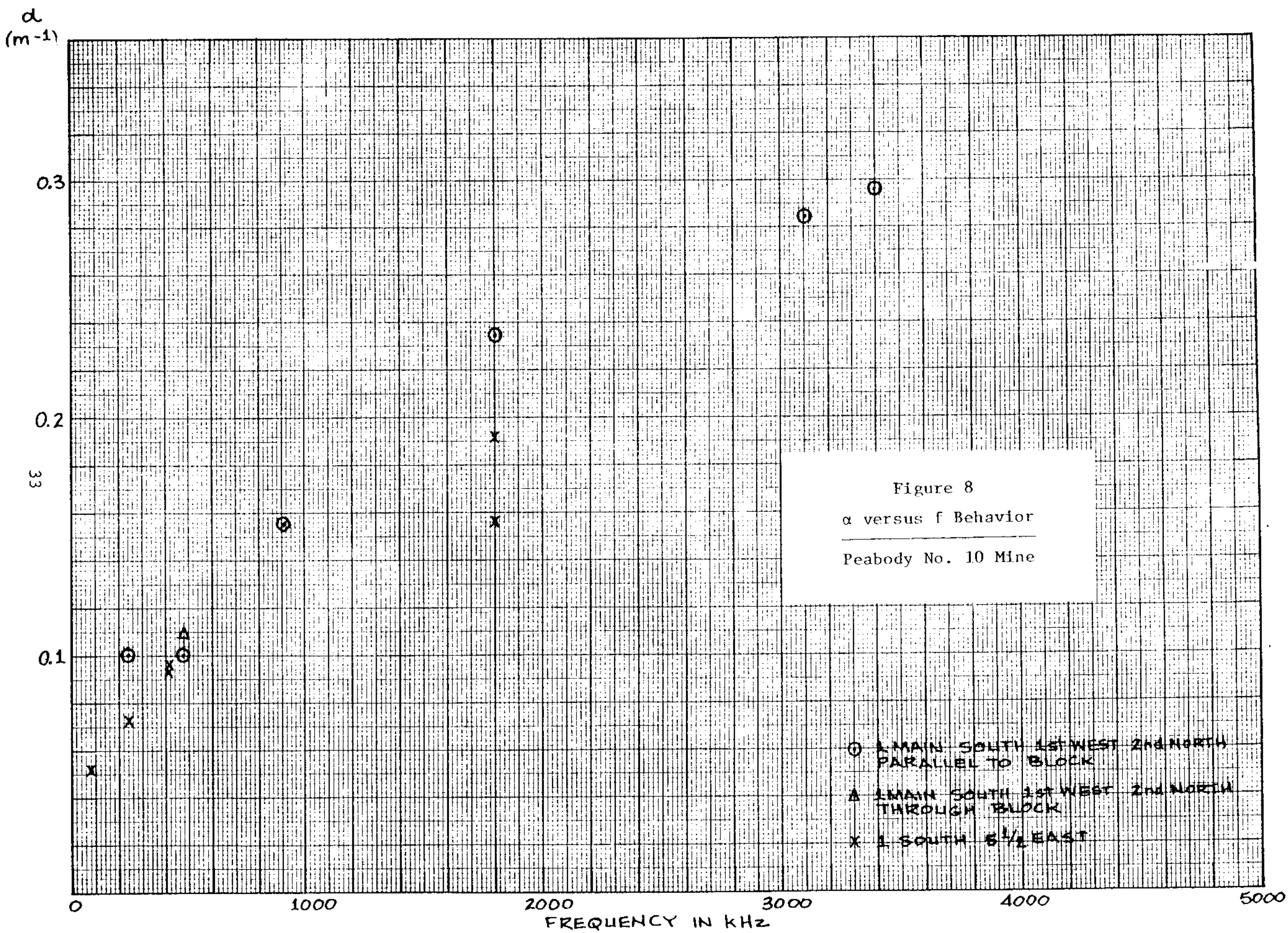


Figure 8

α versus f Behavior

Peabody No. 10 Mine

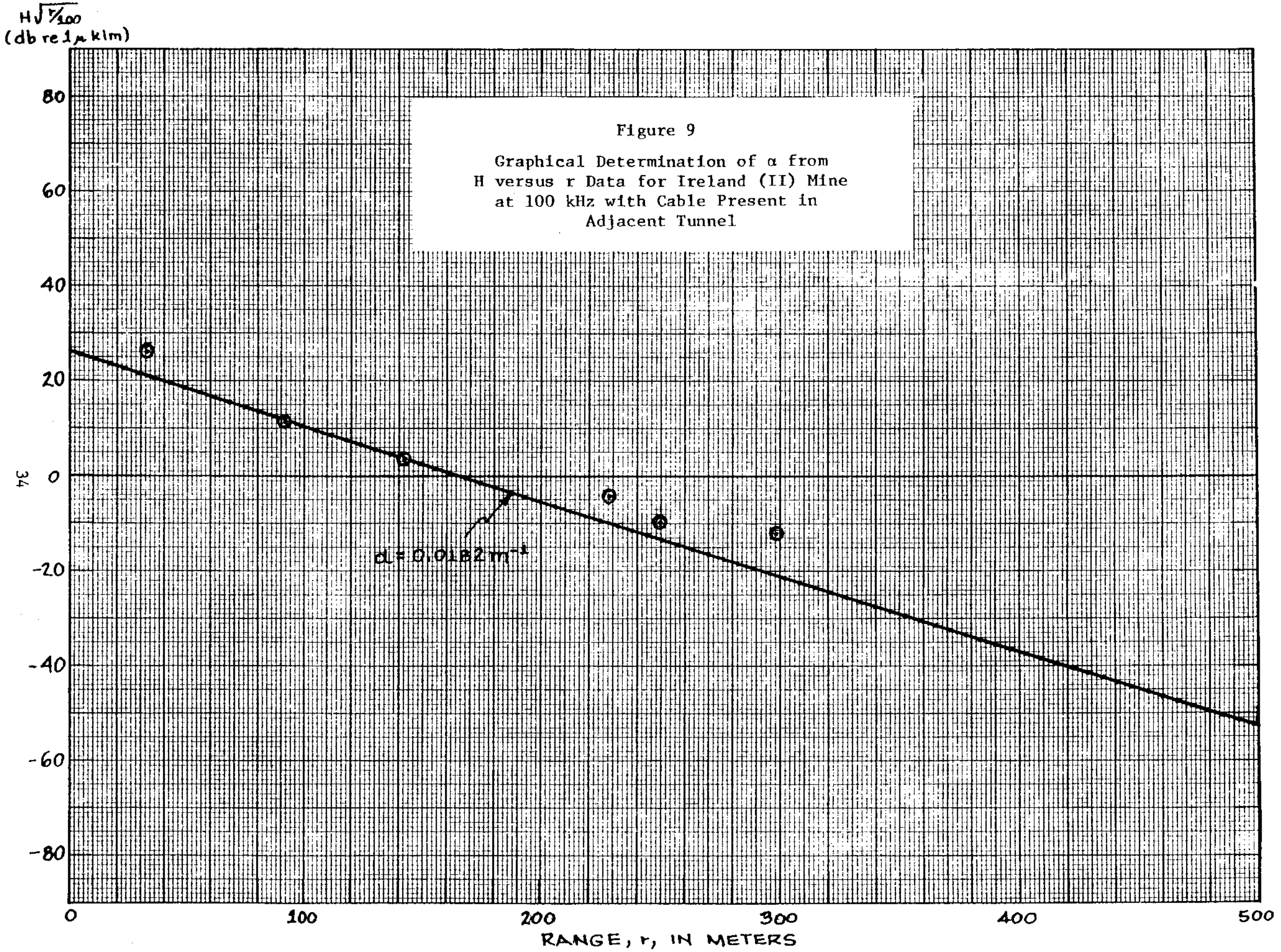


Figure 9

Graphical Determination of α from H versus r Data for Ireland (II) Mine at 100 kHz with Cable Present in Adjacent Tunnel

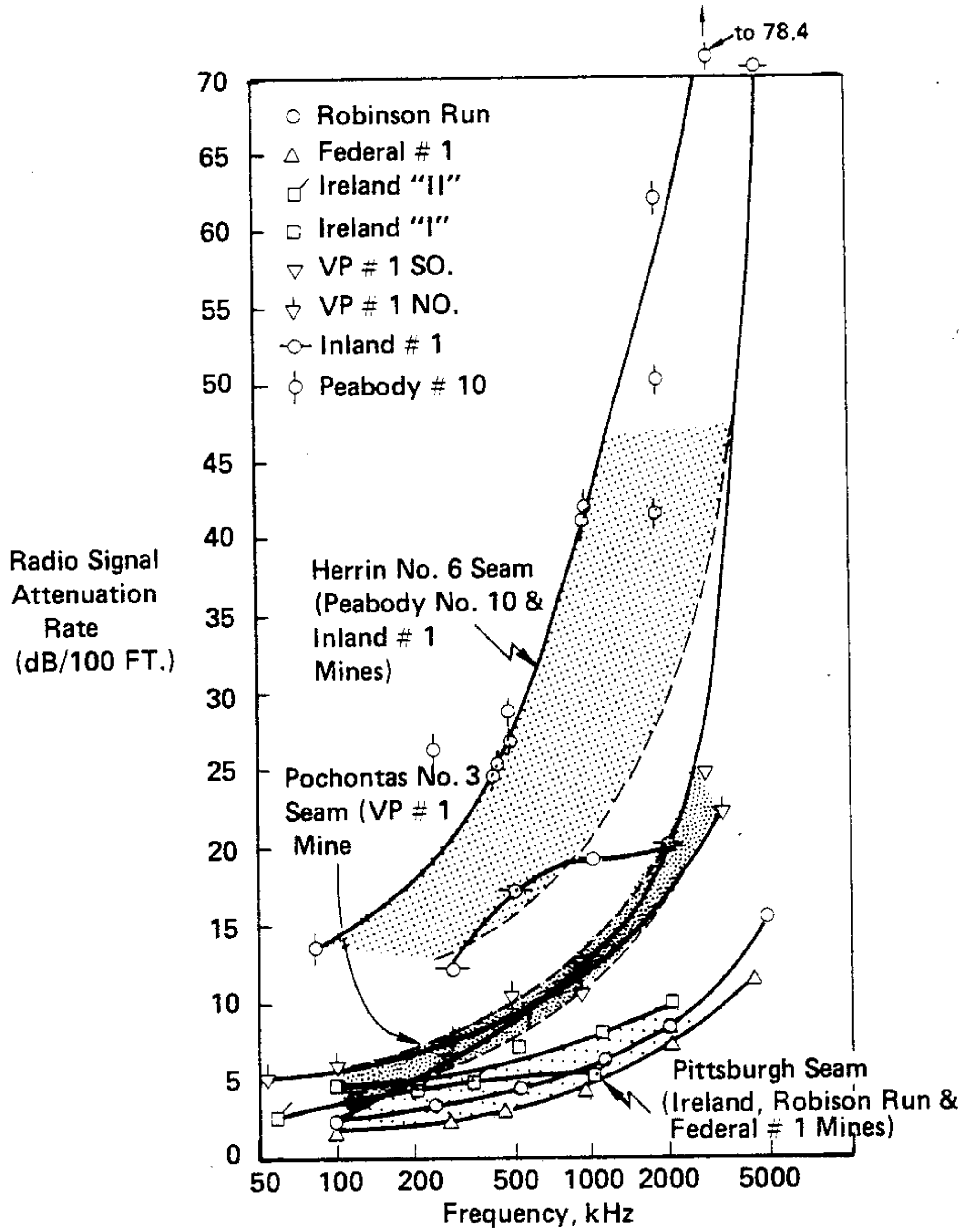


FIGURE 10 COMPOSITE PLOT OF SIGNAL ATTENUATION RATES IN dB/100 FT. FOR SIX MINES IN THREE DIFFERENT COAL SEAMS

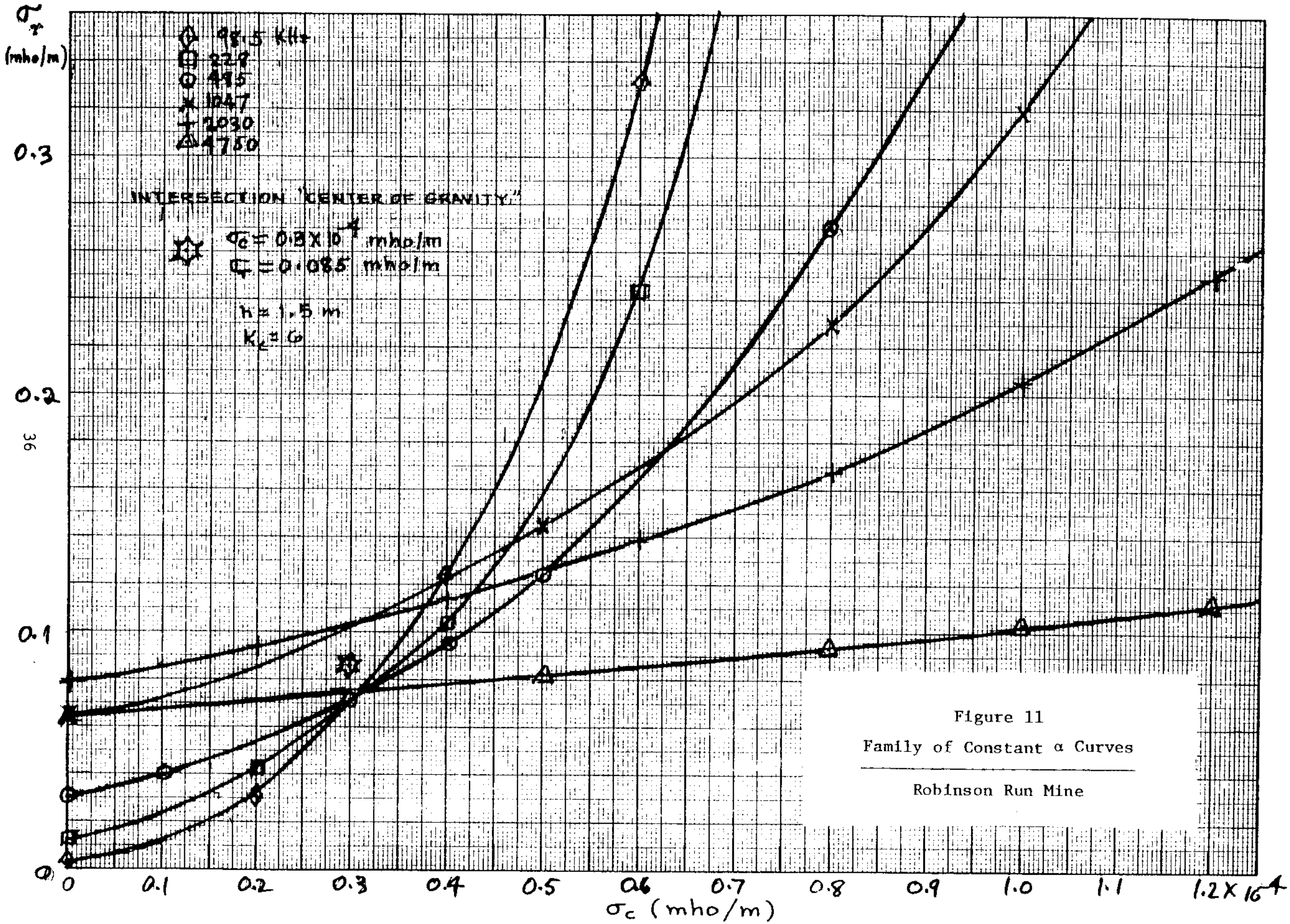


Figure 11

Family of Constant α Curves

Robinson Run Mine

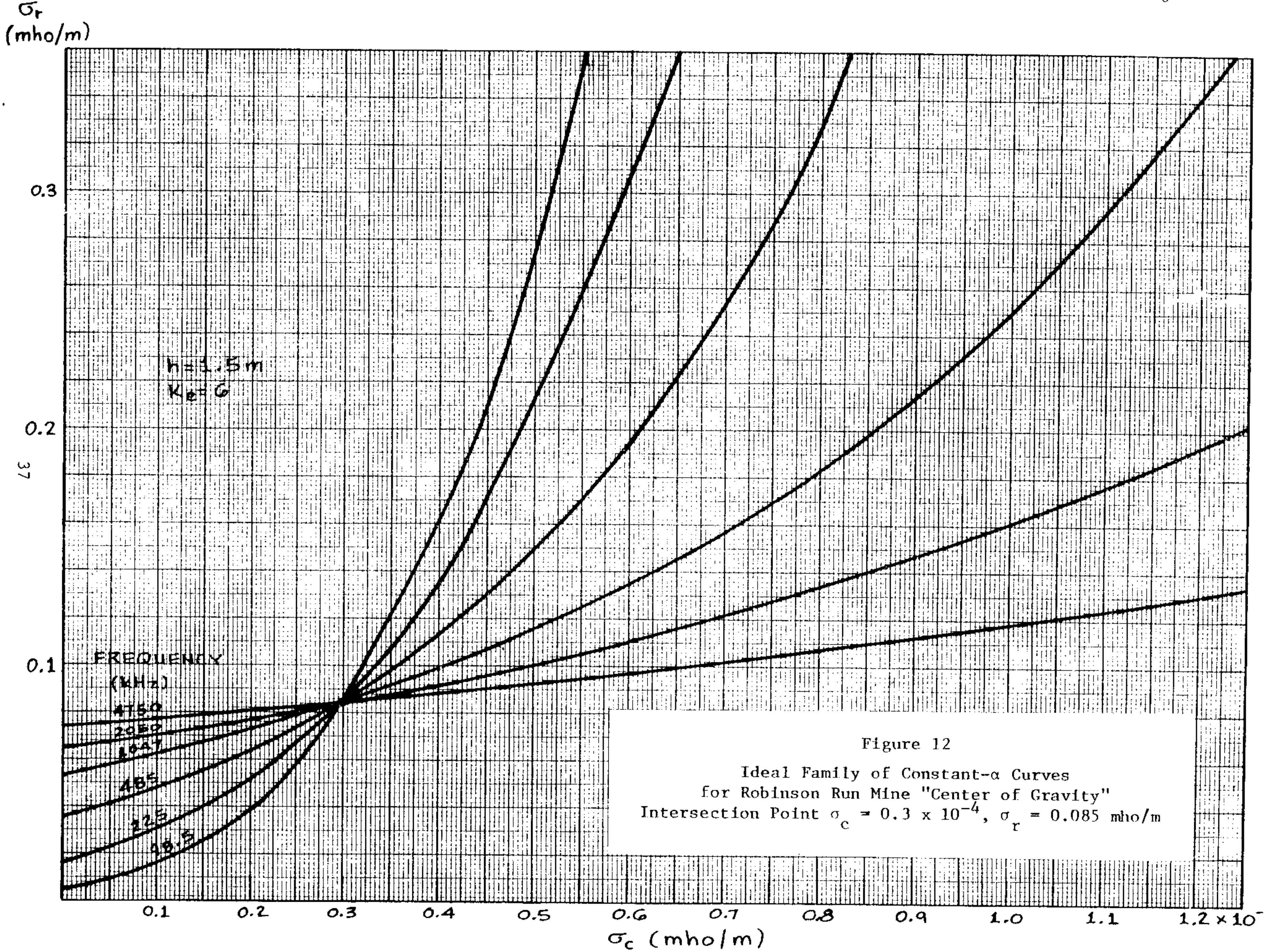


Figure 12

Ideal Family of Constant-α Curves
for Robinson Run Mine "Center of Gravity"
Intersection Point $\sigma_c = 0.3 \times 10^{-4}$, $\sigma_r = 0.085$ mho/m

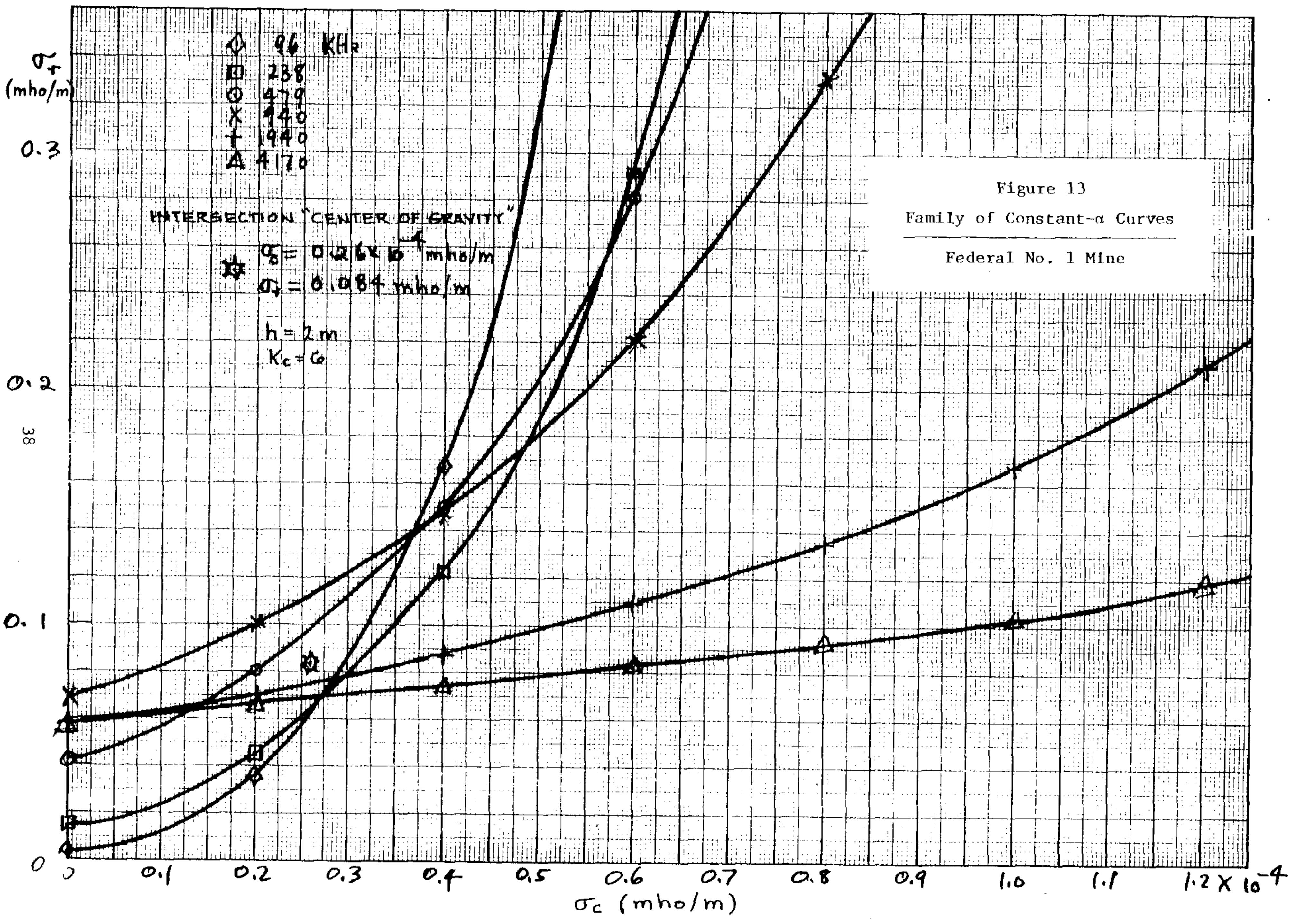


Figure 13

Family of Constant-α Curves

Federal No. 1 Mine

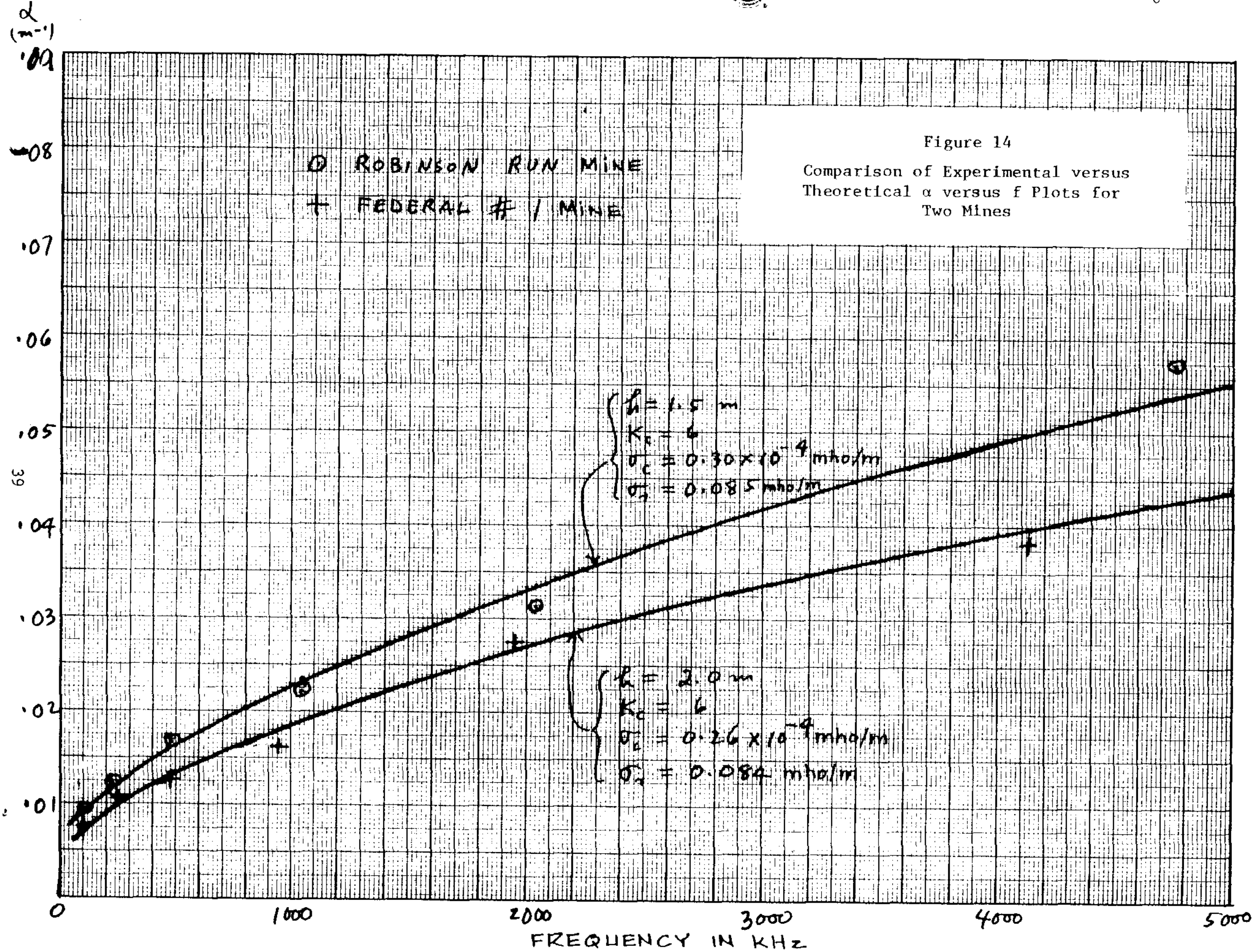


Figure 14

Comparison of Experimental versus Theoretical α versus f Plots for Two Mines

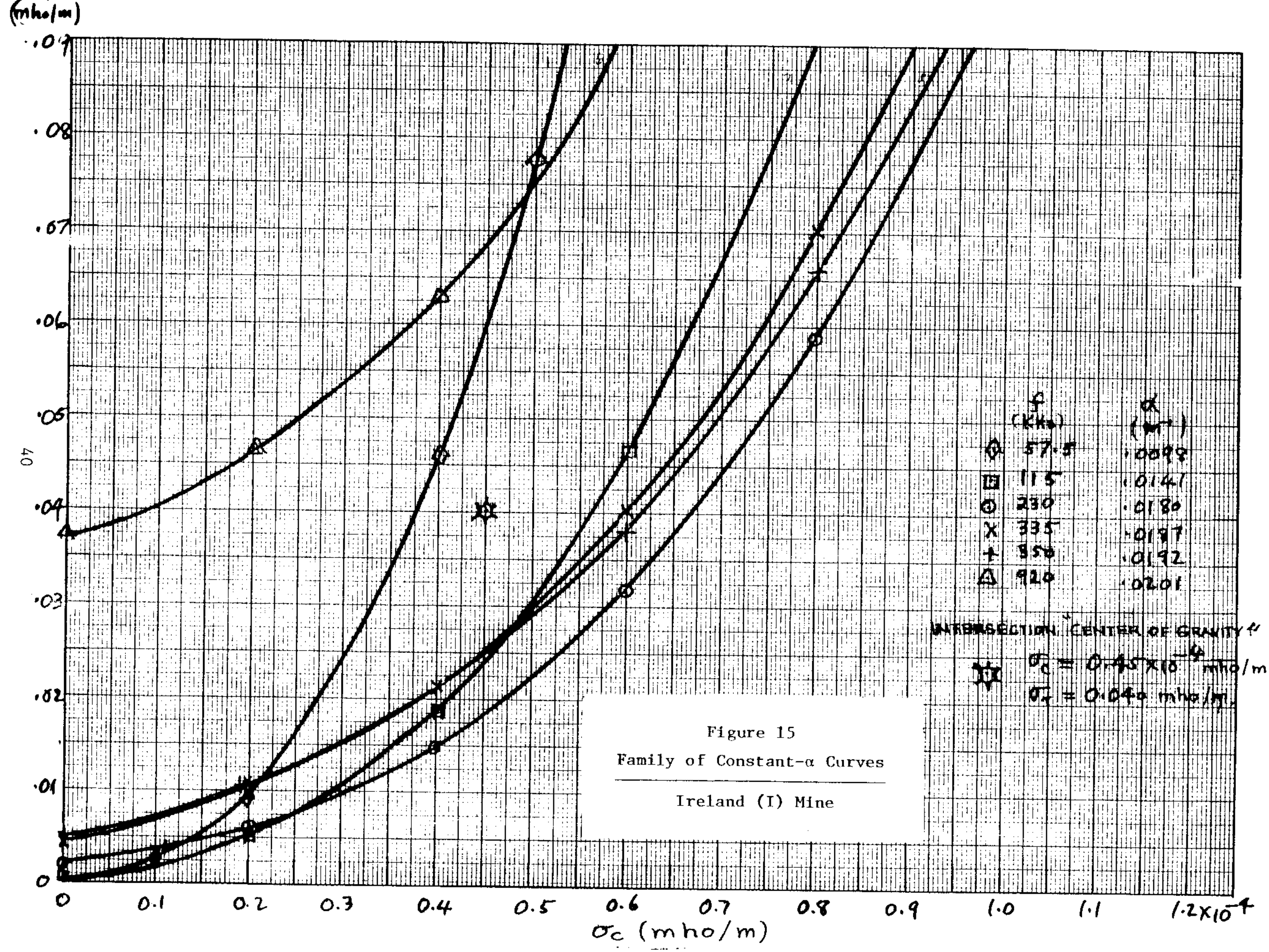


Figure 15

Family of Constant-α Curves

Ireland (I) Mine

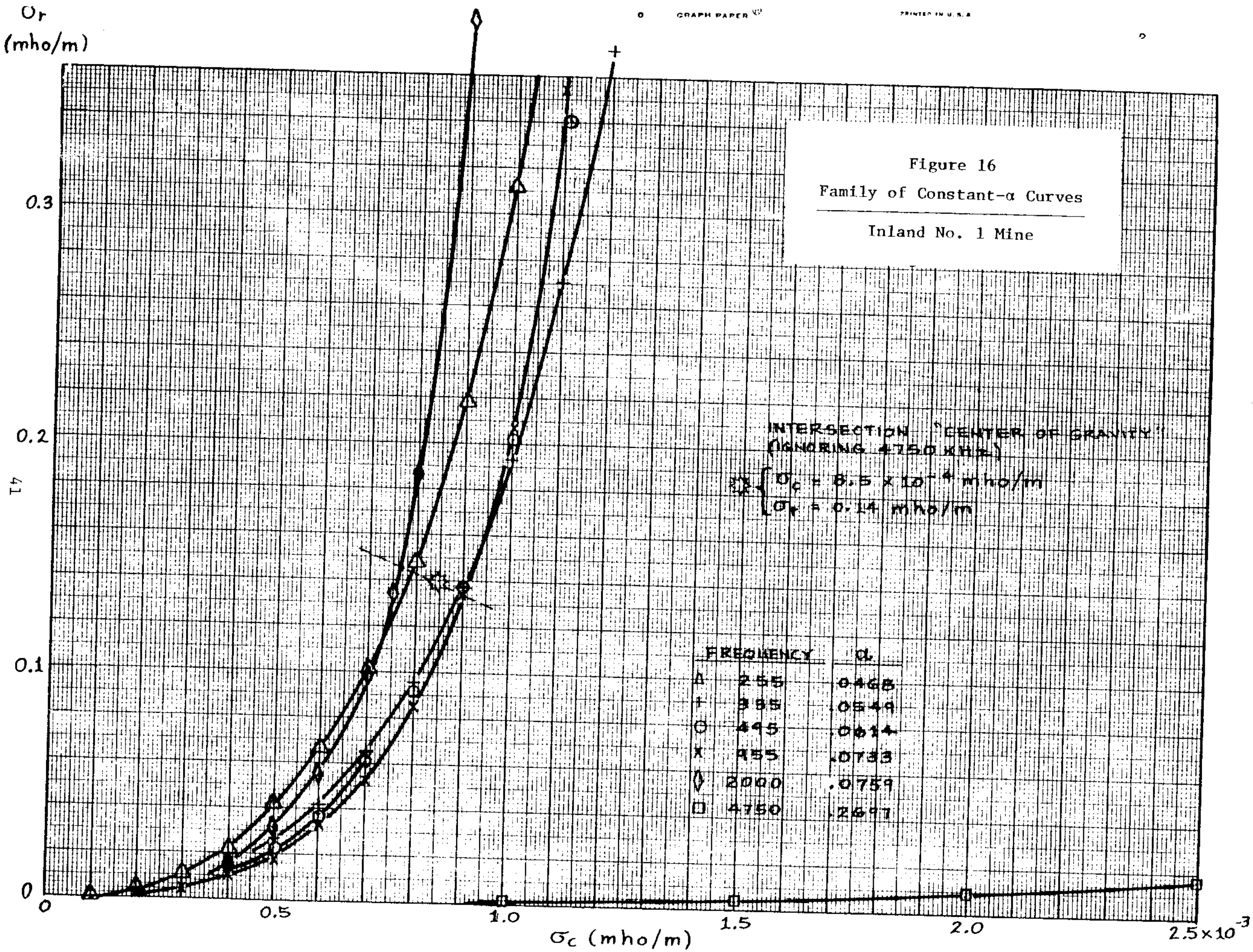


Figure 16
Family of Constant-α Curves
Inland No. 1 Mine

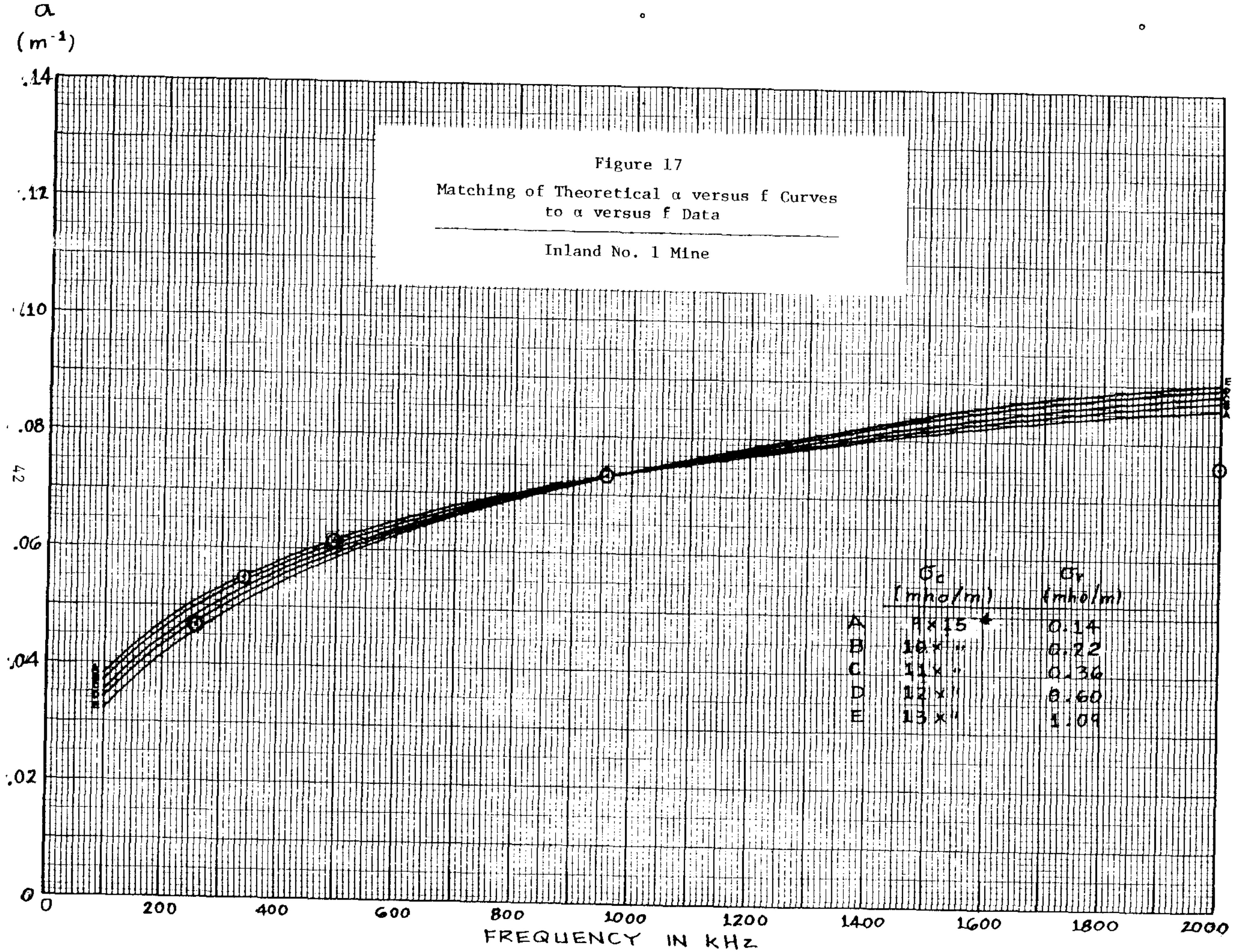


Figure 17

Matching of Theoretical α versus f Curves to α versus f Data

Inland No. 1 Mine

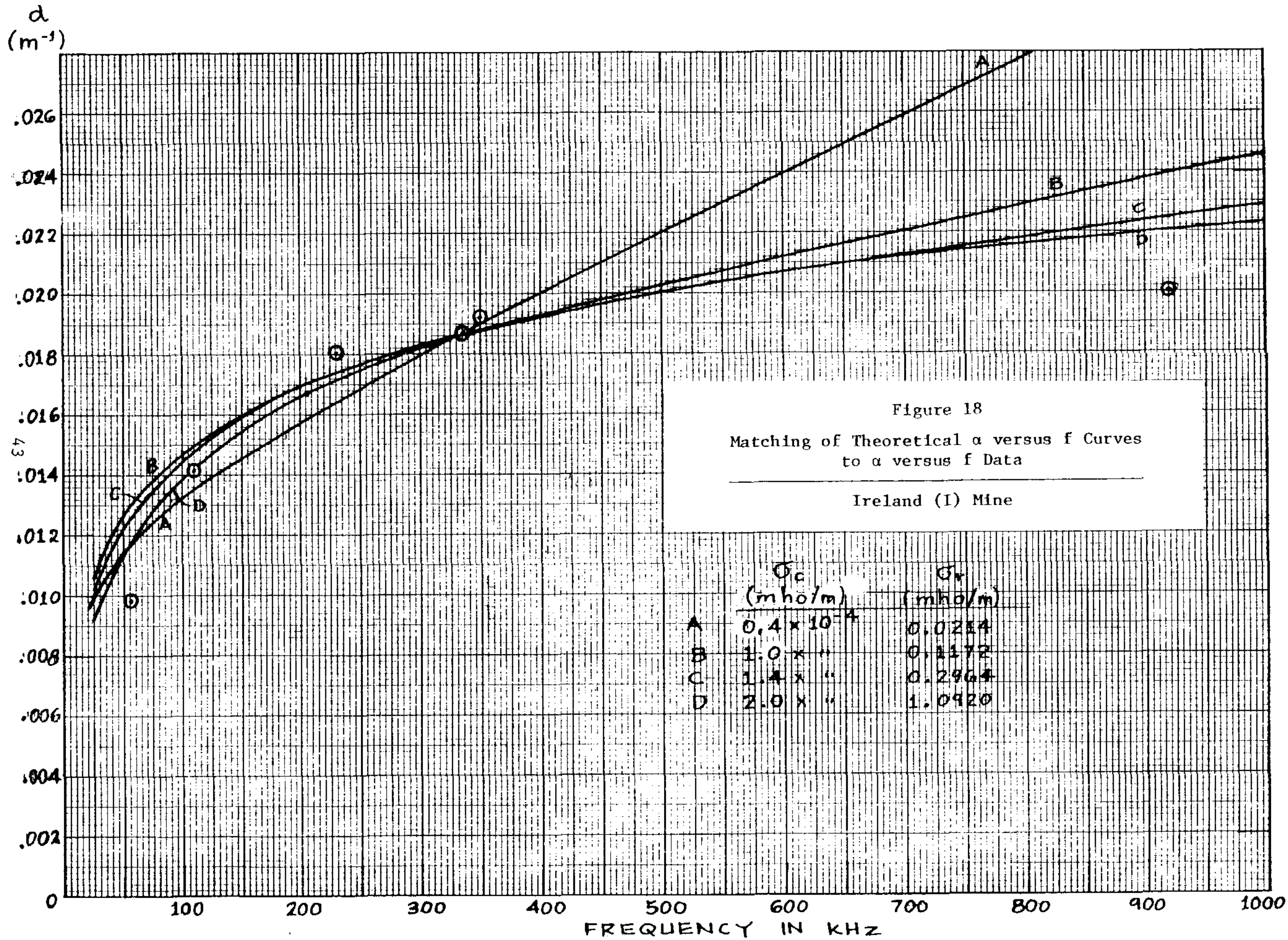


Figure 18

Matching of Theoretical α versus f Curves to α versus f Data

Ireland (I) Mine

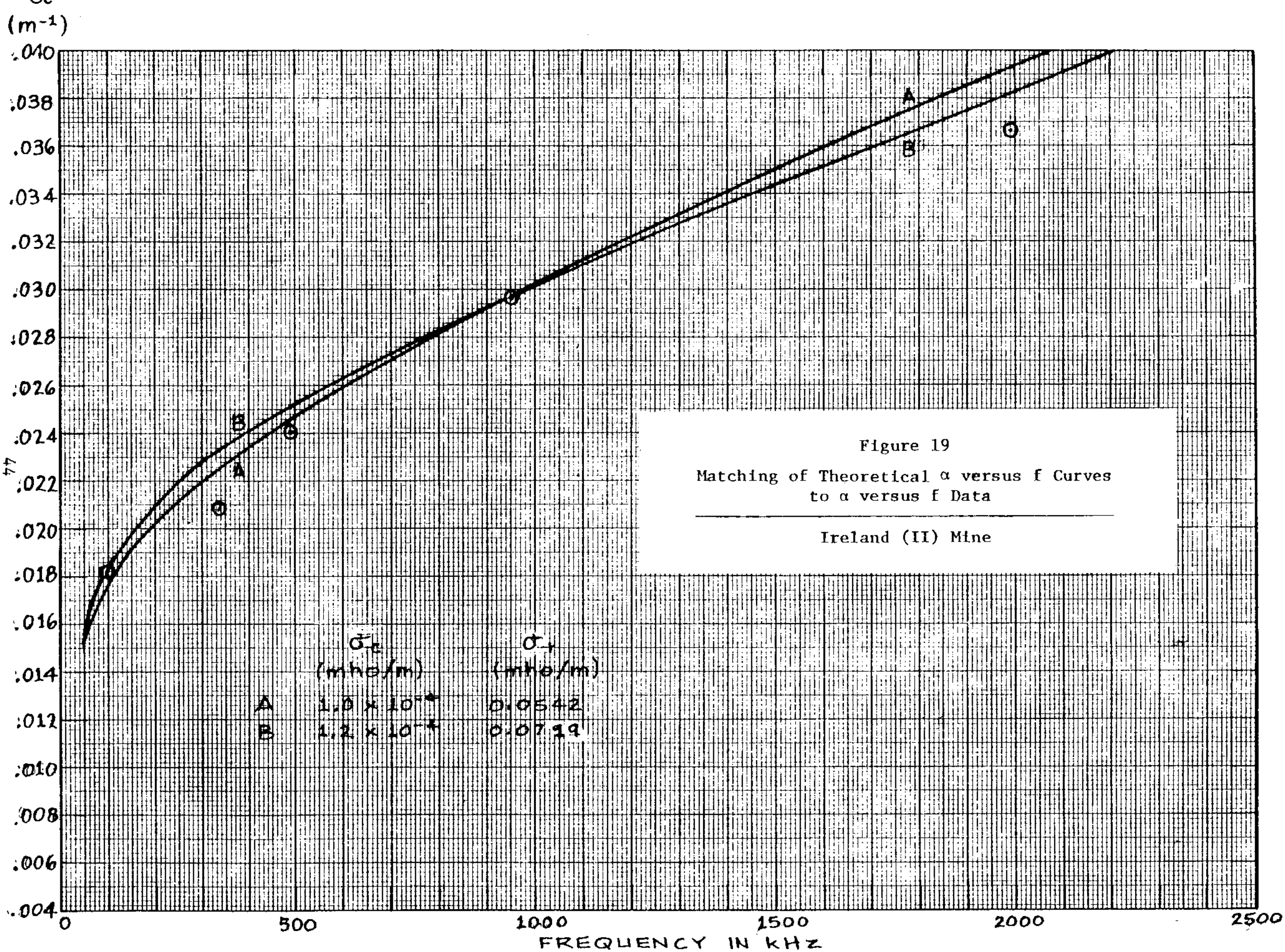


Figure 19

Matching of Theoretical α versus f Curves to α versus f Data

Ireland (II) Mine

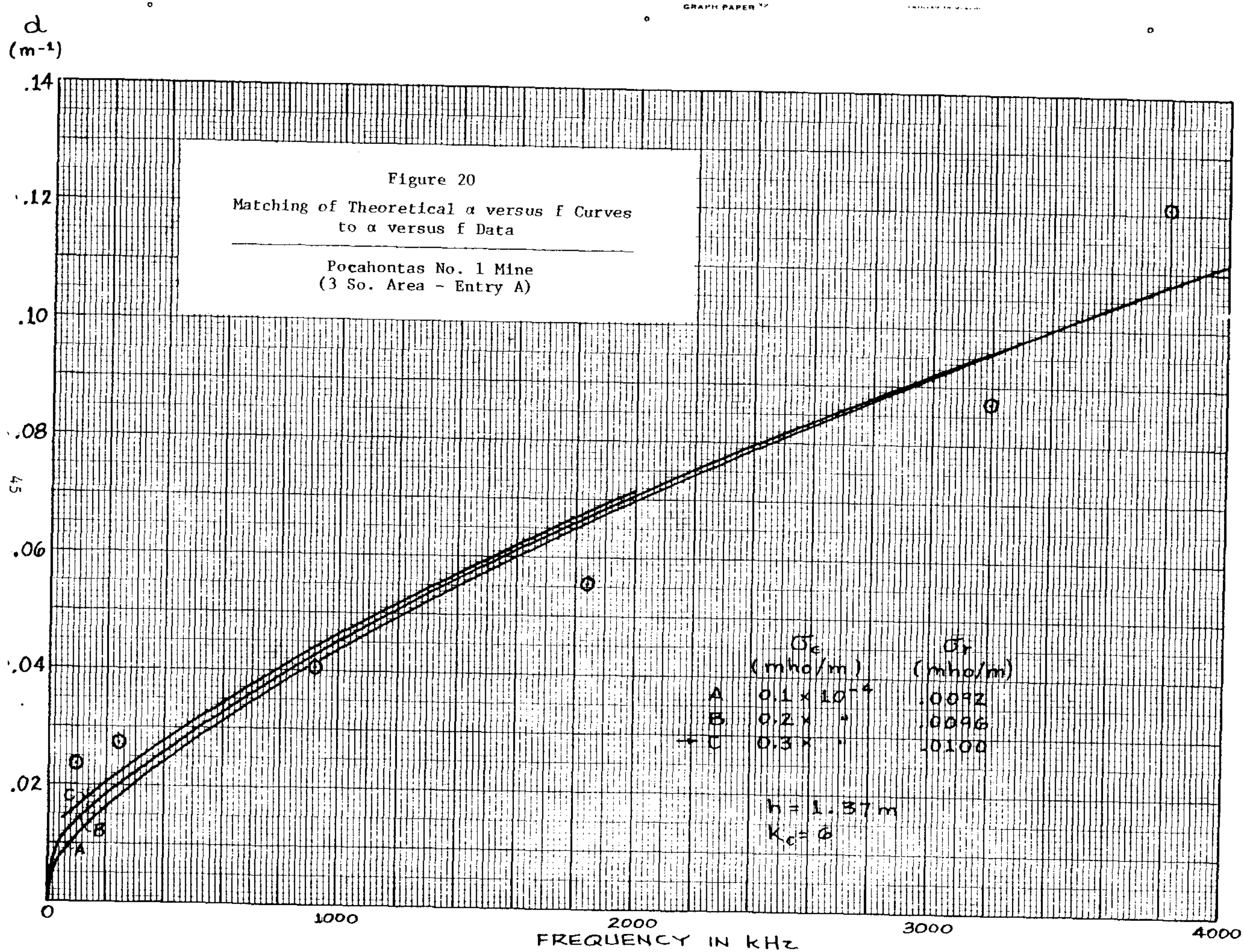


Figure 20
Matching of Theoretical α versus f Curves
to α versus f Data
Pocahontas No. 1 Mine
(3 So. Area - Entry A)
α
(m⁻¹)
.14
.12
.10
.08
.06
.04
.02
0
1000
2000
3000
4000
FREQUENCY IN kHz
σc
(mho/m)
σr
(mho/m)
A 0.1 × 10⁻⁴ .0092
B 0.2 × " .0096
C 0.3 × " .0100
h = 1.37 m
Kc = 6

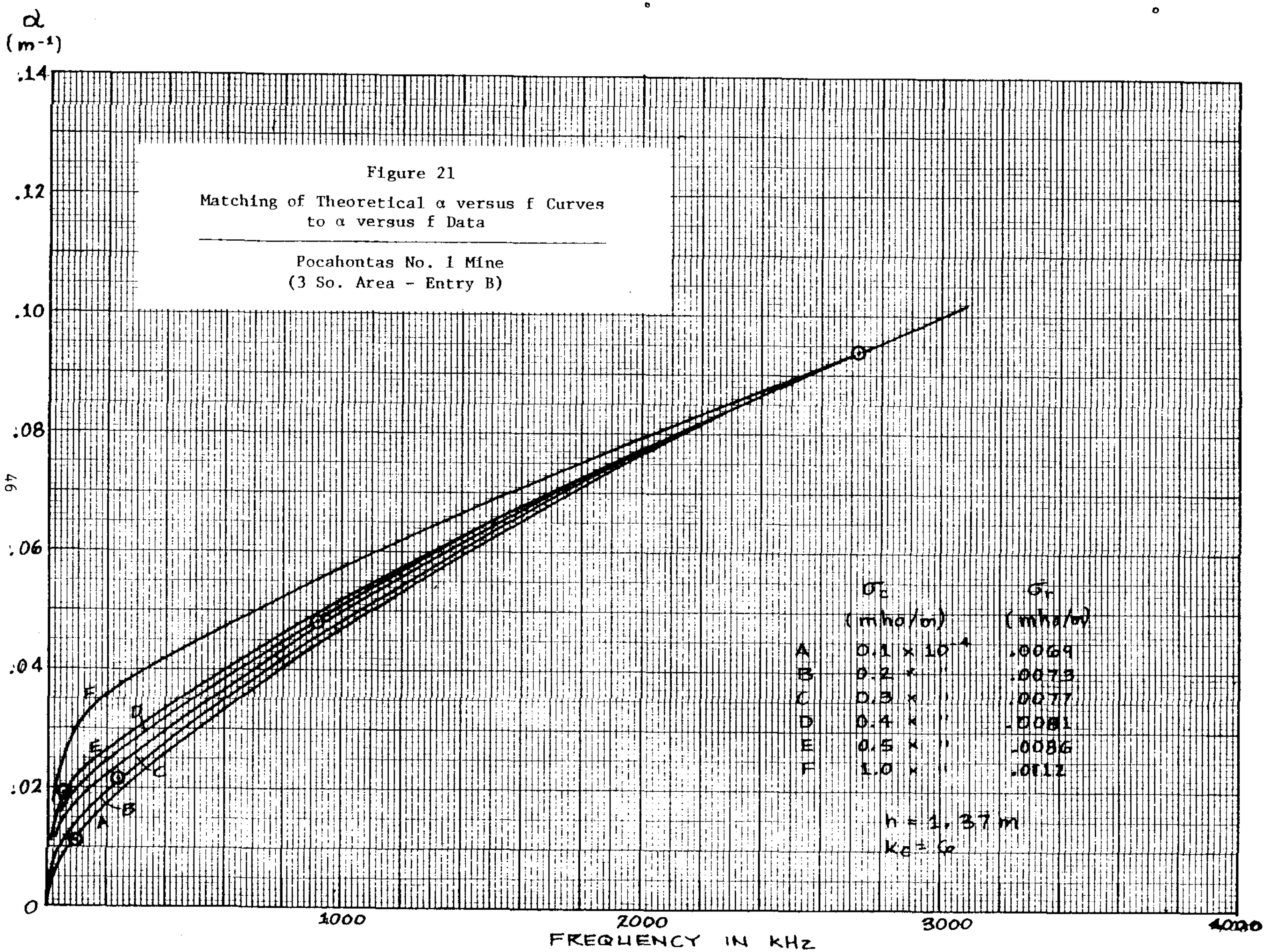


Figure 21

Matching of Theoretical α versus f Curves to α versus f Data

Pocahontas No. 1 Mine
(3 So. Area - Entry B)

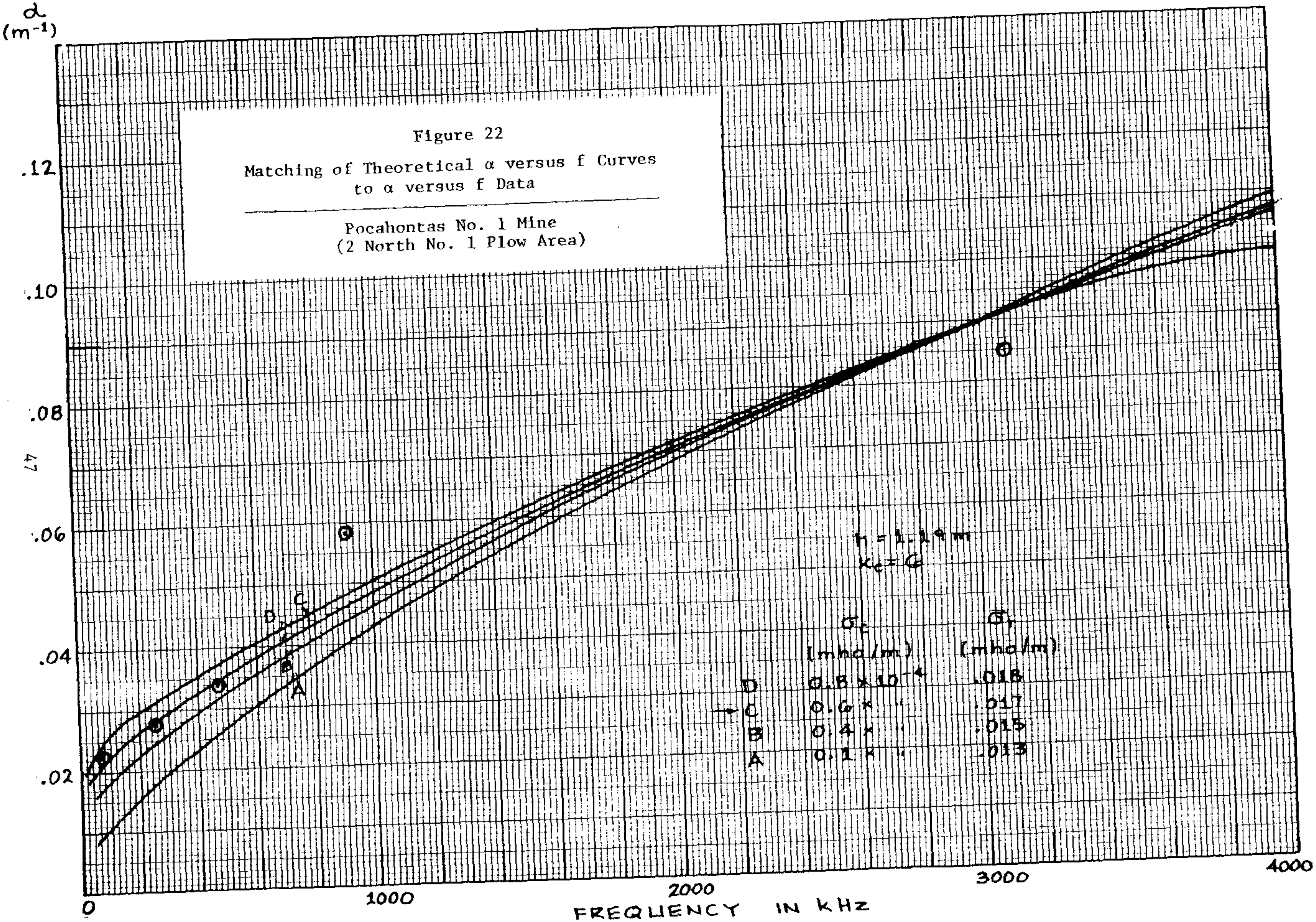


Figure 22

Matching of Theoretical α versus f Curves to α versus f Data

Pocahontas No. 1 Mine
(2 North No. 1 Plow Area)

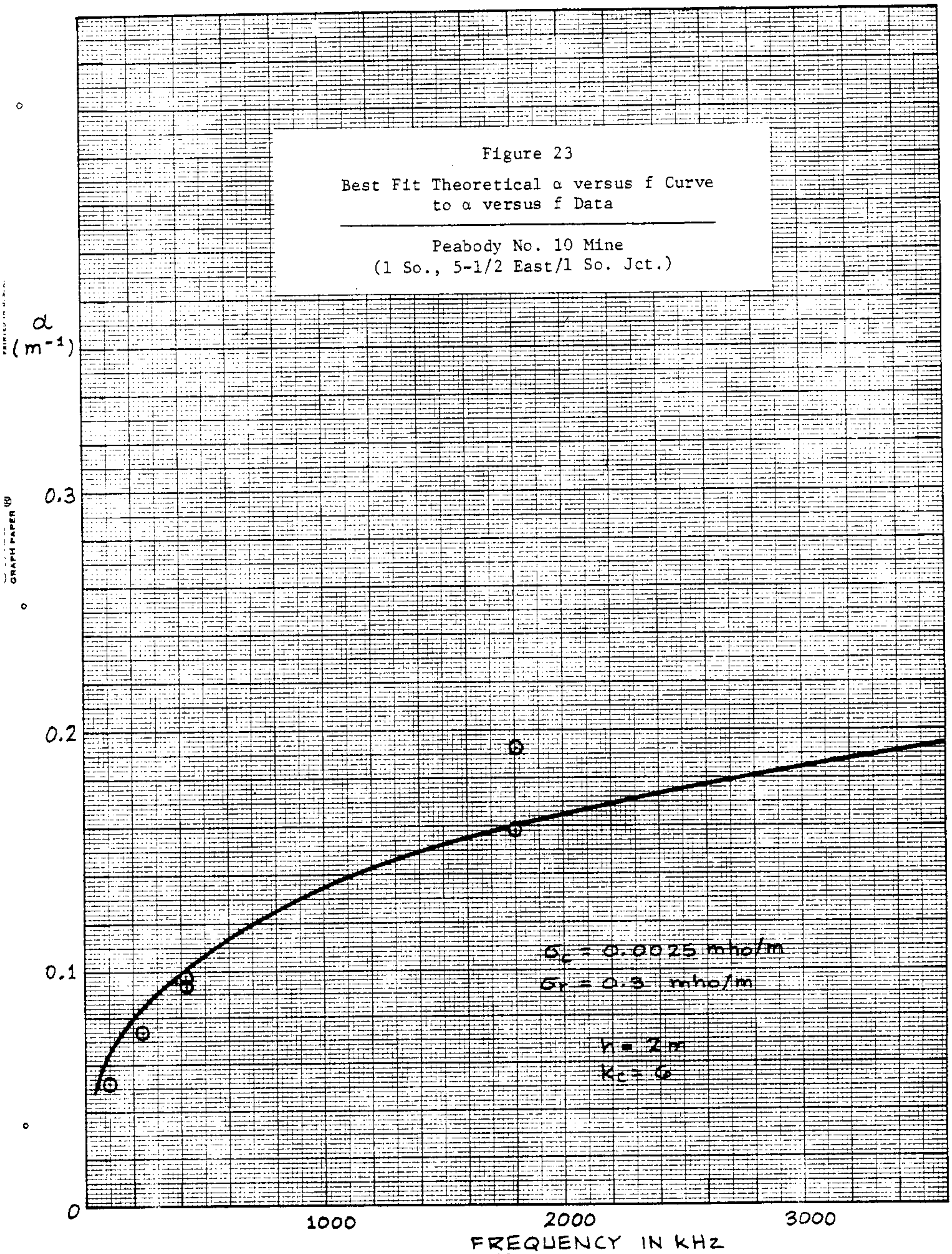


Figure 23
Best Fit Theoretical α versus f Curve
to α versus f Data
Peabody No. 10 Mine
(1 So., 5-1/2 East/1 So. Jct.)
α
(m⁻¹)
0.3
0.2
0.1
0
1000
2000
3000
FREQUENCY IN KHz
σc = 0.0025 mho/m
σr = 0.3 mho/m
h = 2 m
kc = 6

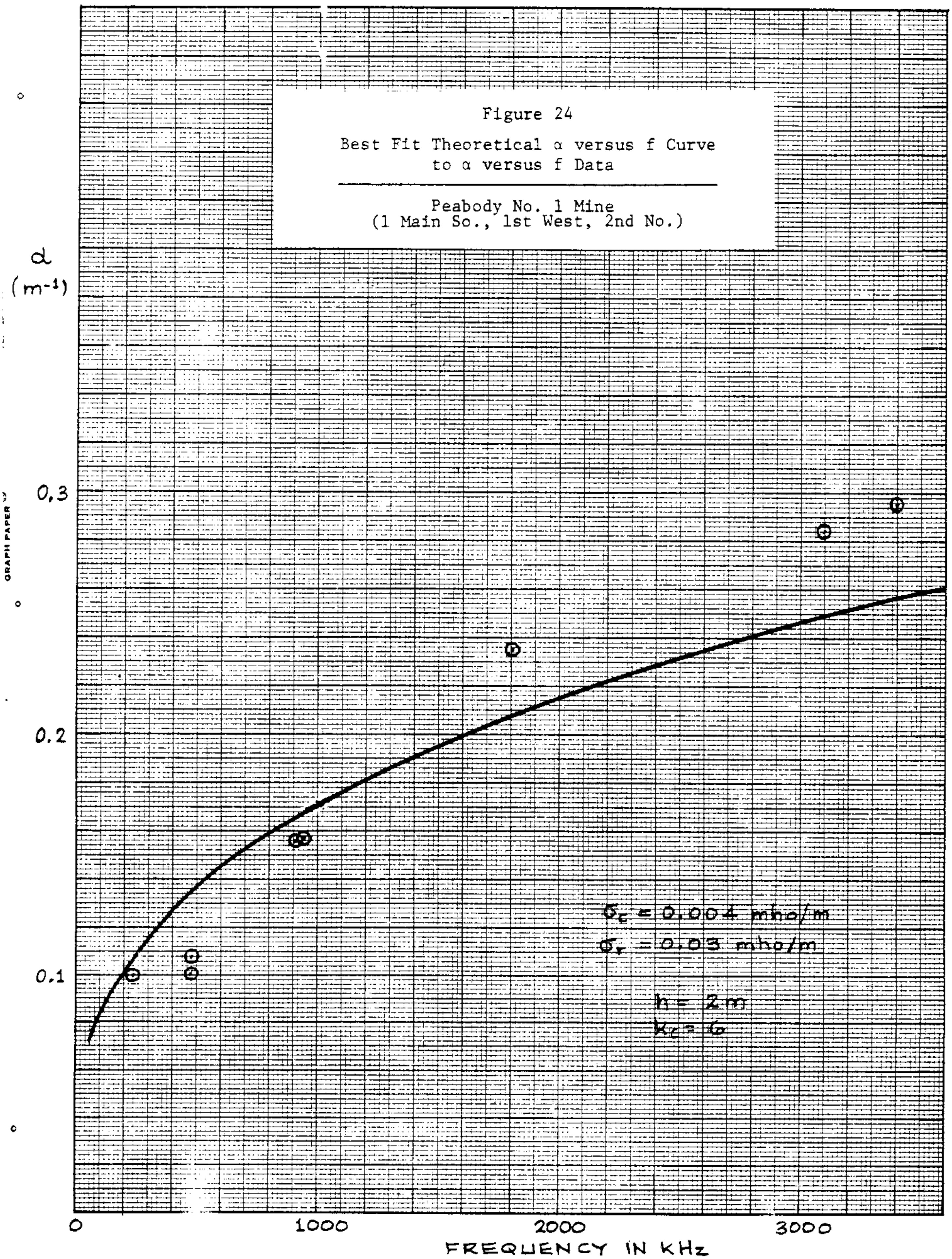


Figure 24

Best Fit Theoretical α versus f Curve to α versus f Data

Peabody No. 1 Mine
(1 Main So., 1st West, 2nd No.)

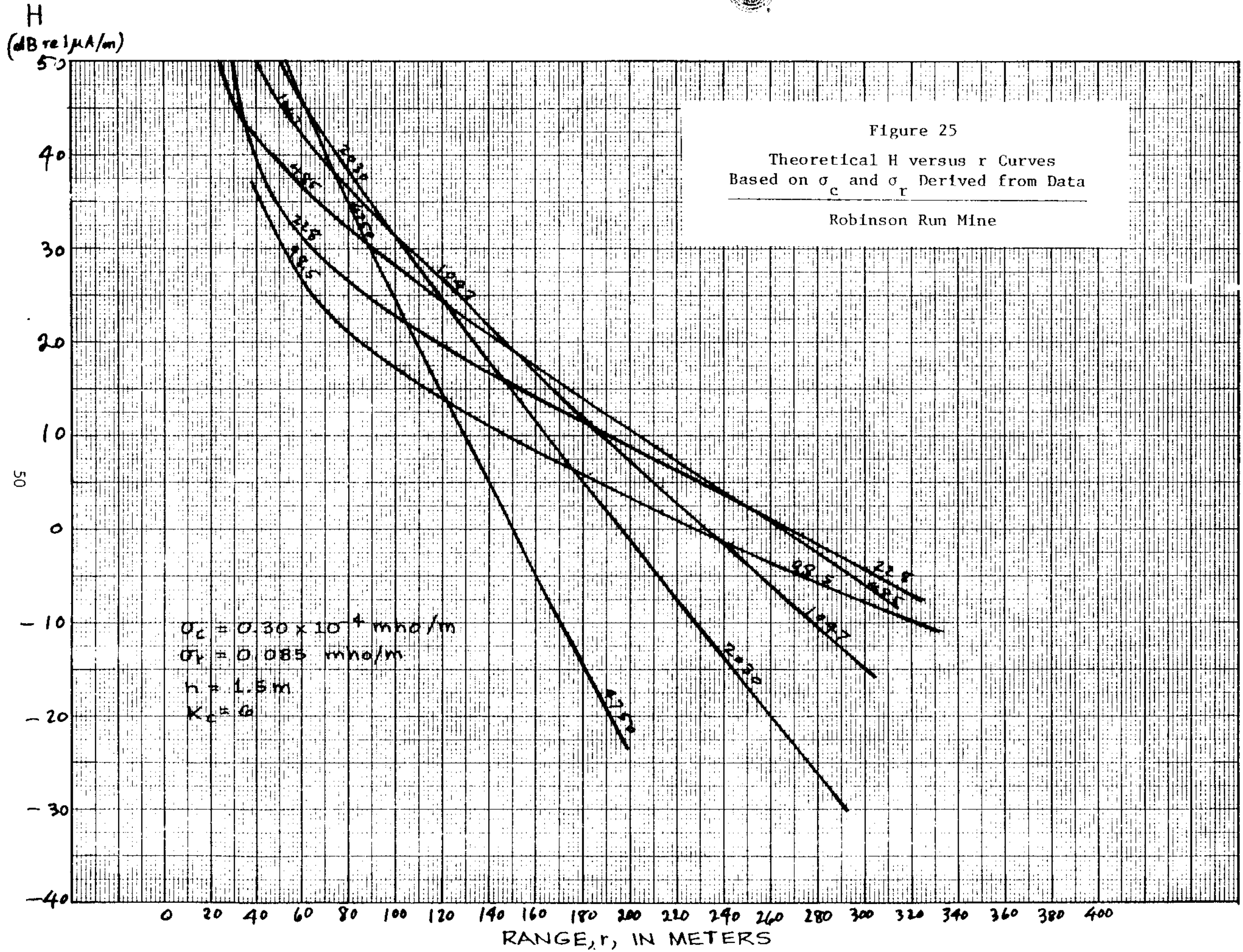


Figure 25

Theoretical H versus r Curves
Based on σ_c and σ_r Derived from Data

Robinson Run Mine

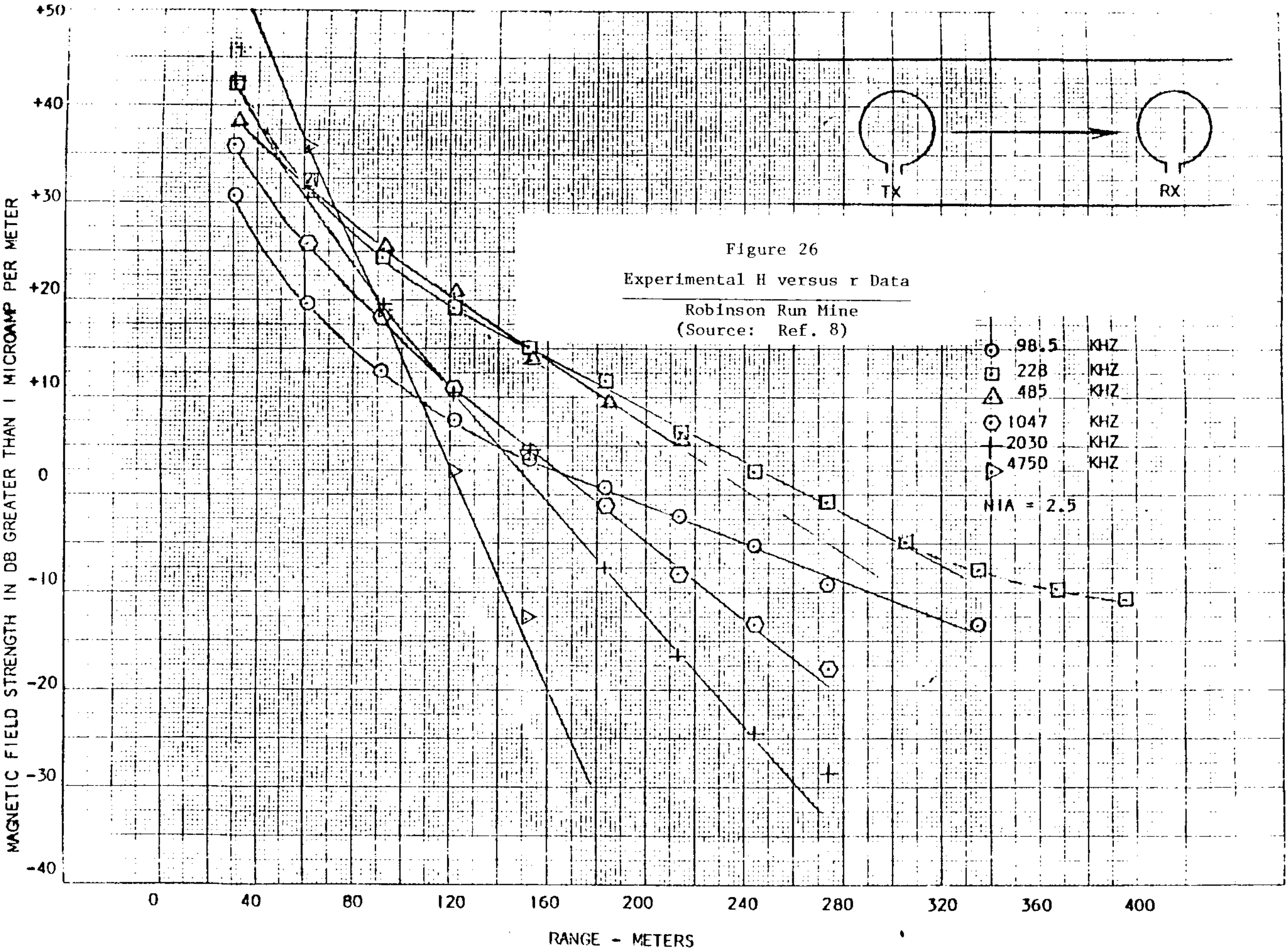


Figure 26

Experimental H versus r Data

Robinson Run Mine
(Source: Ref. 8)

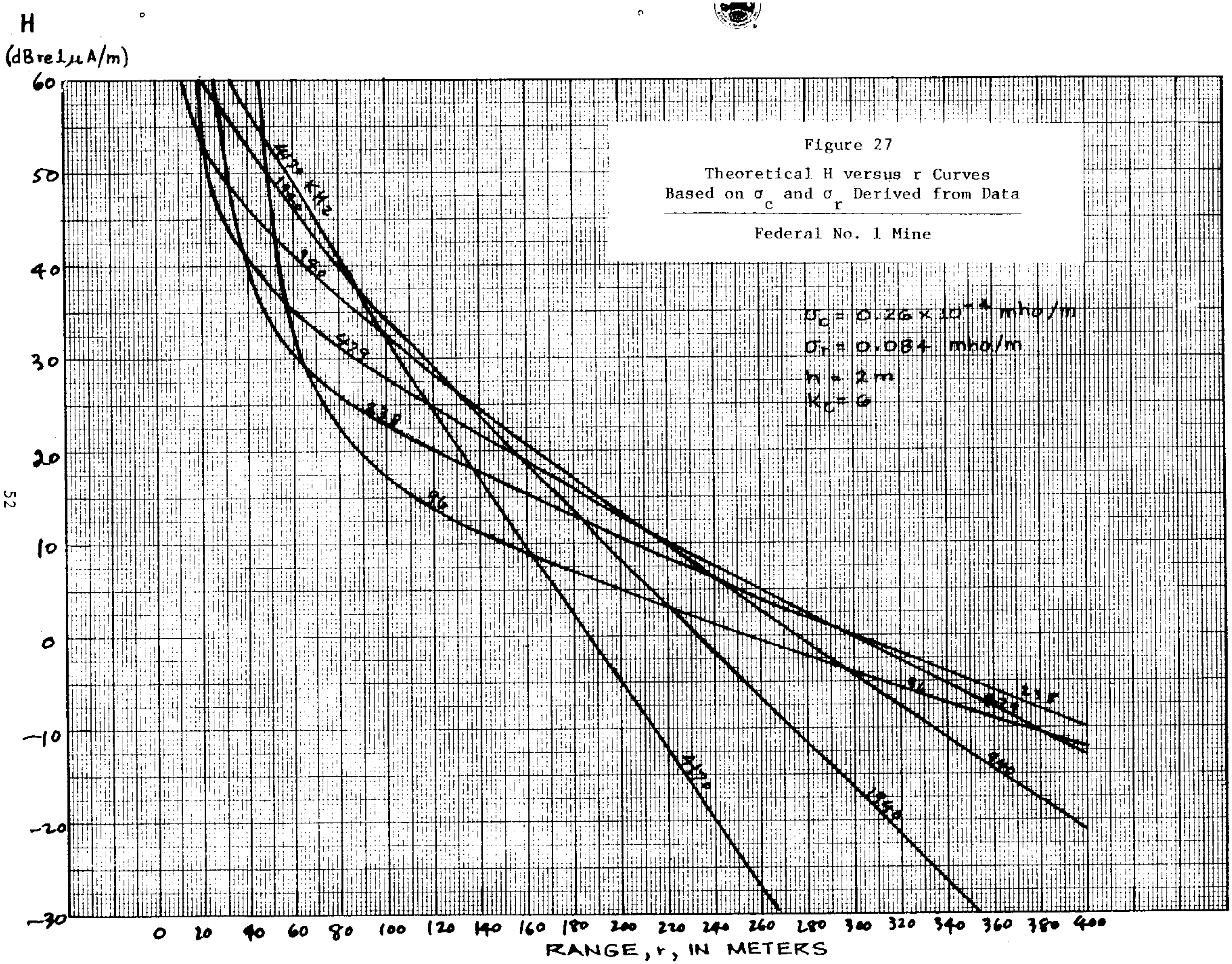


Figure 27

Theoretical H versus r Curves
Based on σ_c and σ_r Derived from Data

Federal No. 1 Mine

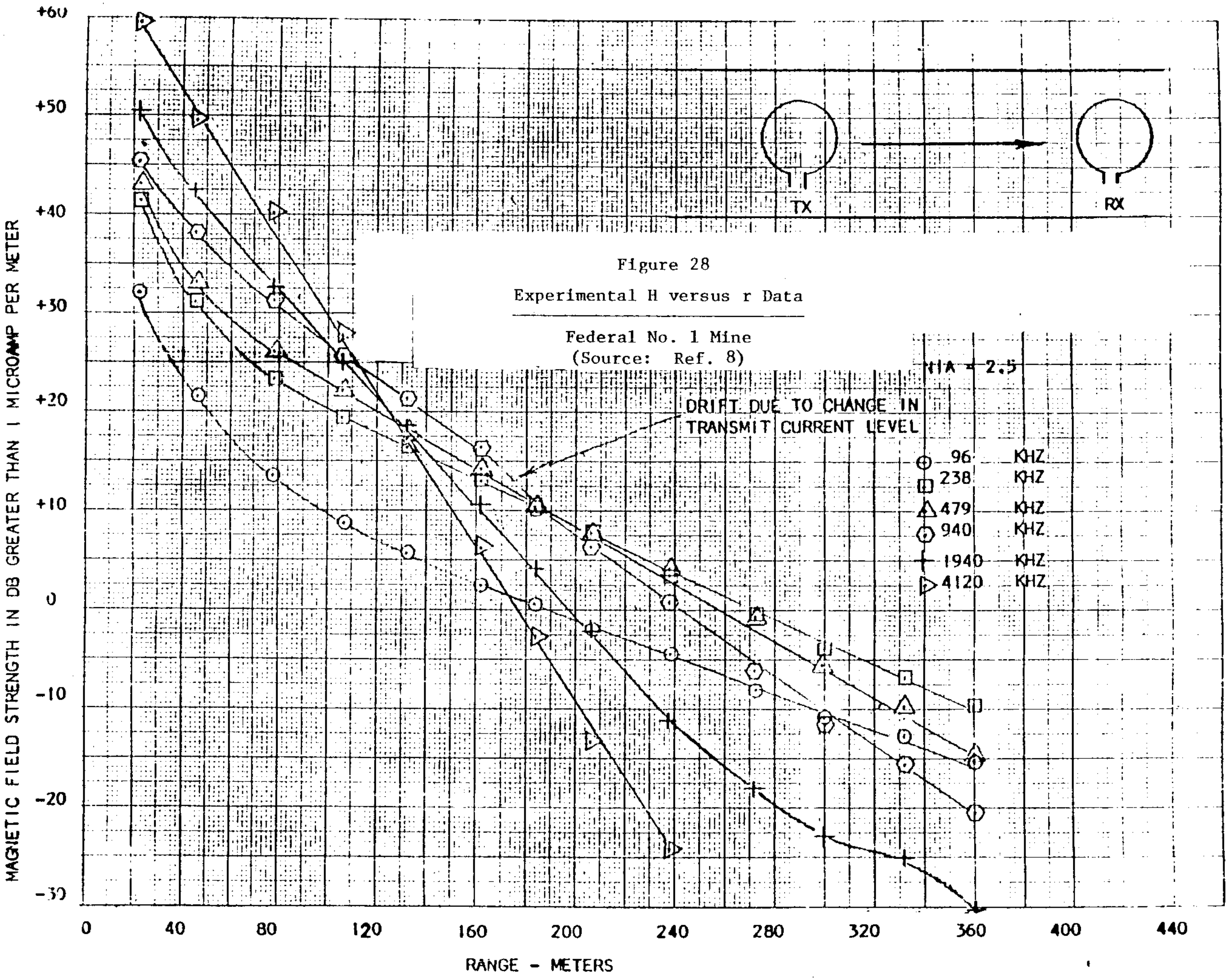


Figure 28

Experimental H versus r Data

Federal No. 1 Mine
(Source: Ref. 8)

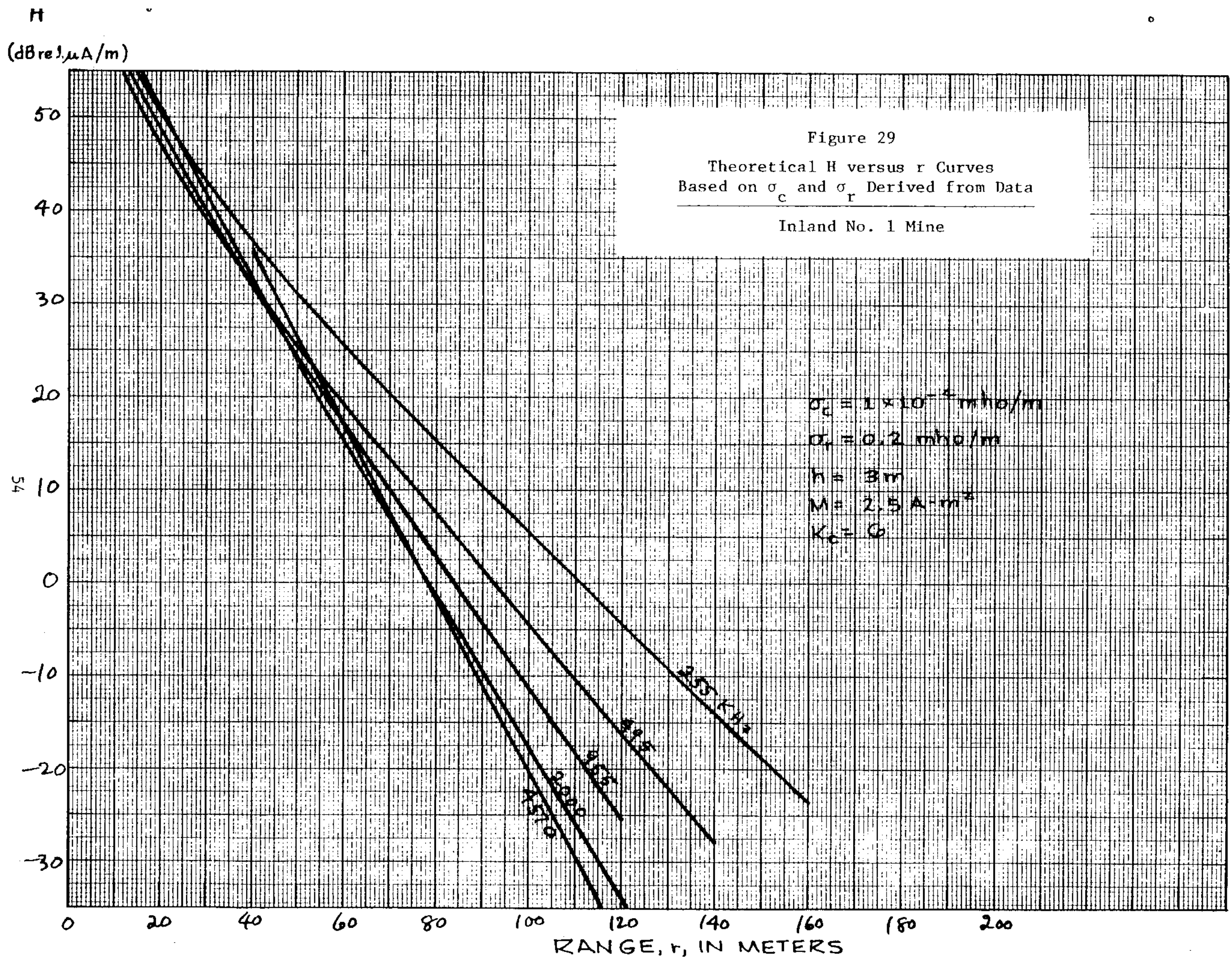


Figure 29

Theoretical H versus r Curves
Based on σ_c and σ_r Derived from Data

Inland No. 1 Mine

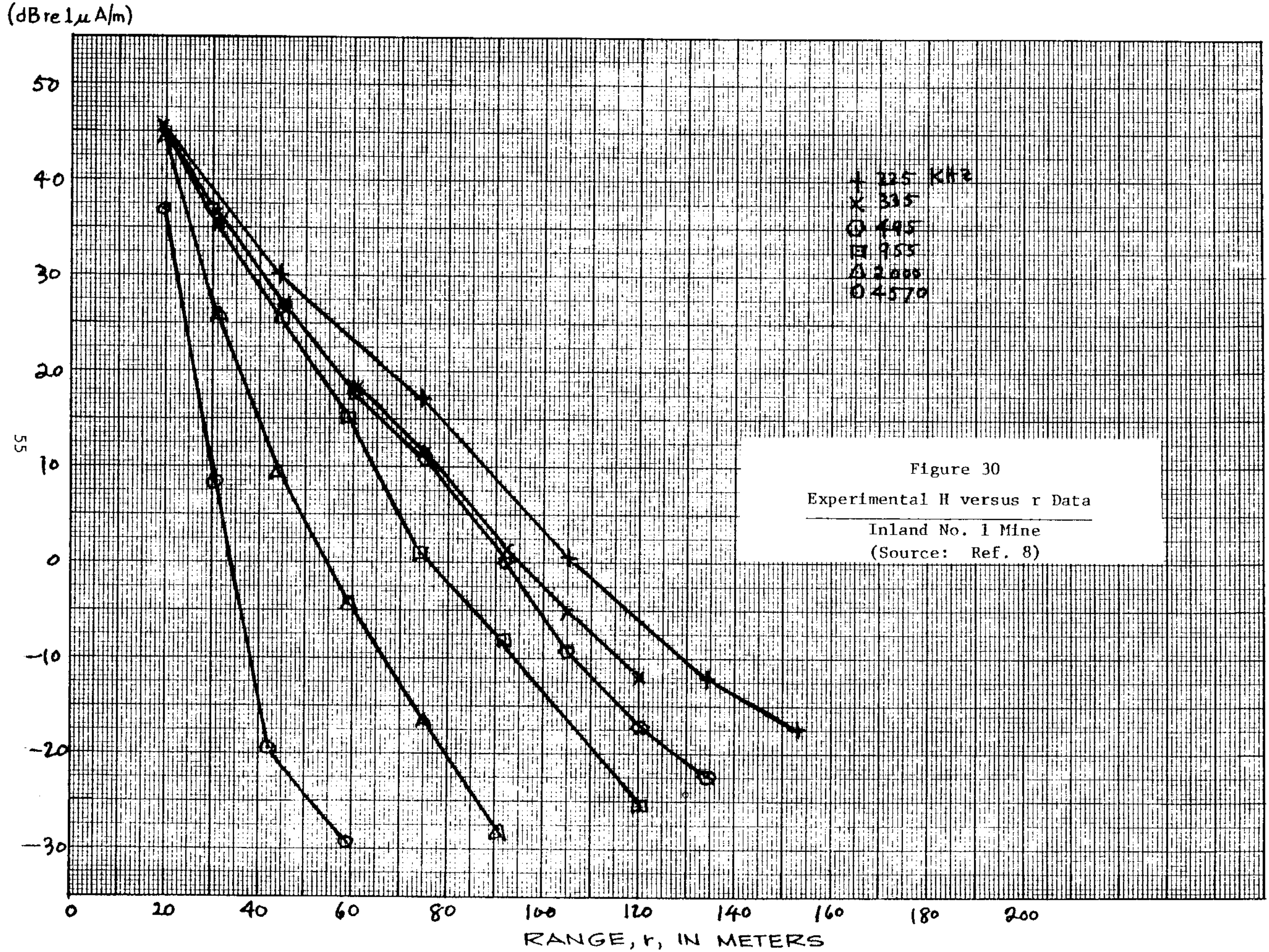


Figure 30

Experimental H versus r Data

Inland No. 1 Mine
(Source: Ref. 8)

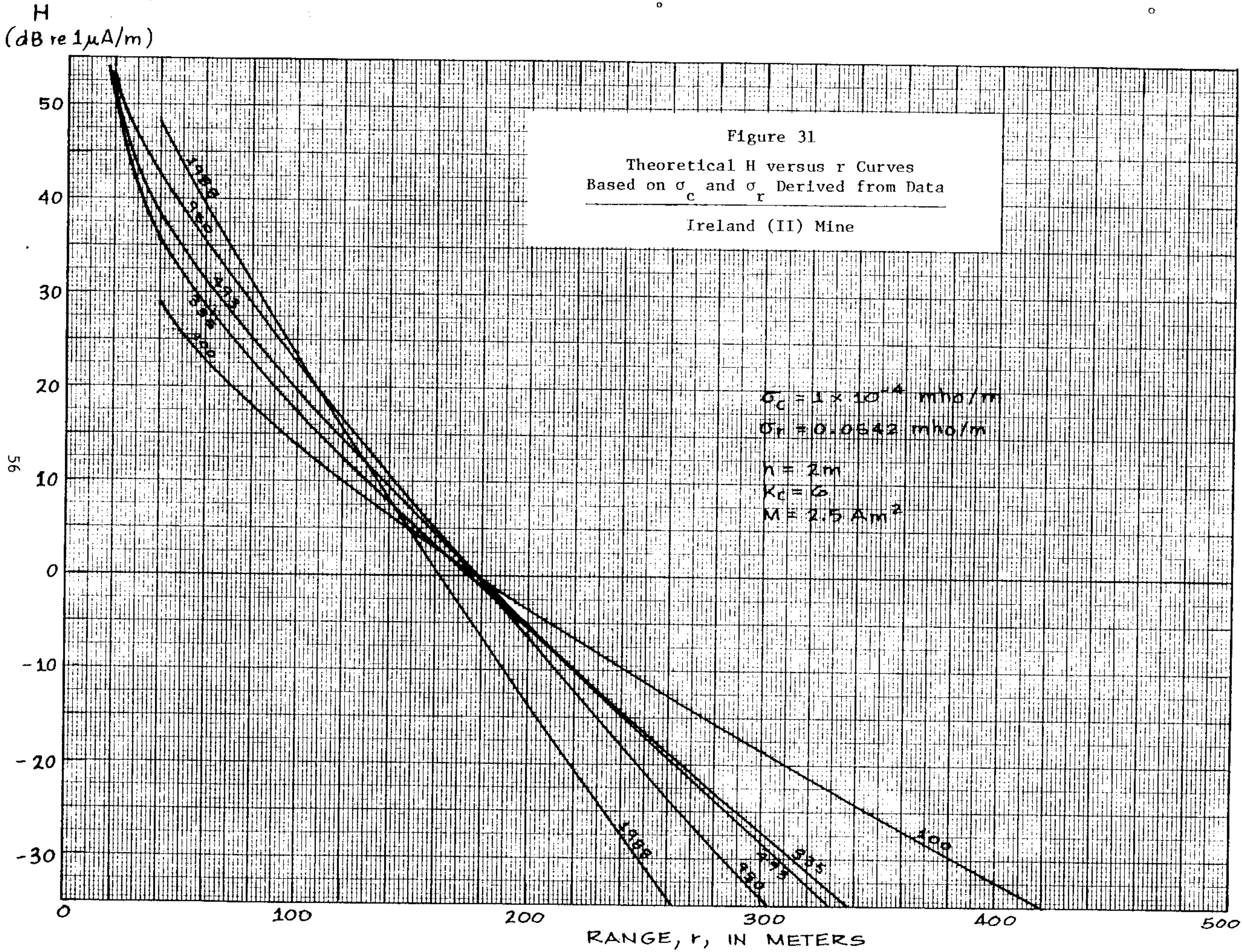


Figure 31

Theoretical H versus r Curves
Based on σ_c and σ_r Derived from Data

Ireland (II) Mine

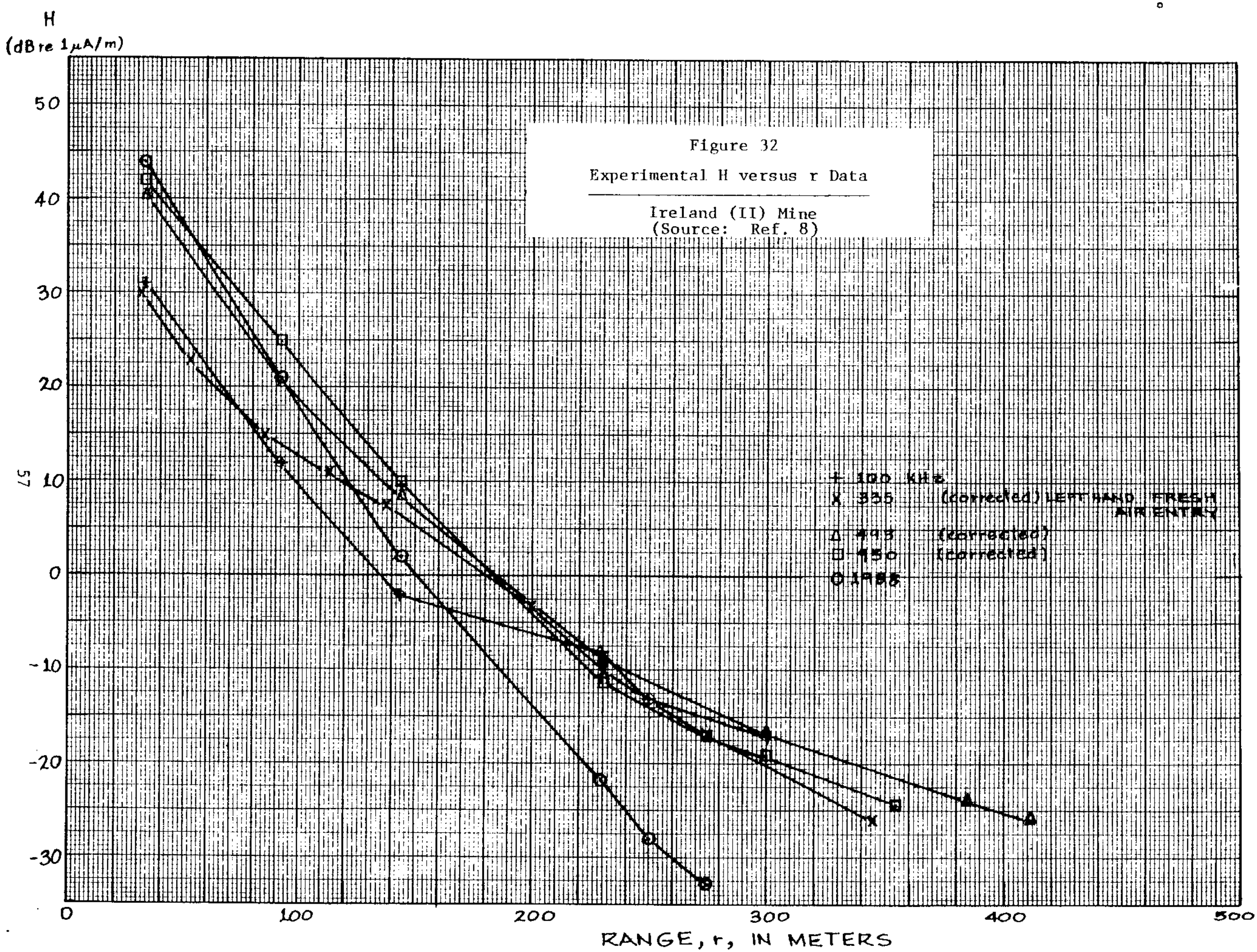


Figure 32

Experimental H versus r Data

Ireland (II) Mine
(Source: Ref. 8)

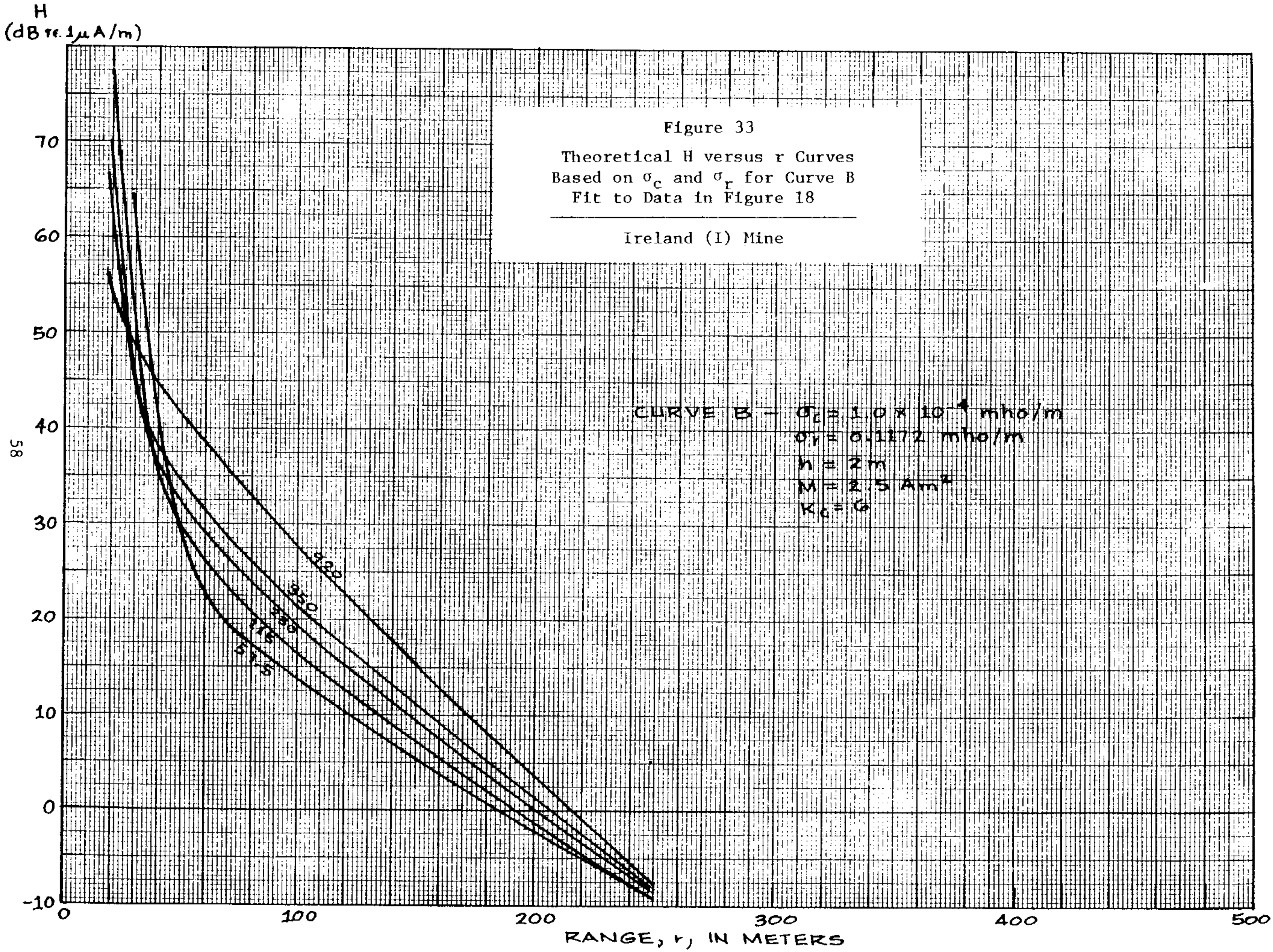


Figure 33

Theoretical H versus r Curves
Based on σ_c and σ_r for Curve B
Fit to Data in Figure 18

Ireland (I) Mine

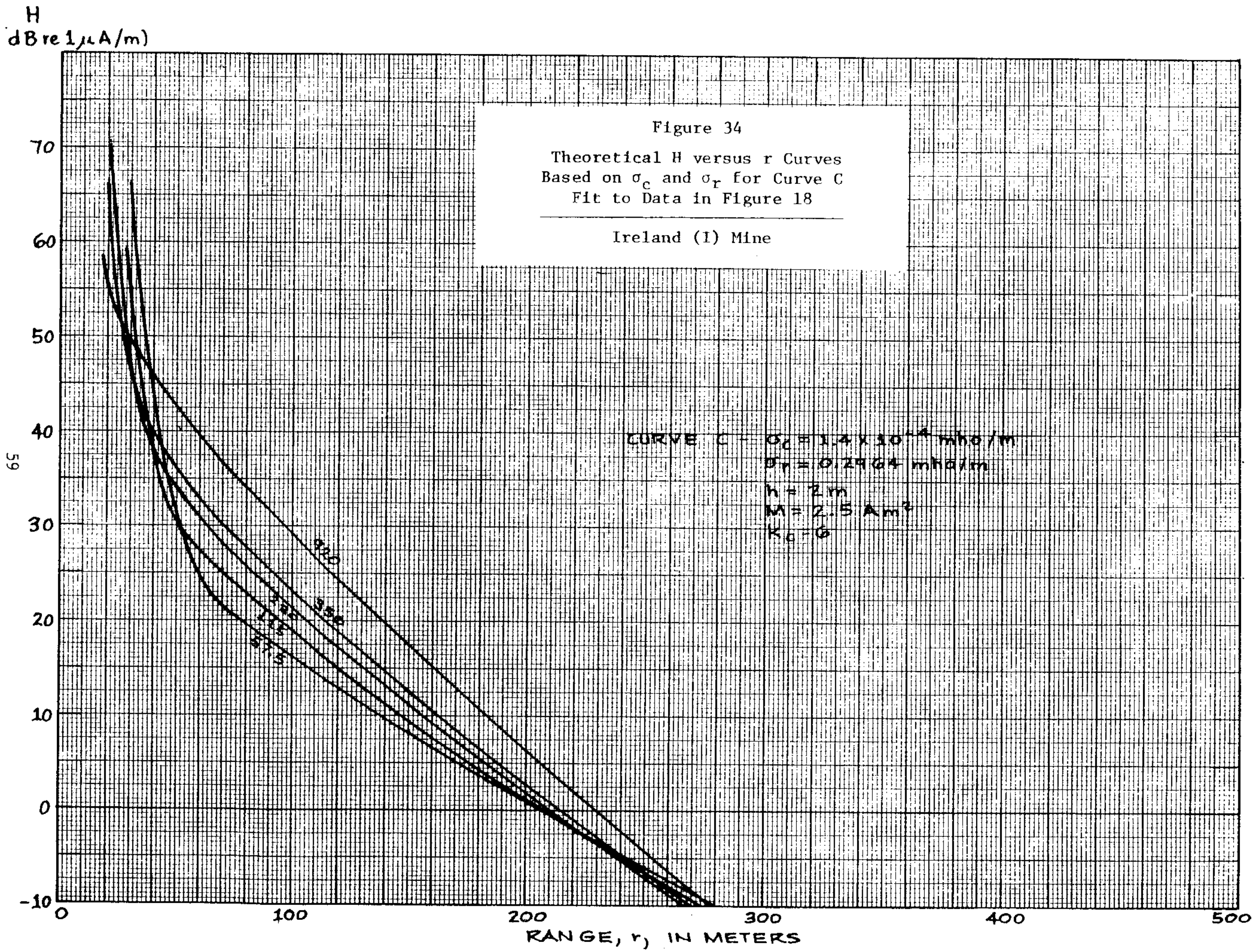


Figure 34

Theoretical H versus r Curves
Based on σ_c and σ_r for Curve C
Fit to Data in Figure 18

Ireland (I) Mine

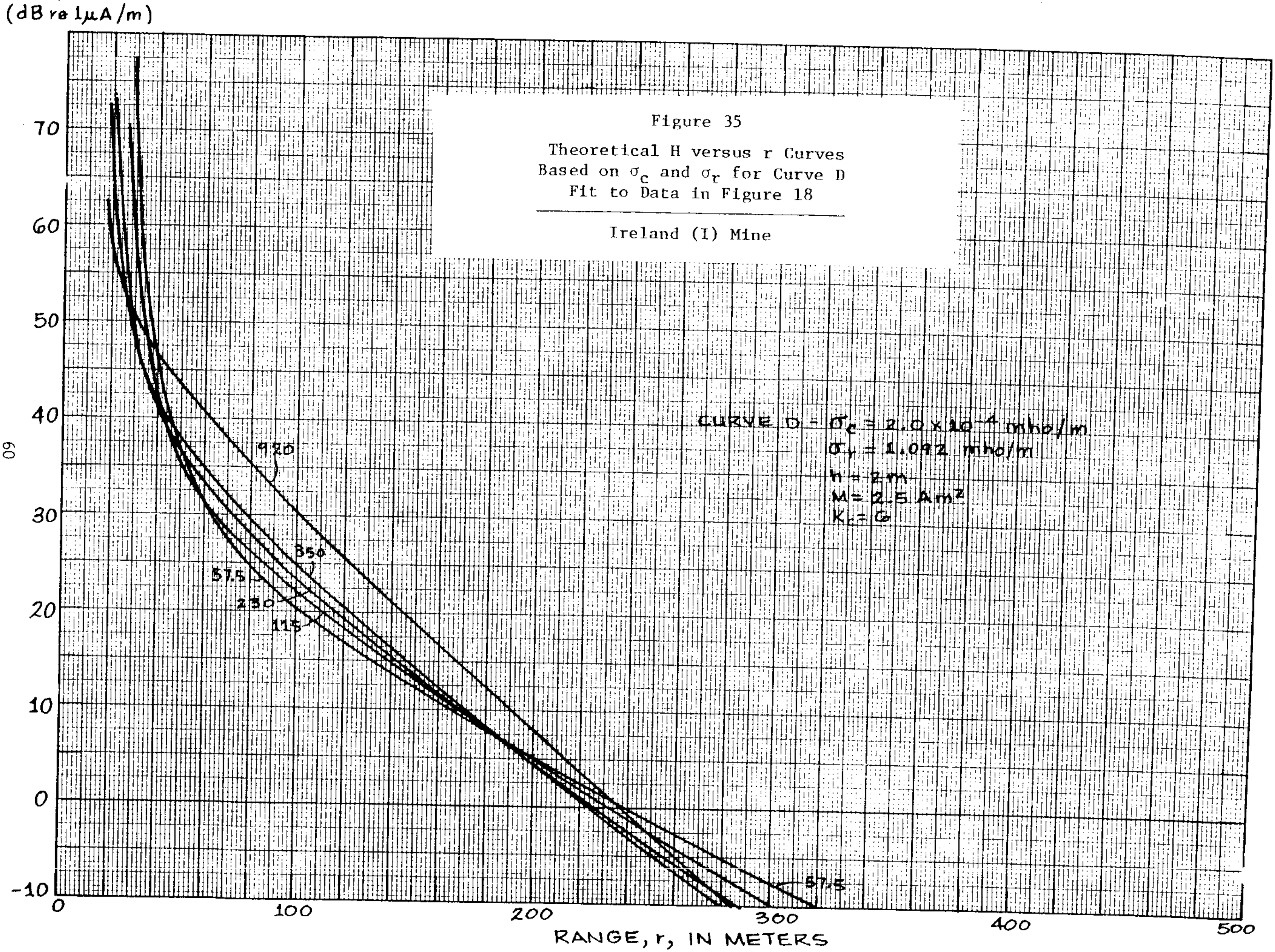


Figure 35

Theoretical H versus r Curves
Based on σ_c and σ_r for Curve D
Fit to Data in Figure 18

Ireland (I) Mine

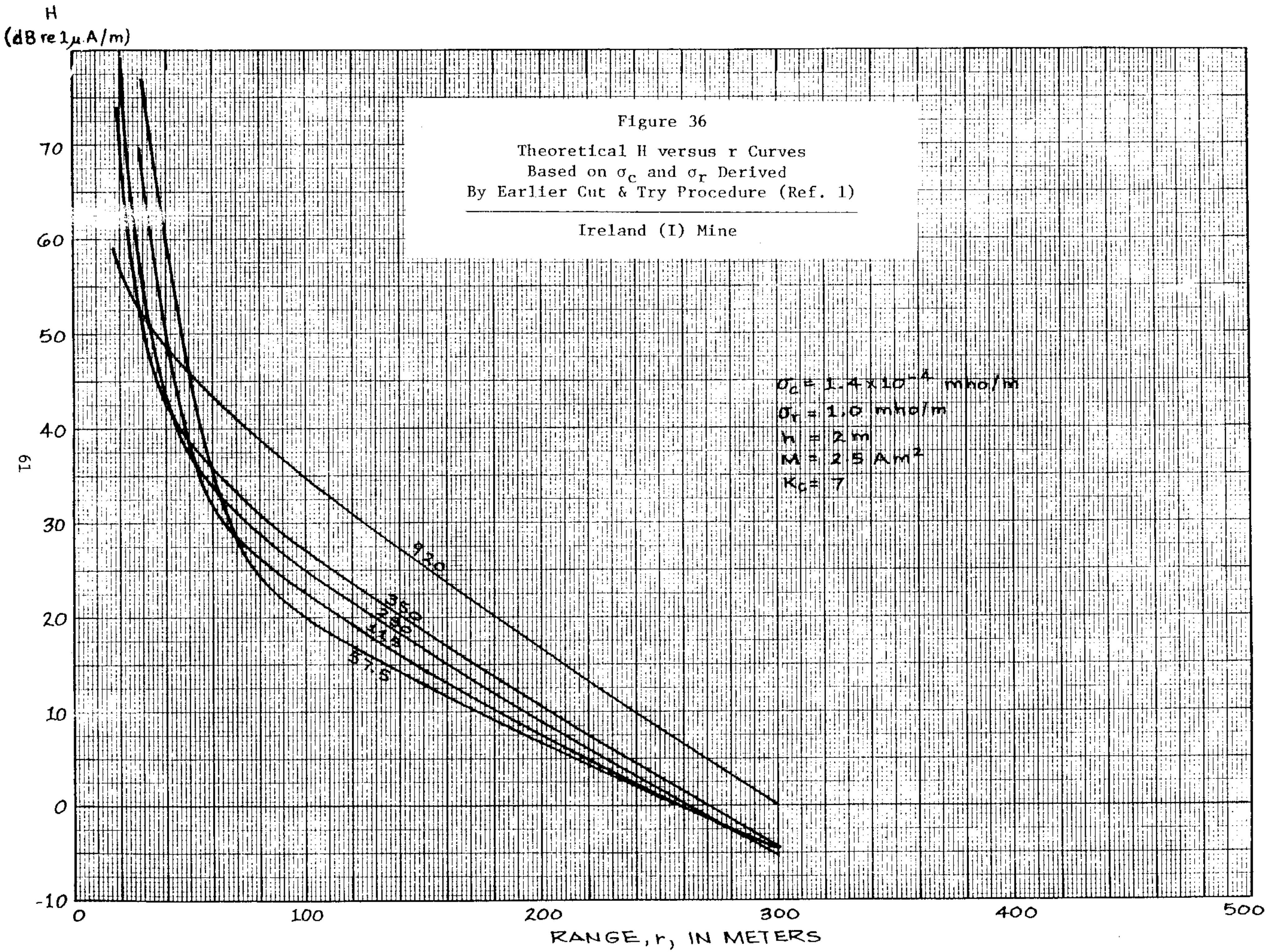


Figure 36

Theoretical H versus r Curves
Based on σ_c and σ_r Derived
By Earlier Cut & Try Procedure (Ref. 1)

Ireland (I) Mine

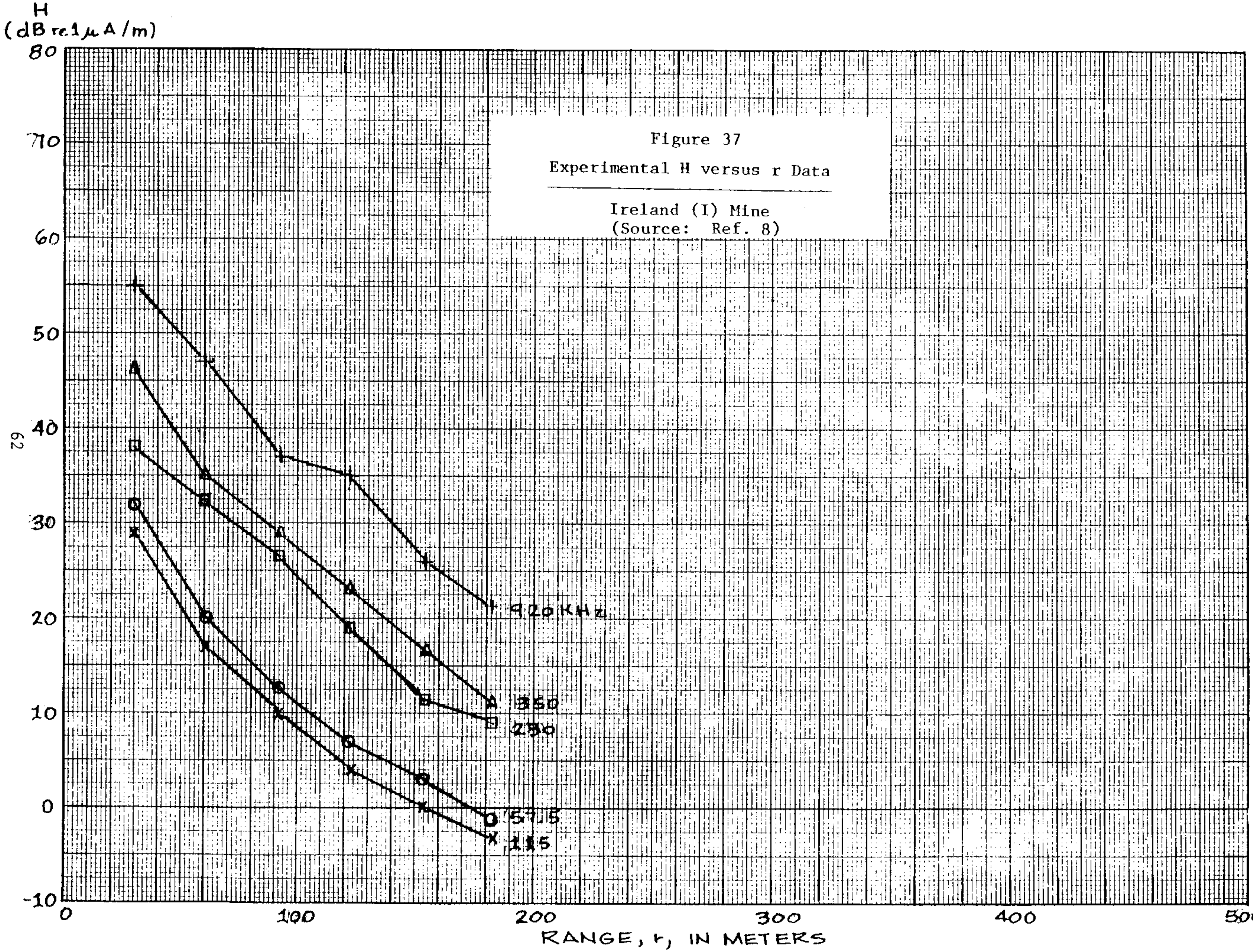


Figure 37

Experimental H versus r Data

Ireland (I) Mine
(Source: Ref. 8)

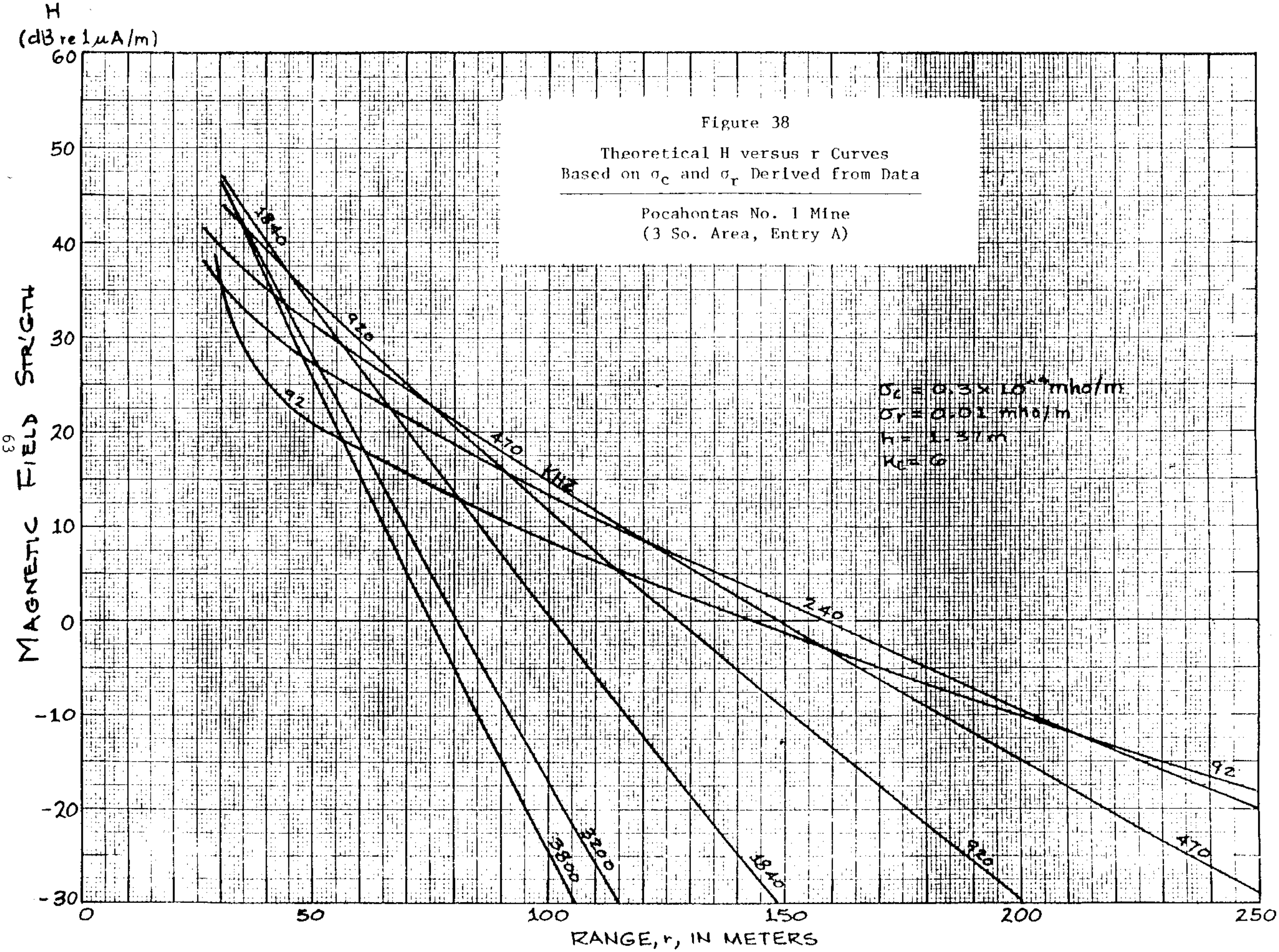


Figure 38

Theoretical H versus r Curves
Based on σ_c and σ_r Derived from Data

Pocahontas No. 1 Mine
(3 So. Area, Entry A)

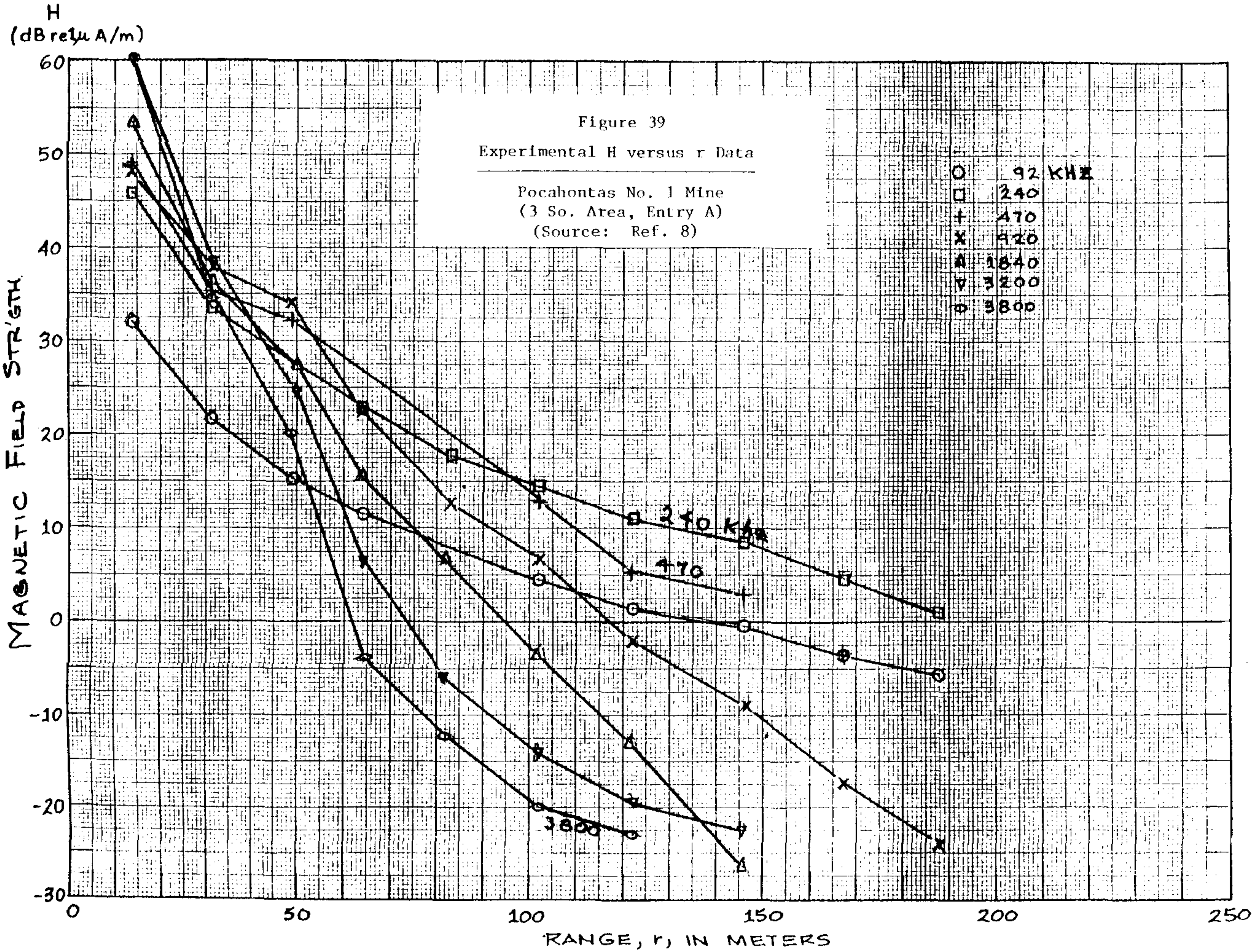


Figure 39

Experimental H versus r Data

Pocahontas No. 1 Mine
(3 So. Area, Entry A)
(Source: Ref. 8)

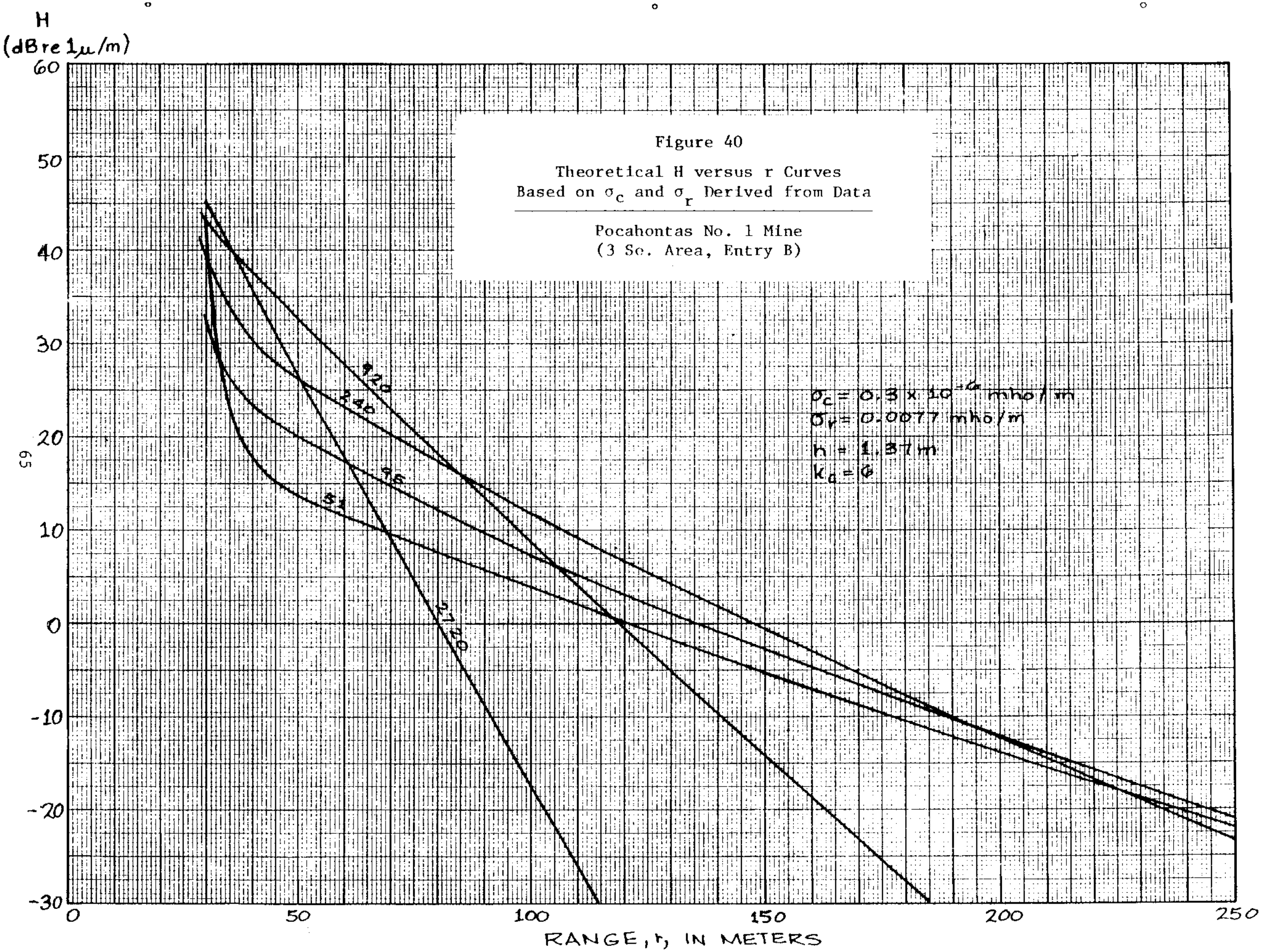


Figure 40

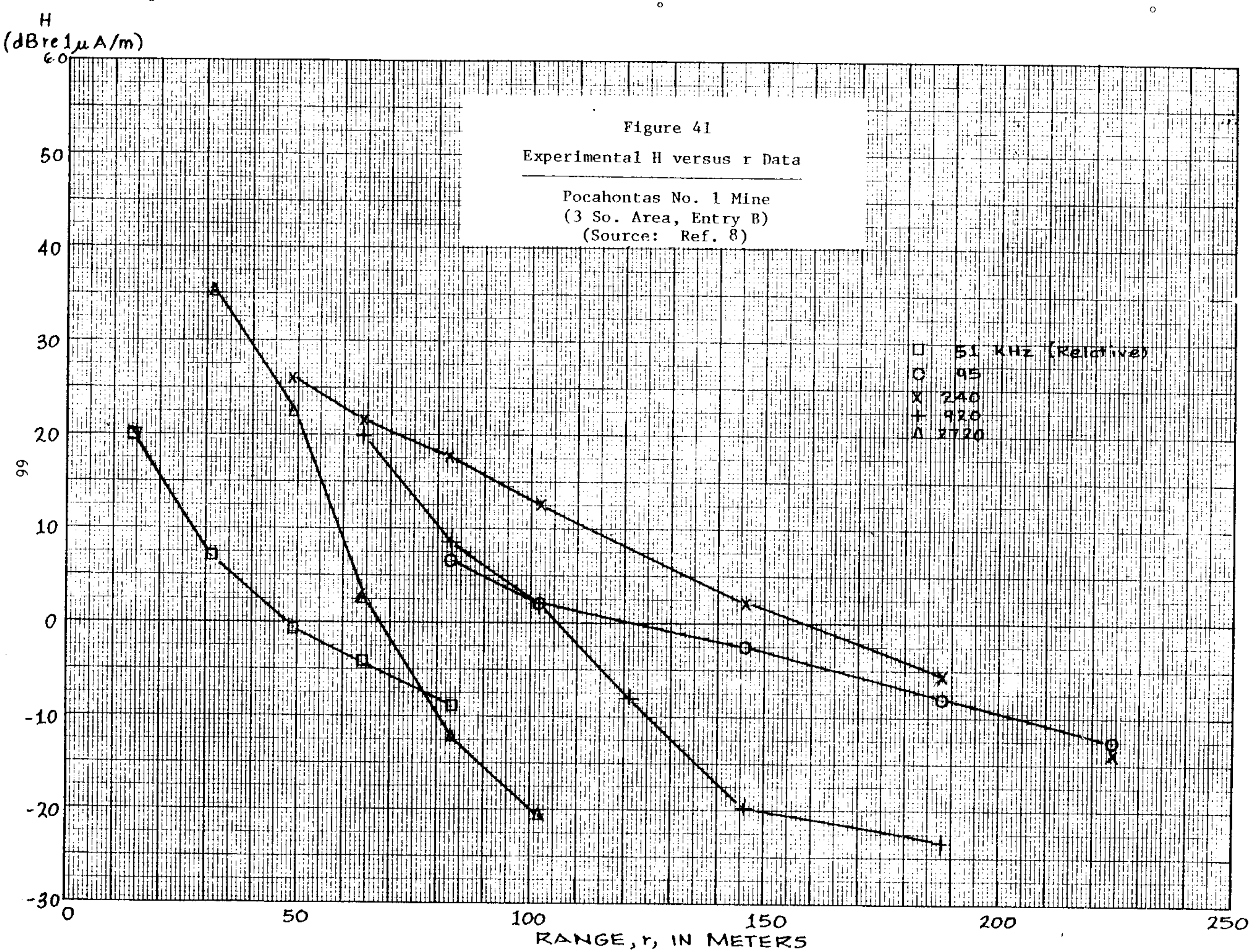
Theoretical H versus r Curves
Based on σ_c and σ_r Derived from Data

Pocahontas No. 1 Mine
(3 So. Area, Entry B)

Figure 41

Experimental H versus r Data

Pocahontas No. 1 Mine
(3 So. Area, Entry B)
(Source: Ref. 8)



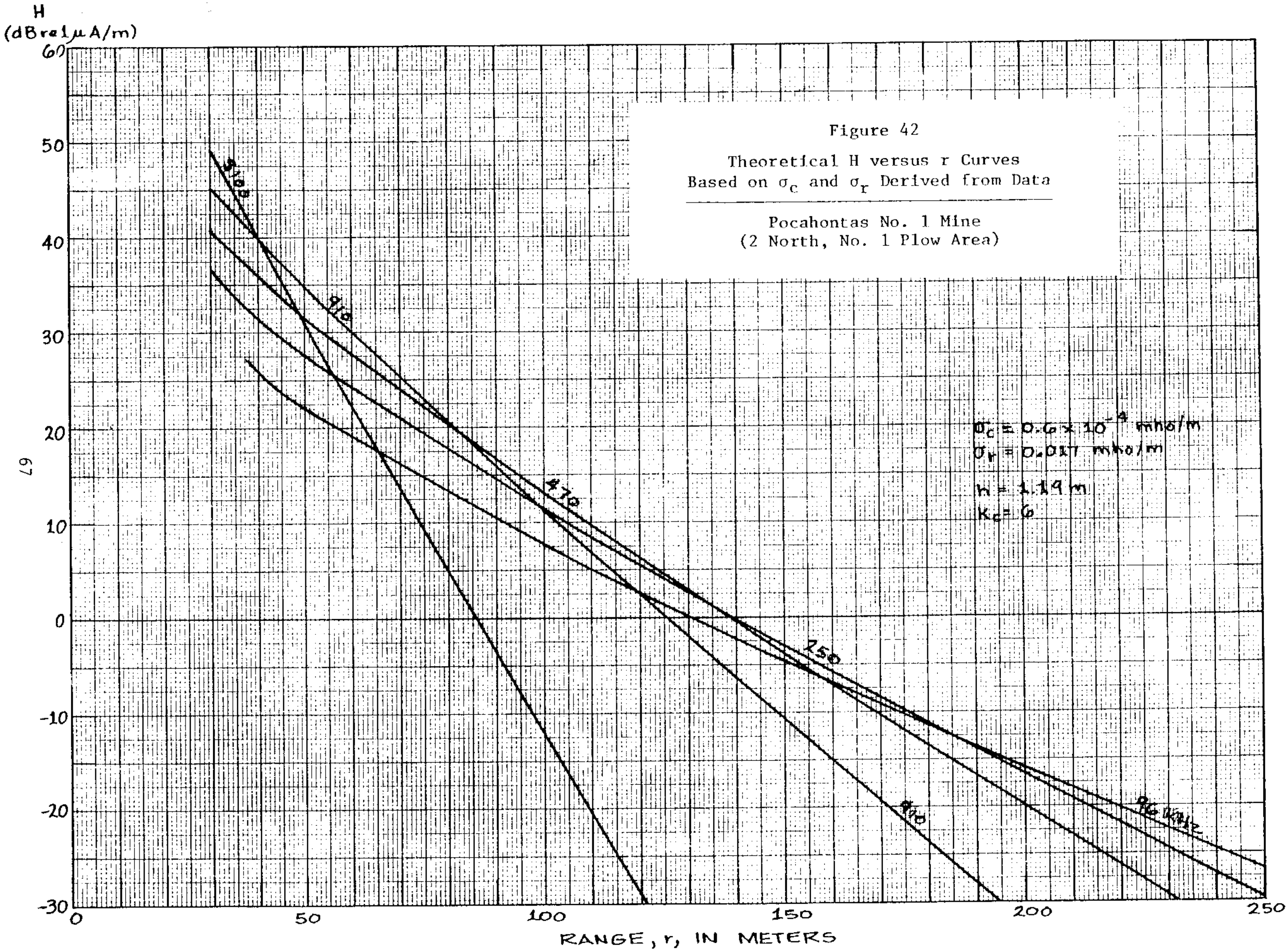


Figure 42

Theoretical H versus r Curves
Based on σ_c and σ_r Derived from Data

Pocahontas No. 1 Mine
(2 North, No. 1 Plow Area)

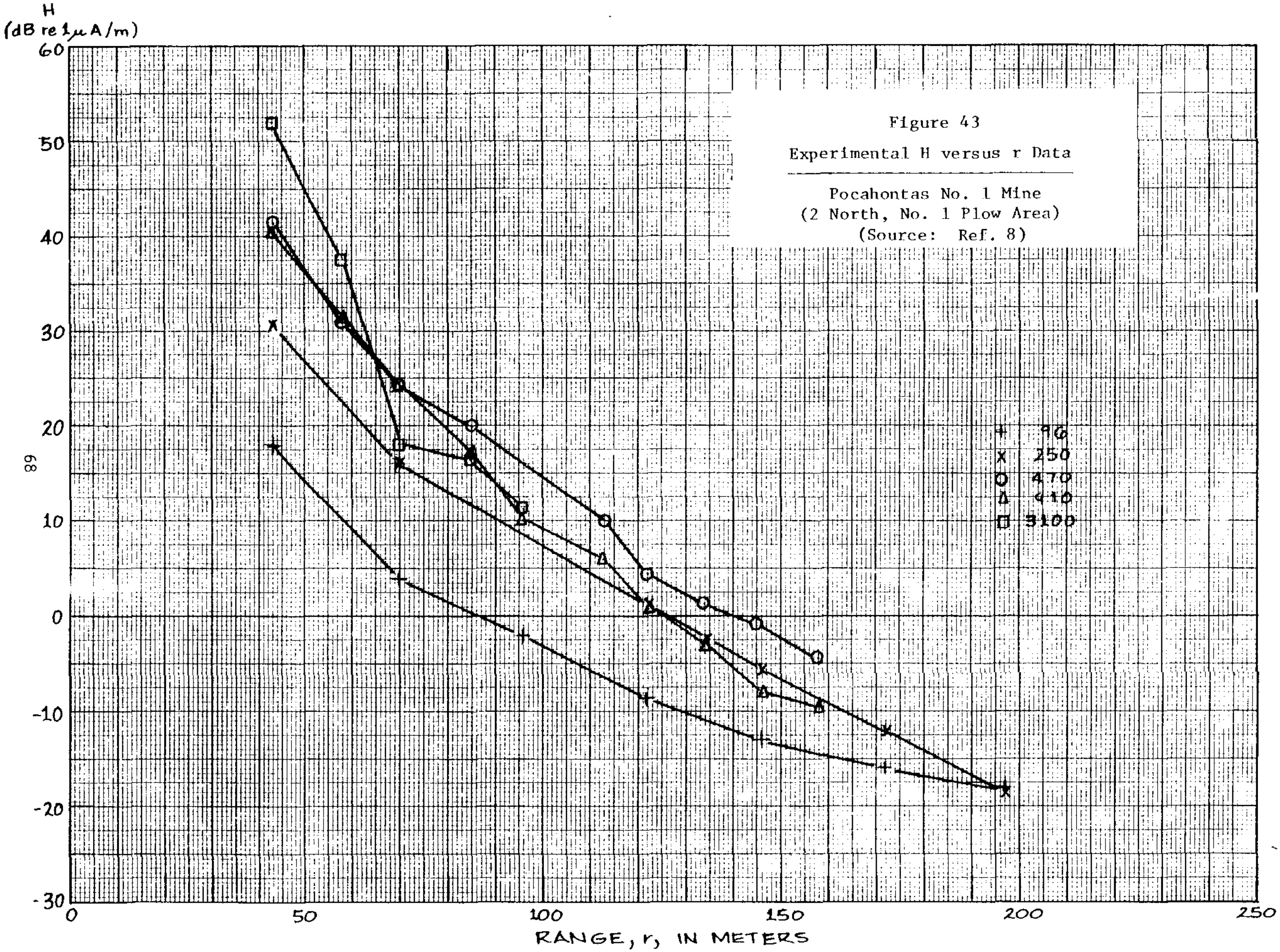


Figure 43

Experimental H versus r Data

Pocahontas No. 1 Mine
(2 North, No. 1 Plow Area)
(Source: Ref. 8)

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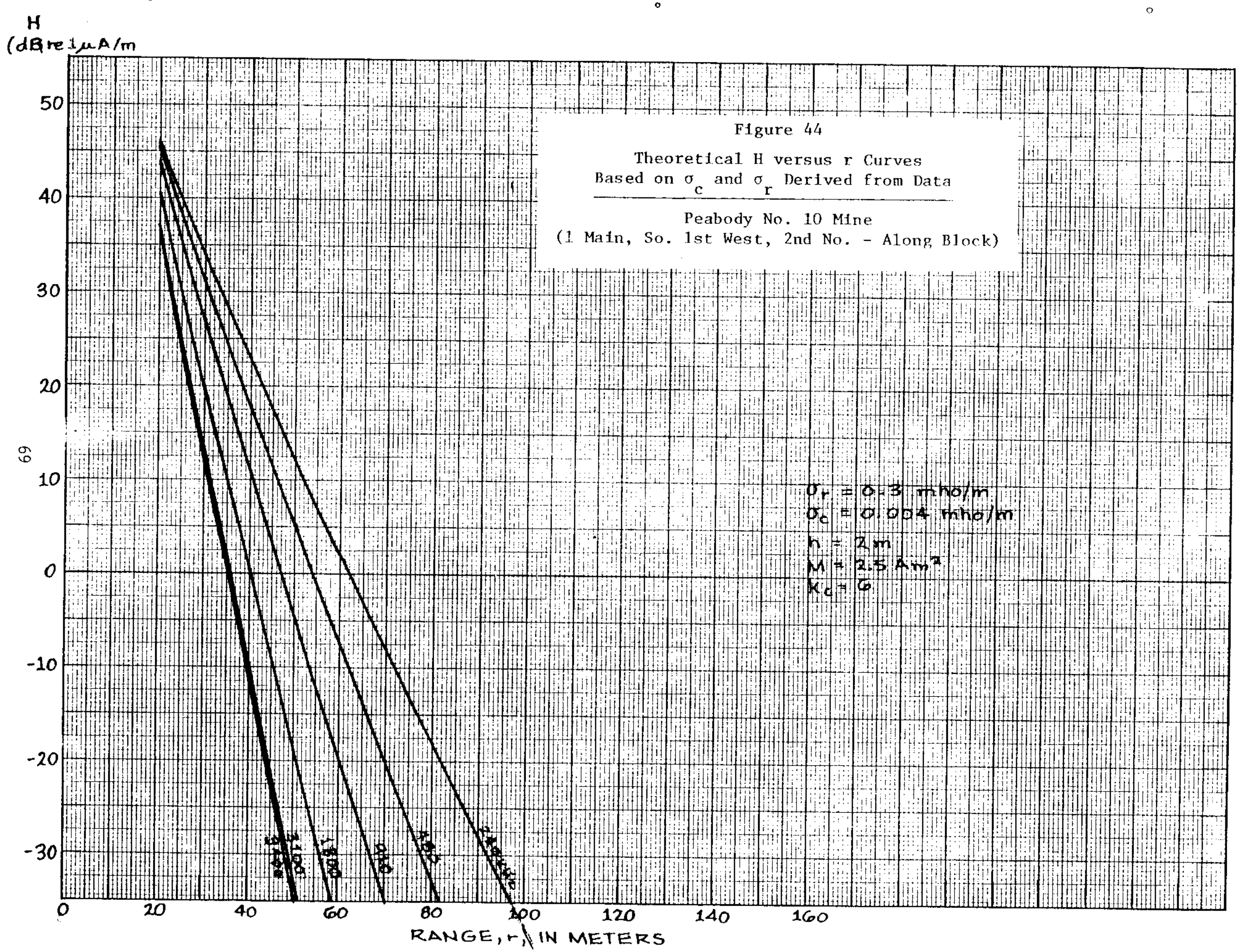


Figure 44

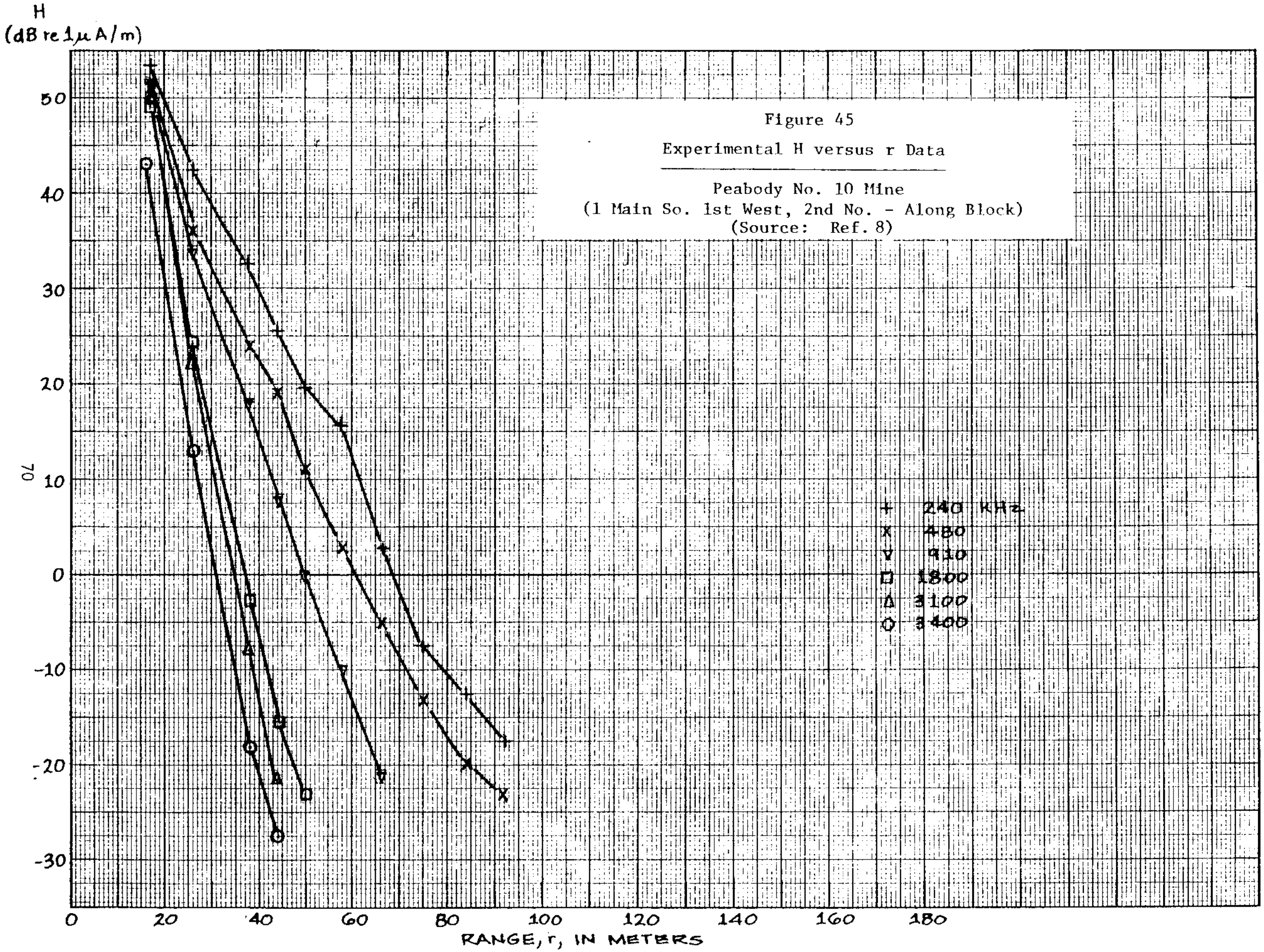
Theoretical H versus r Curves
Based on σ_c and σ_r Derived from Data

Peabody No. 10 Mine
(1 Main, So. 1st West, 2nd No. - Along Block)

Figure 45

Experimental H versus r Data

Peabody No. 10 Mine
(1 Main So. 1st West, 2nd No. - Along Block)
(Source: Ref. 8)



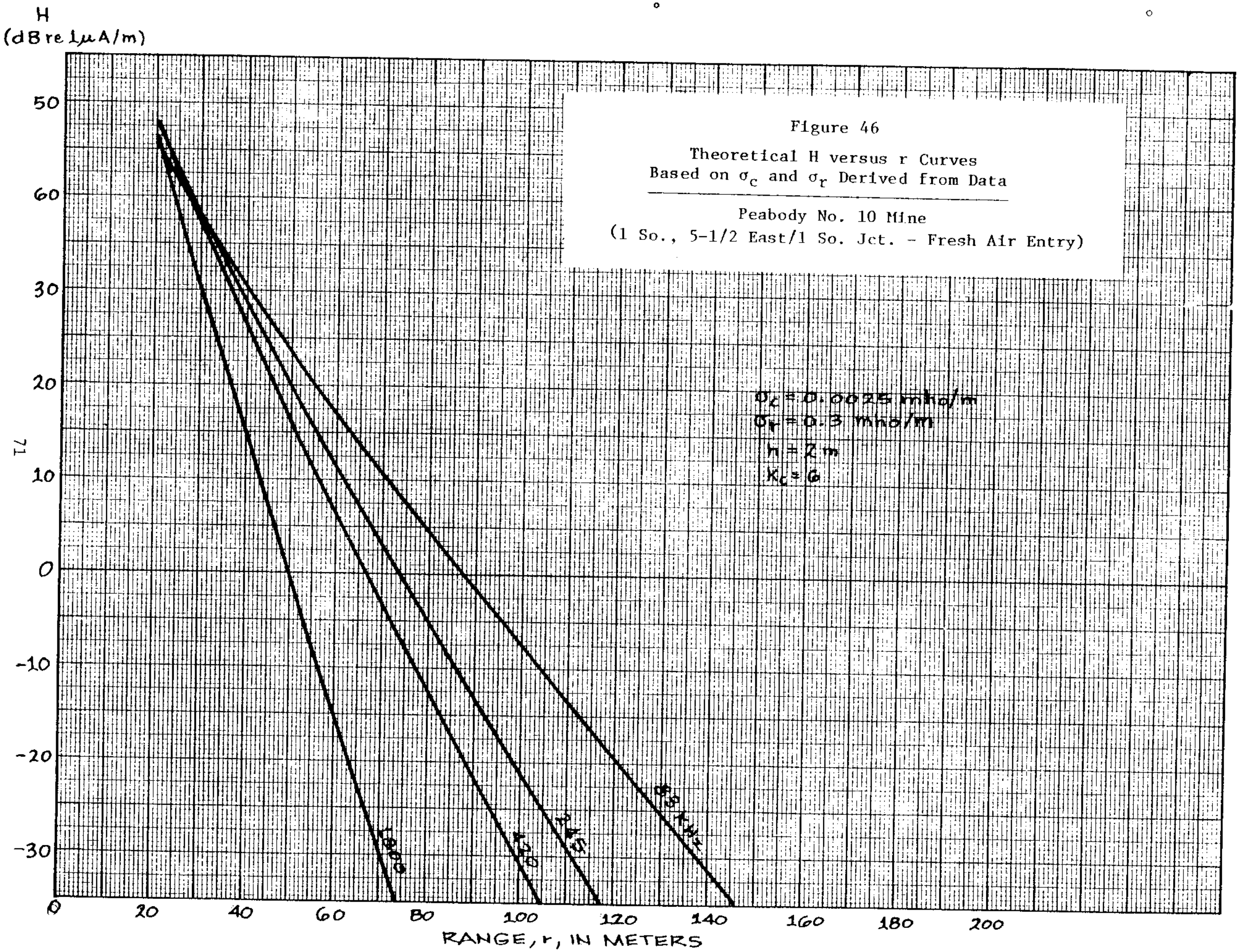


Figure 46

Theoretical H versus r Curves
Based on σ_c and σ_r Derived from Data

Peabody No. 10 Mine
(1 So., 5-1/2 East/1 So. Jct. - Fresh Air Entry)

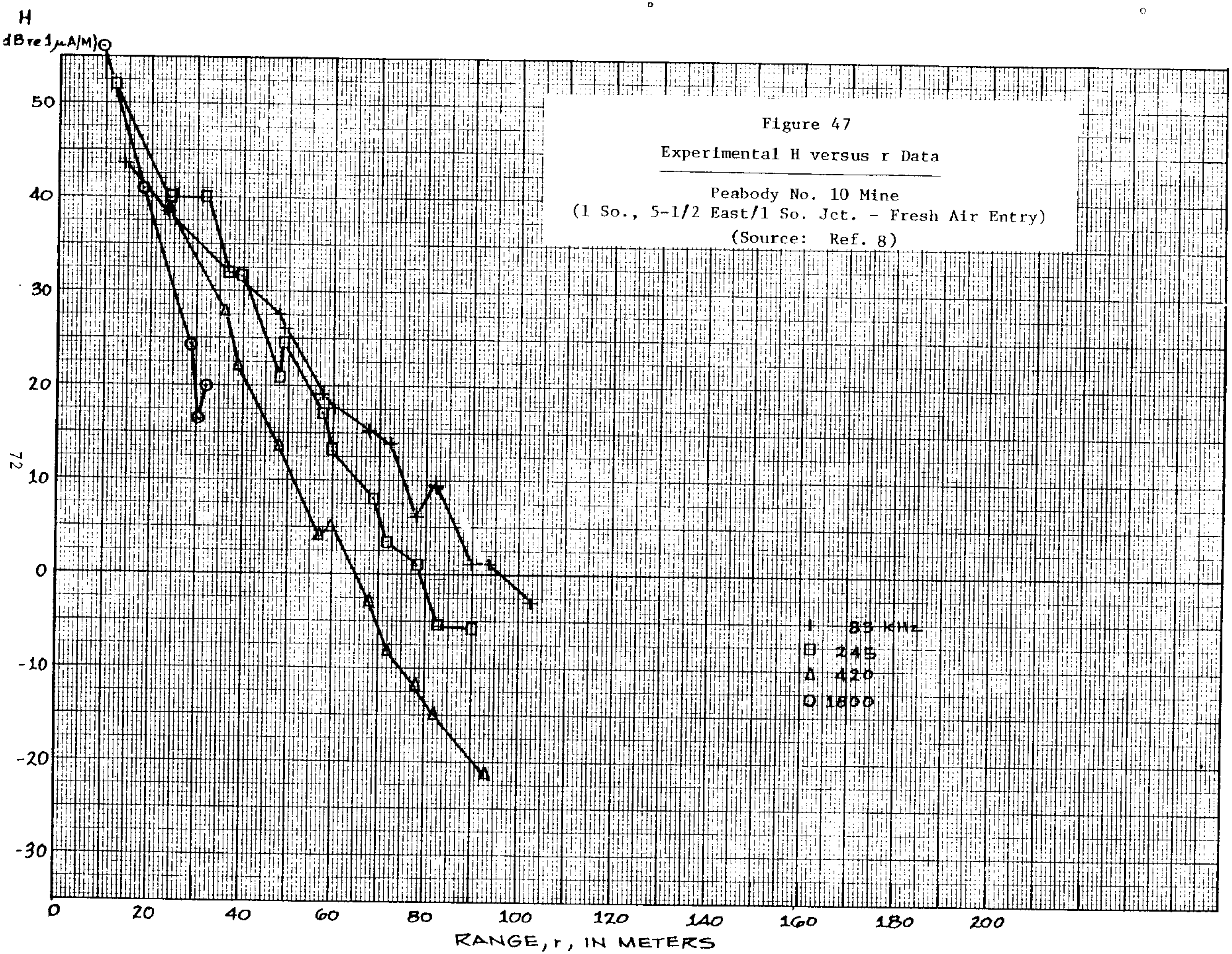


Figure 47
Experimental H versus r Data
Peabody No. 10 Mine
(1 So., 5-1/2 East/1 So. Jct. - Fresh Air Entry)
(Source: Ref. 8)
H
dB re 1 μA/M
50
40
30
20
10
0
-10
-20
-30
0
20
40
60
80
100
120
140
160
180
200
RANGE, r, IN METERS
+ 83 KHz
□ 245
Δ 420
O 1800

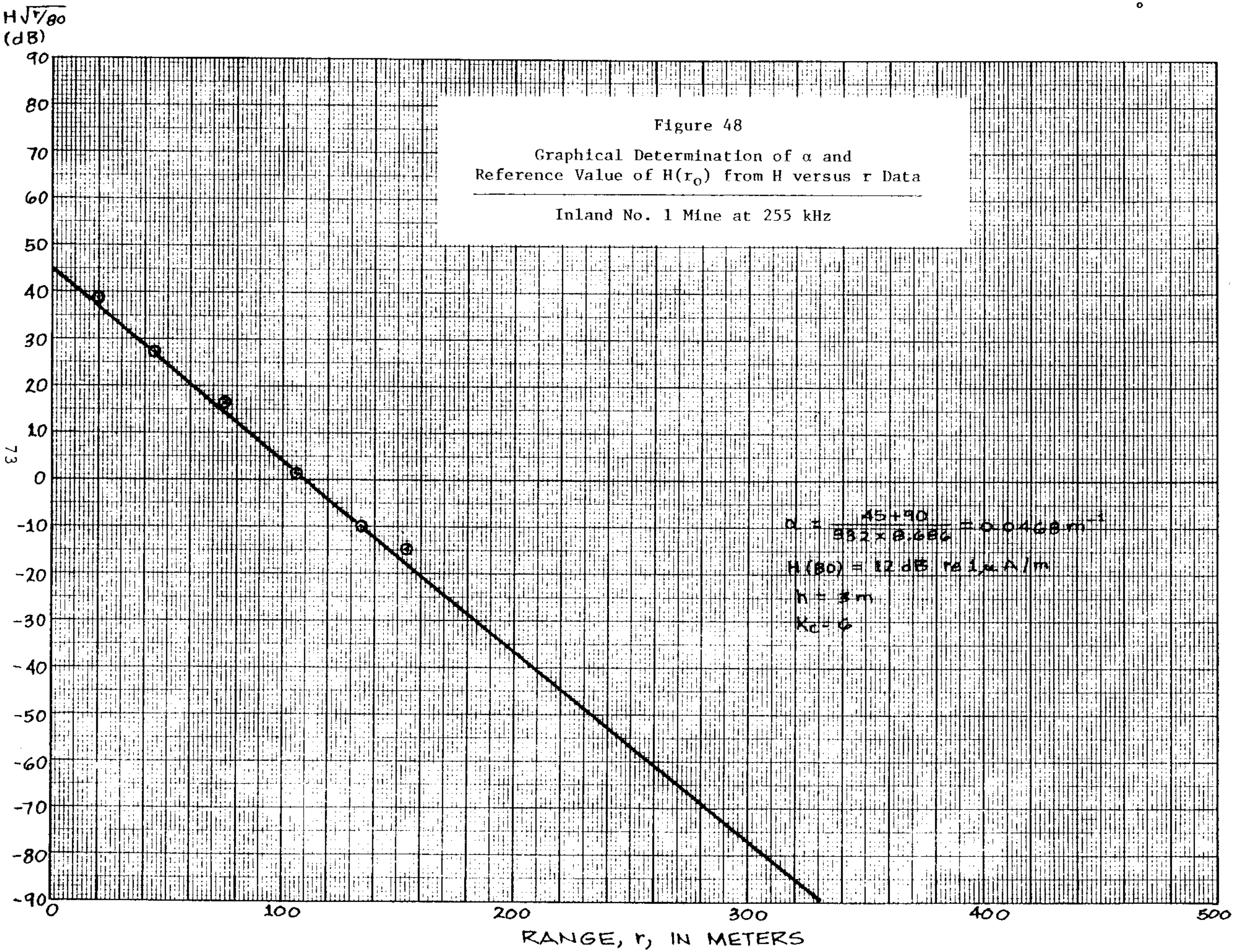


Figure 48

Graphical Determination of α and Reference Value of $H(r_o)$ from H versus r Data

Inland No. 1 Mine at 255 kHz

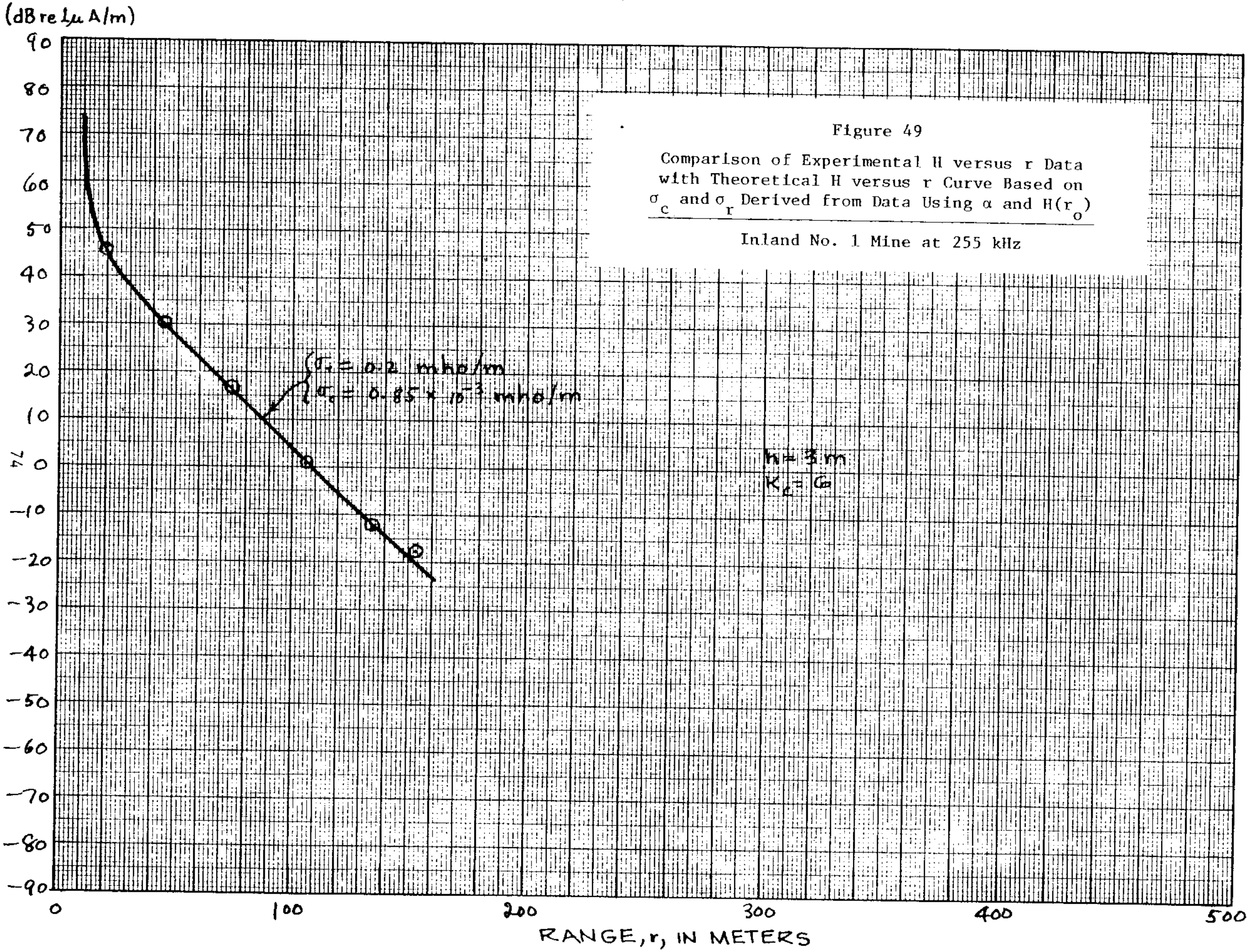


Figure 49

Comparison of Experimental H versus r Data with Theoretical H versus r Curve Based on σ_c and σ_r Derived from Data Using α and $H(r_o)$

Inland No. 1 Mine at 255 kHz

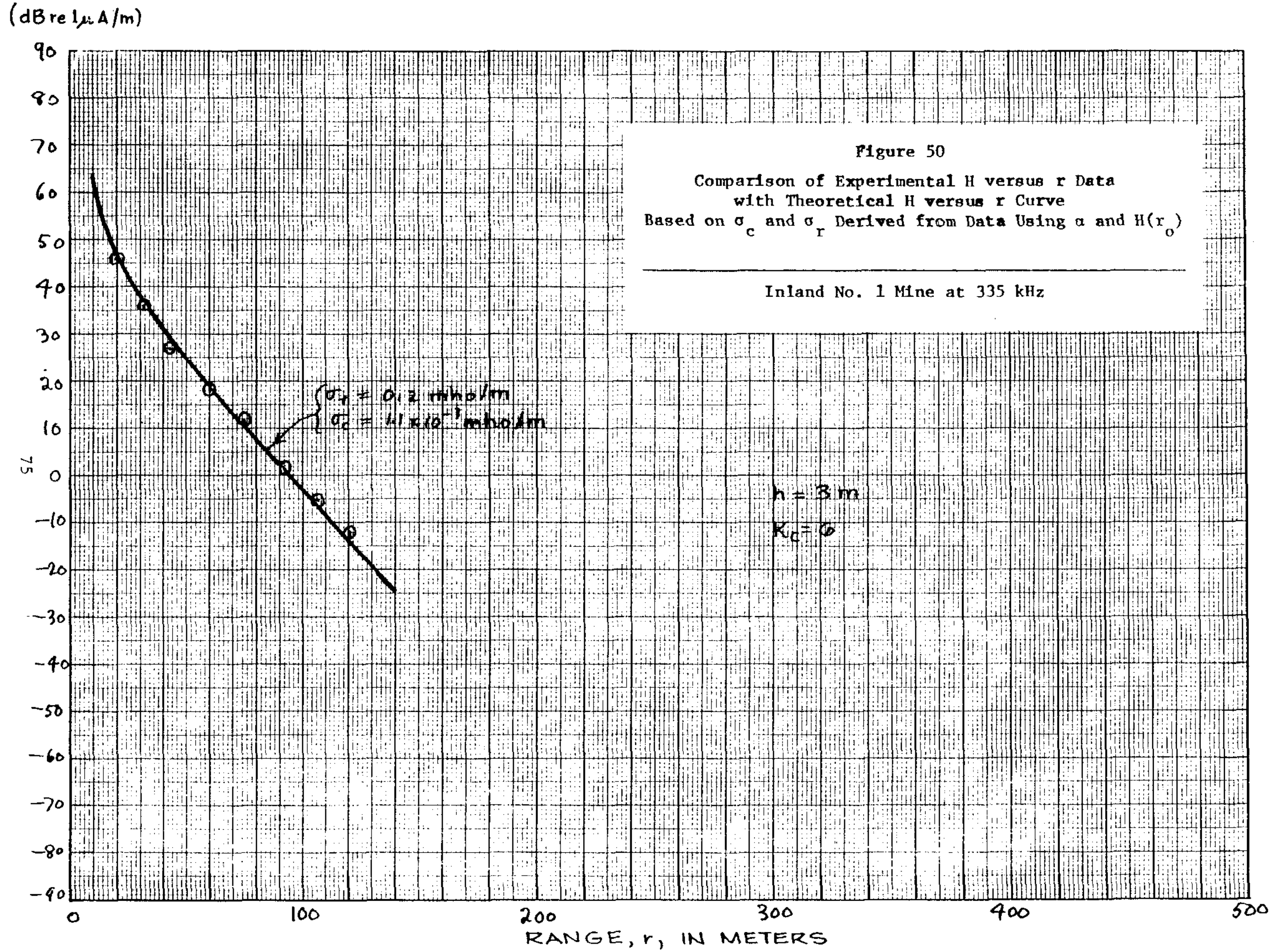


Figure 50

Comparison of Experimental H versus r Data with Theoretical H versus r Curve Based on σ_c and σ_r Derived from Data Using α and $H(r_o)$

Inland No. 1 Mine at 335 kHz

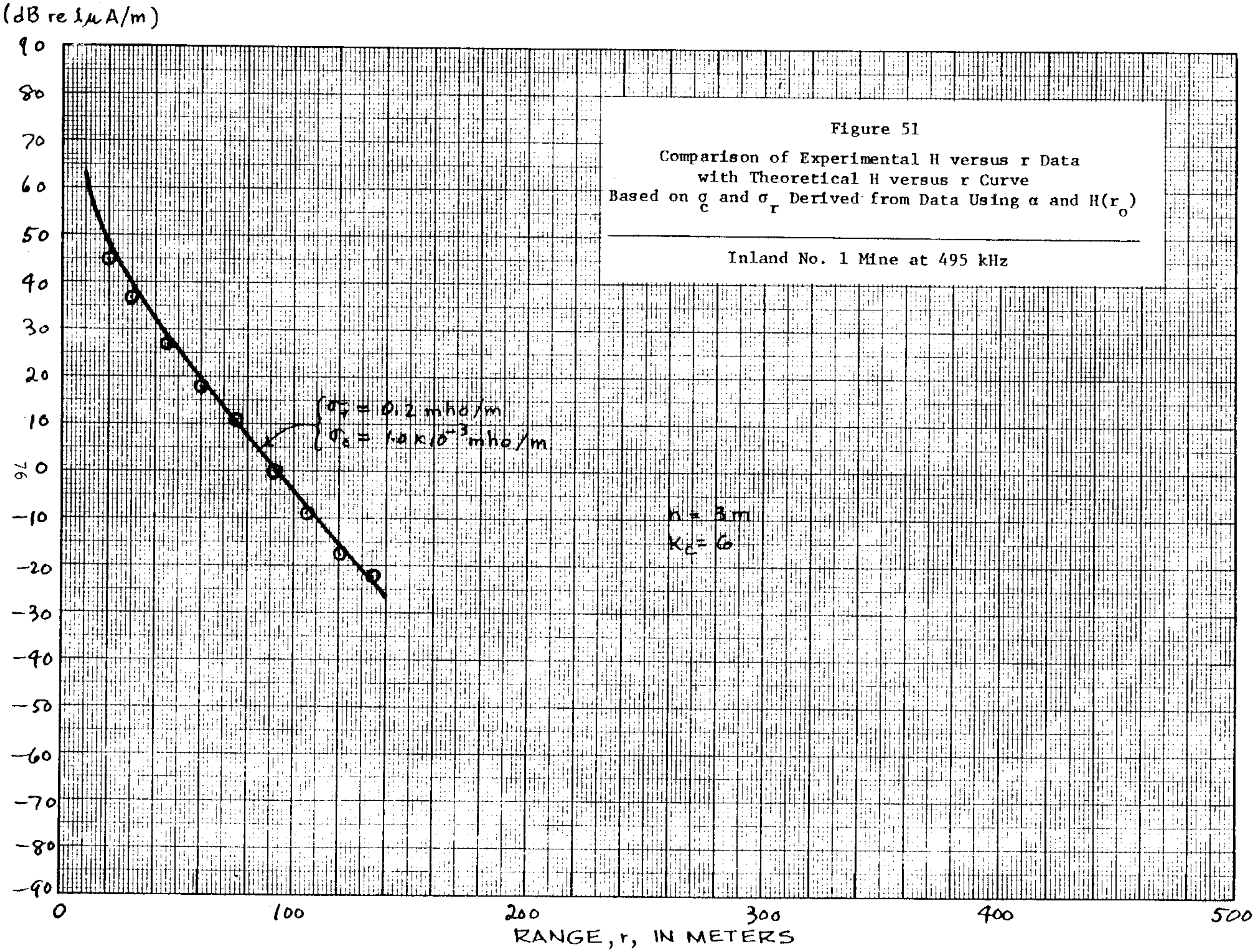


Figure 51

Comparison of Experimental H versus r Data with Theoretical H versus r Curve Based on σ_c and σ_r Derived from Data Using α and $H(r_o)$

Inland No. 1 Mine at 495 kHz

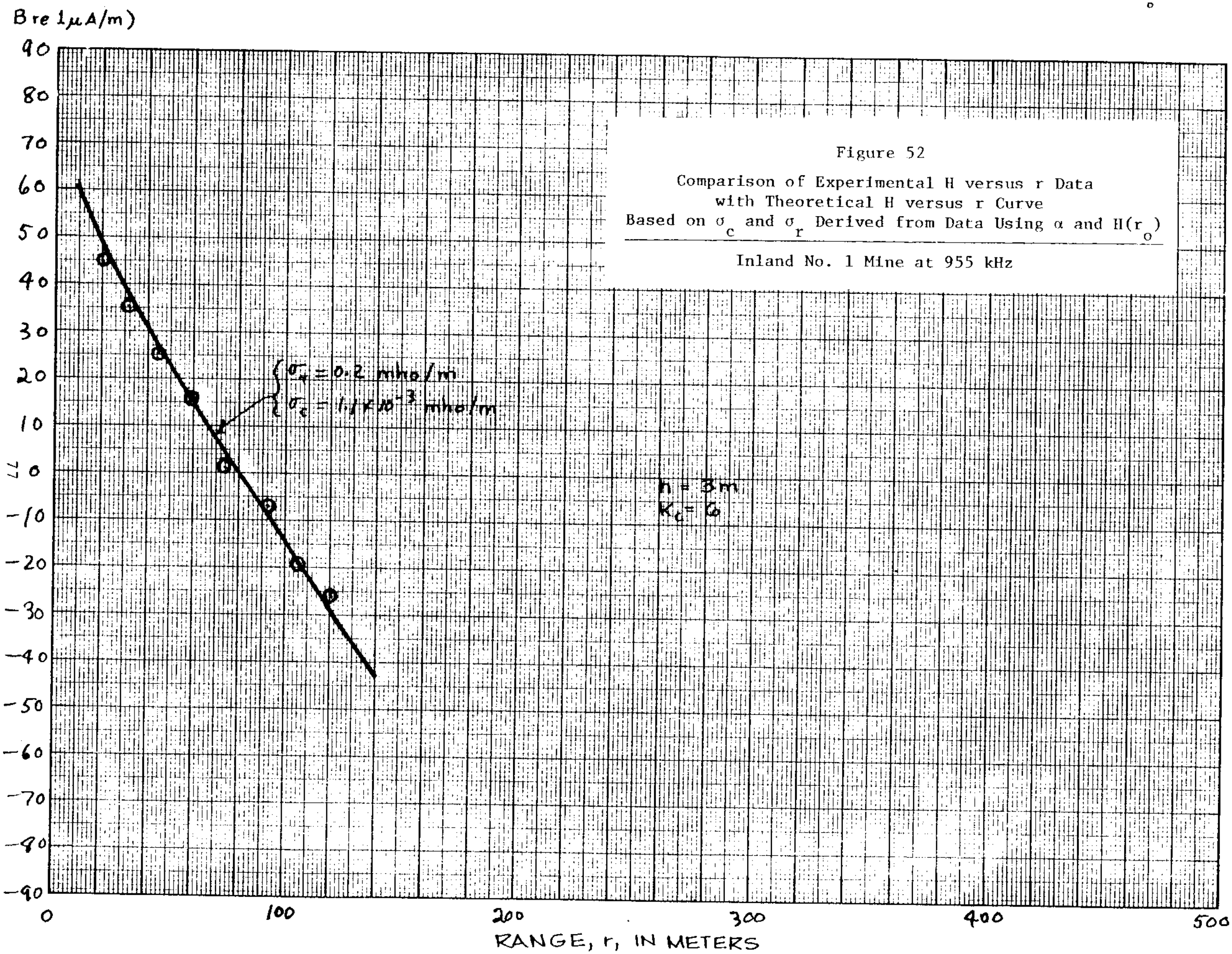


Figure 52

Comparison of Experimental H versus r Data
with Theoretical H versus r Curve
Based on σ_c and σ_r Derived from Data Using α and $H(r_o)$

Inland No. 1 Mine at 955 kHz

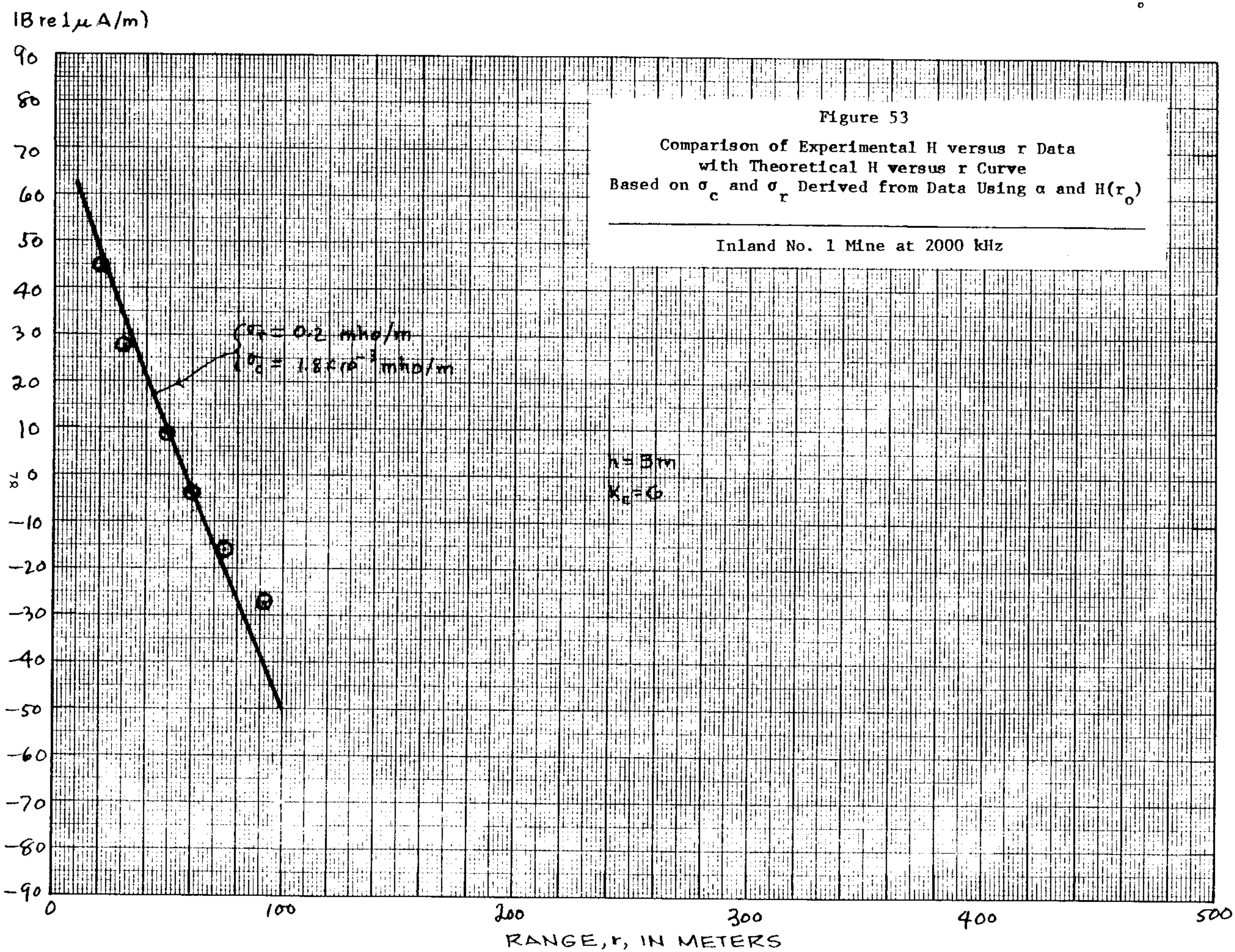


Figure 53

Comparison of Experimental H versus r Data with Theoretical H versus r Curve Based on σ_c and σ_r Derived from Data Using α and $H(r_o)$

Inland No. 1 Mine at 2000 kHz

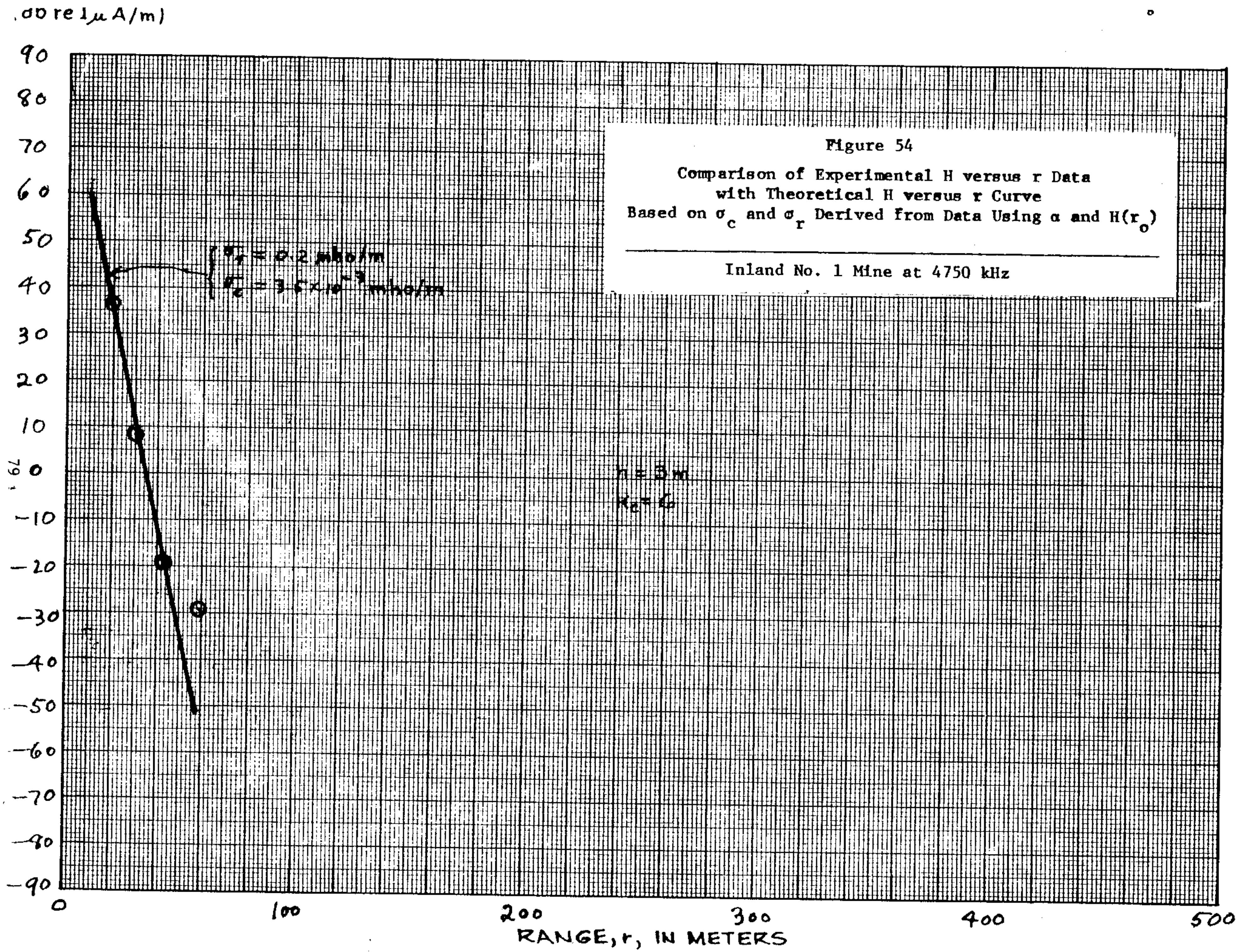


Figure 54

Comparison of Experimental H versus r Data with Theoretical H versus r Curve Based on σ_c and σ_r Derived from Data Using α and $H(r_o)$

Inland No. 1 Mine at 4750 kHz

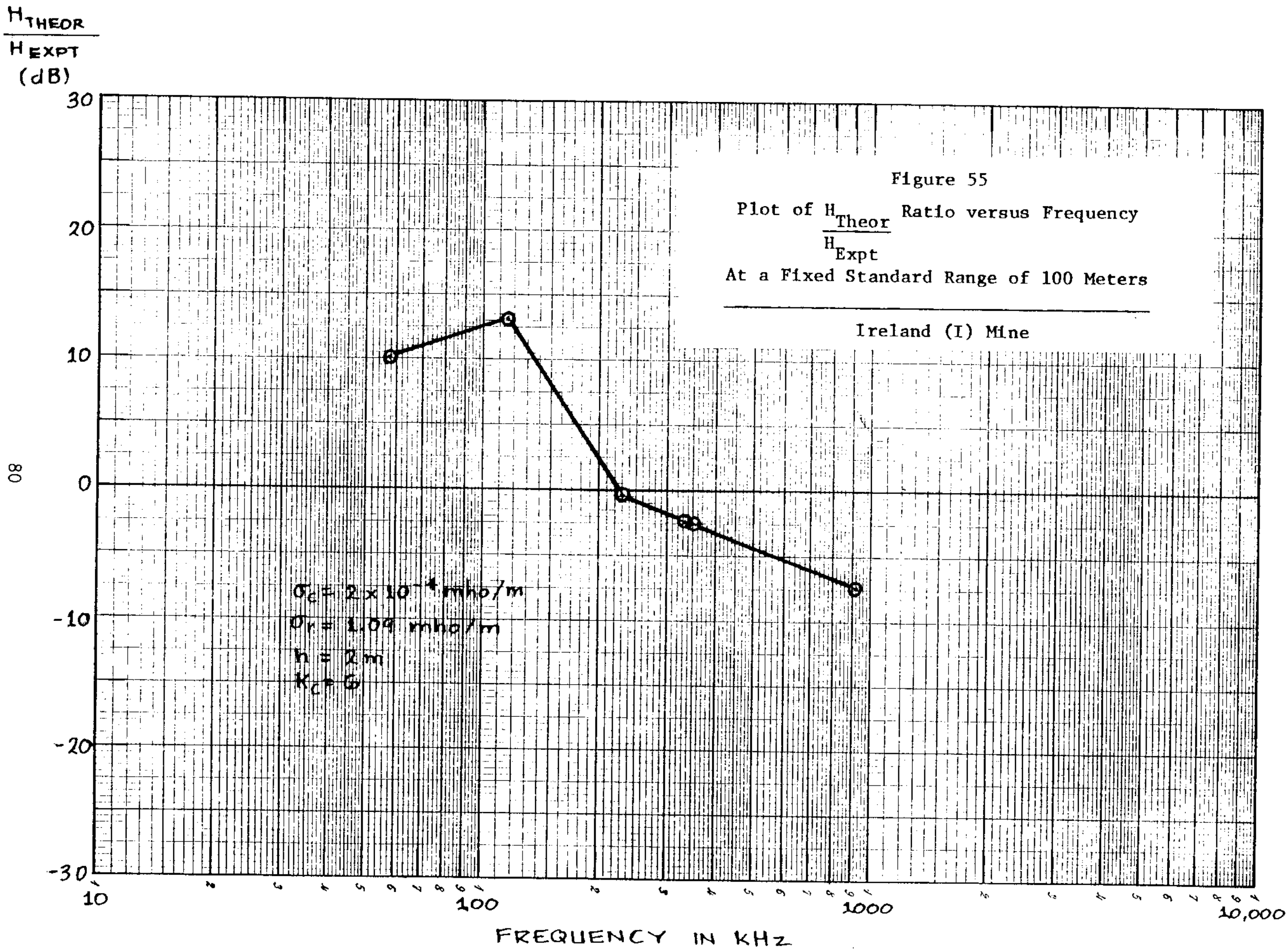


Figure 55

Plot of $\frac{H_{Theor}}{H_{Expt}}$ Ratio versus Frequency

At a Fixed Standard Range of 100 Meters

Ireland (I) Mine

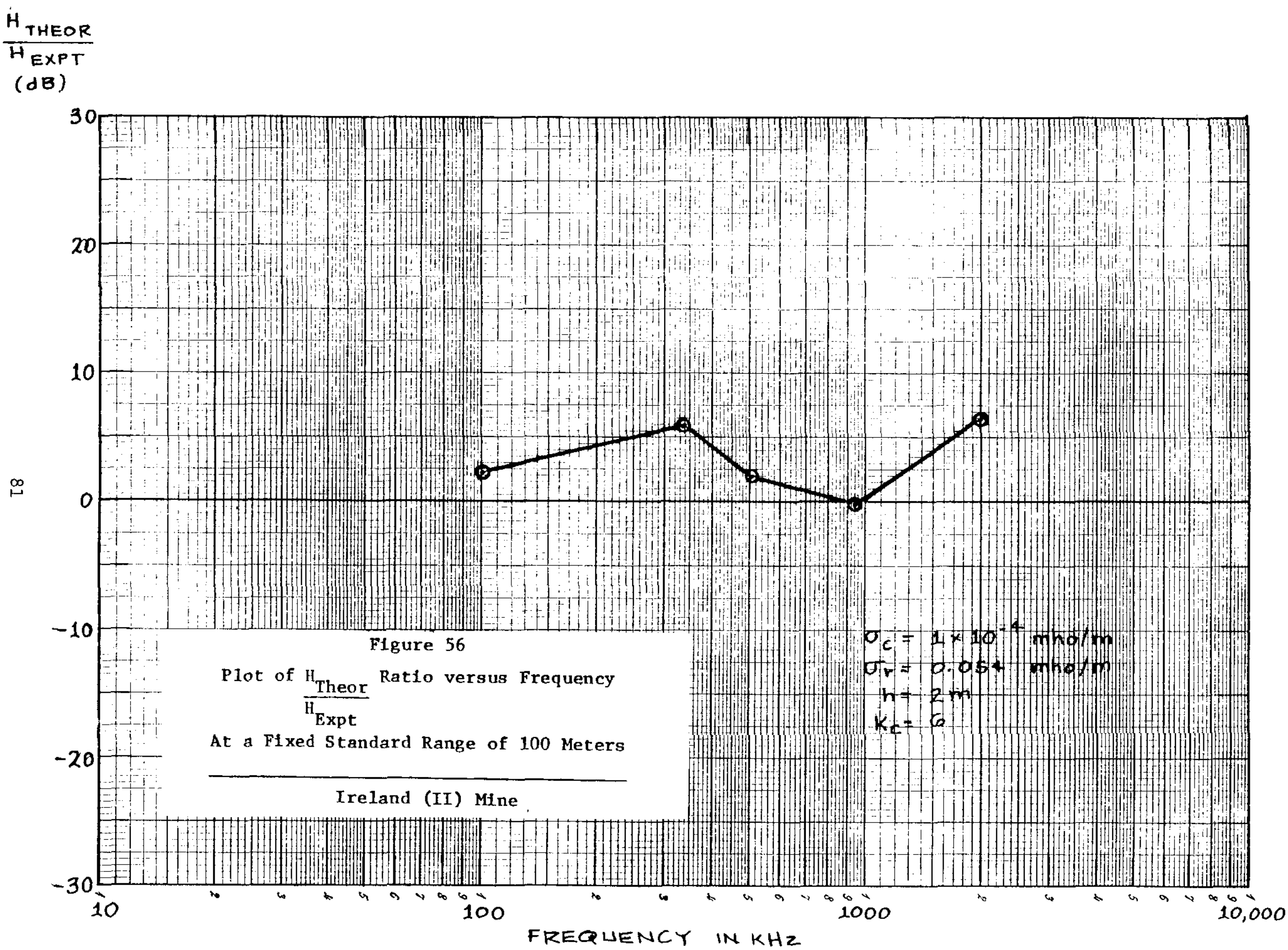


Figure 56

Plot of $\frac{H_{Theor}}{H_{Expt}}$ Ratio versus Frequency

At a Fixed Standard Range of 100 Meters

Ireland (II) Mine

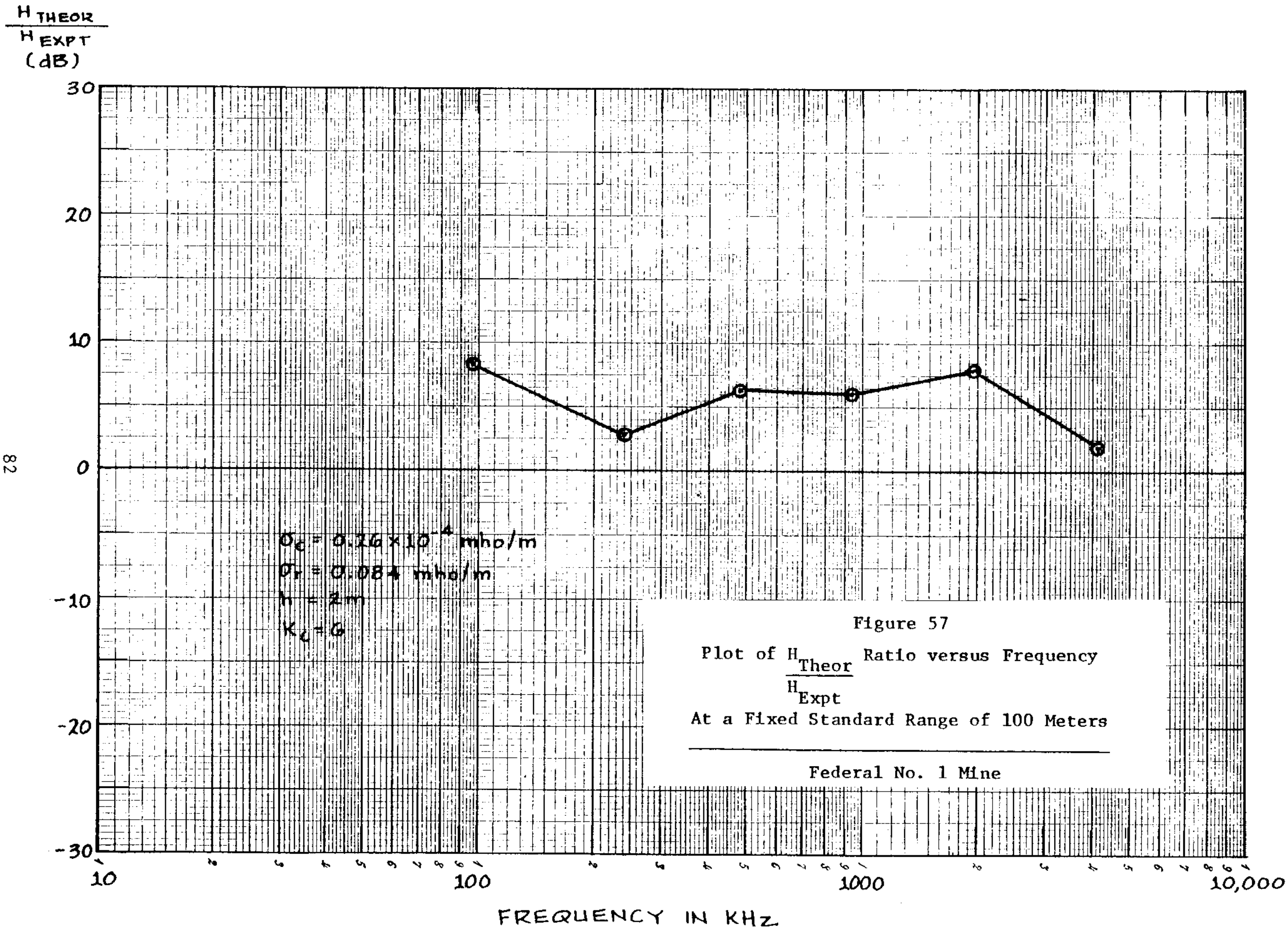


Figure 57

Plot of $\frac{H_{Theor}}{H_{Expt}}$ Ratio versus Frequency

At a Fixed Standard Range of 100 Meters

Federal No. 1 Mine

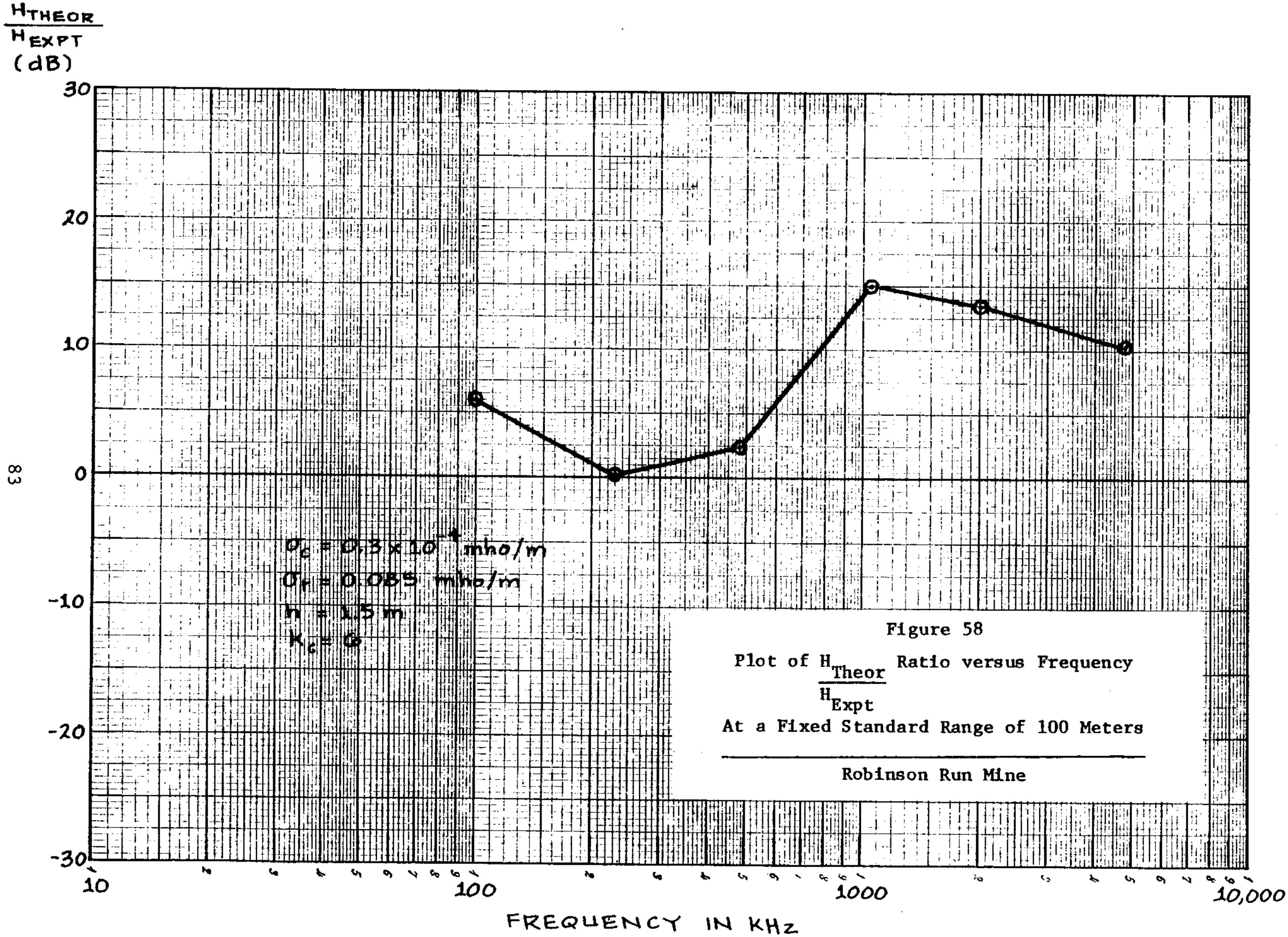


Figure 58

Plot of $\frac{H_{Theor}}{H_{Expt}}$ Ratio versus Frequency
At a Fixed Standard Range of 100 Meters

Robinson Run Mine

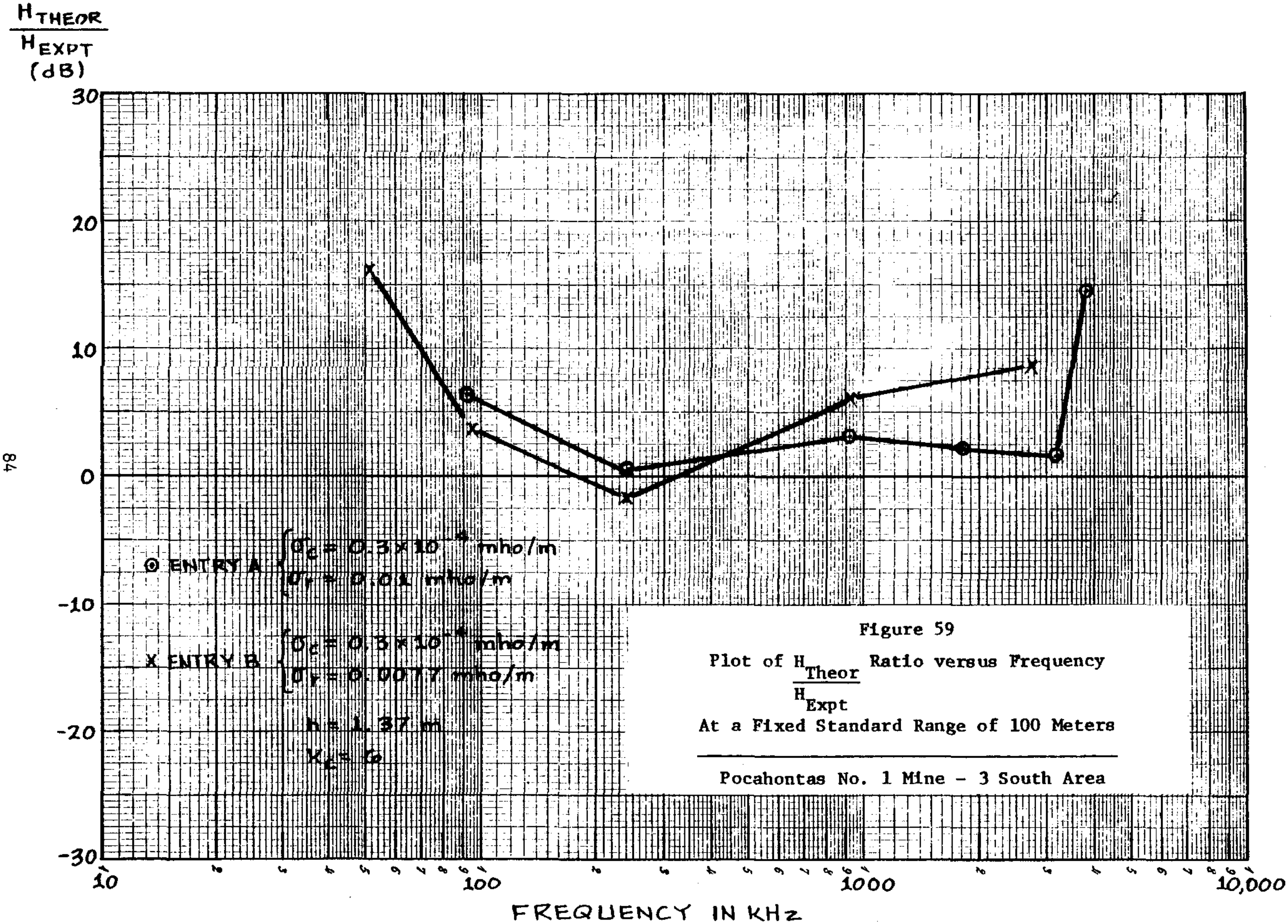


Figure 59

Plot of $\frac{H_{Theor}}{H_{Expt}}$ Ratio versus Frequency

At a Fixed Standard Range of 100 Meters

Pocahontas No. 1 Mine - 3 South Area

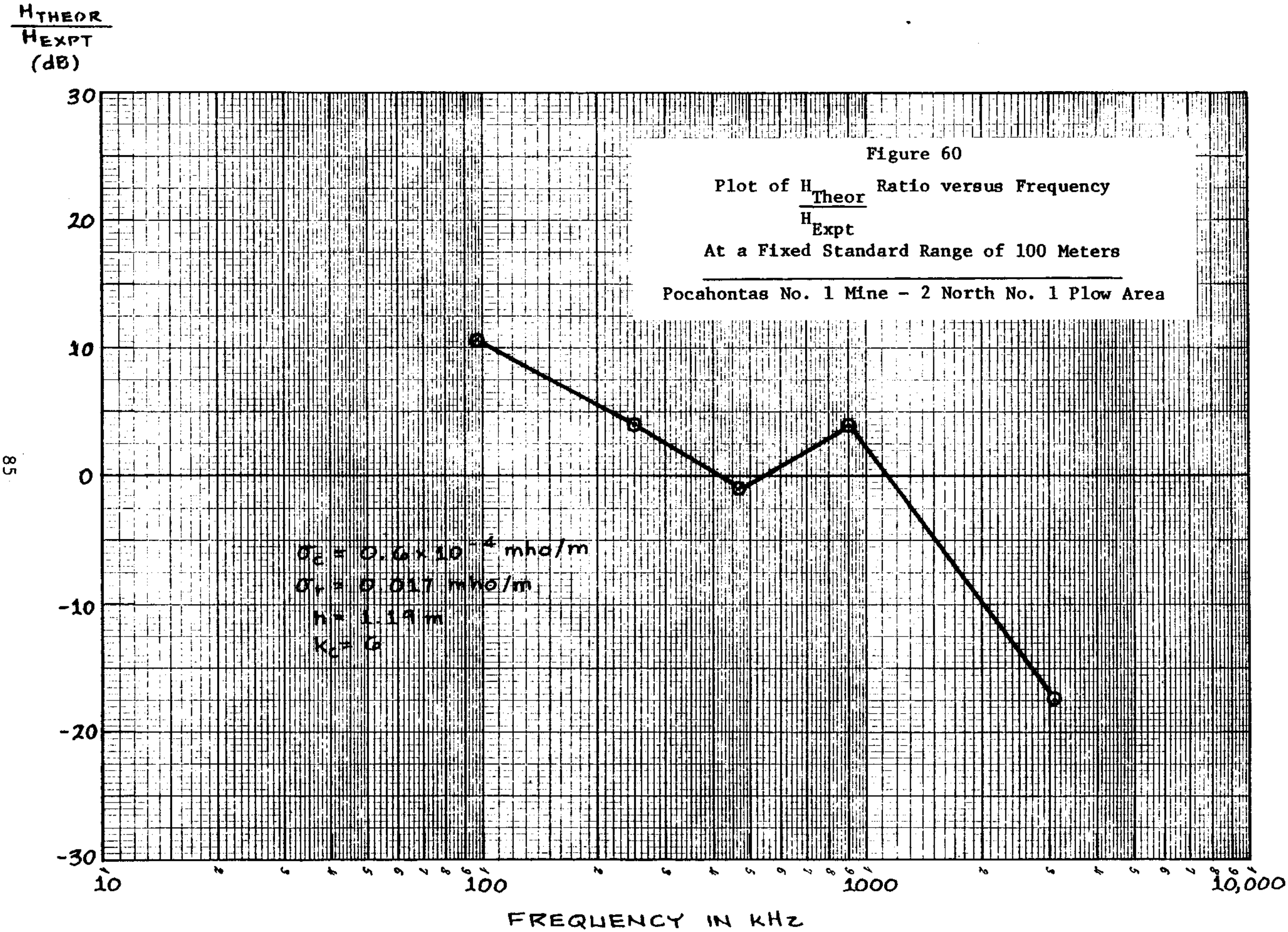


Figure 60
Plot of $\frac{H_{Theor}}{H_{Expt}}$ Ratio versus Frequency
At a Fixed Standard Range of 100 Meters
Pocahontas No. 1 Mine - 2 North No. 1 Plow Area
$\frac{H_{THEOR}}{H_{EXPT}}$ (dB)
30
20
10
0
-10
-20
-30
$\sigma_c = 0.6 \times 10^{-4}$ mho/m
$\sigma_r = 0.017$ mho/m
h = 1.19 m
$K_c = 6$
10
100
1000
10,000
FREQUENCY IN kHz

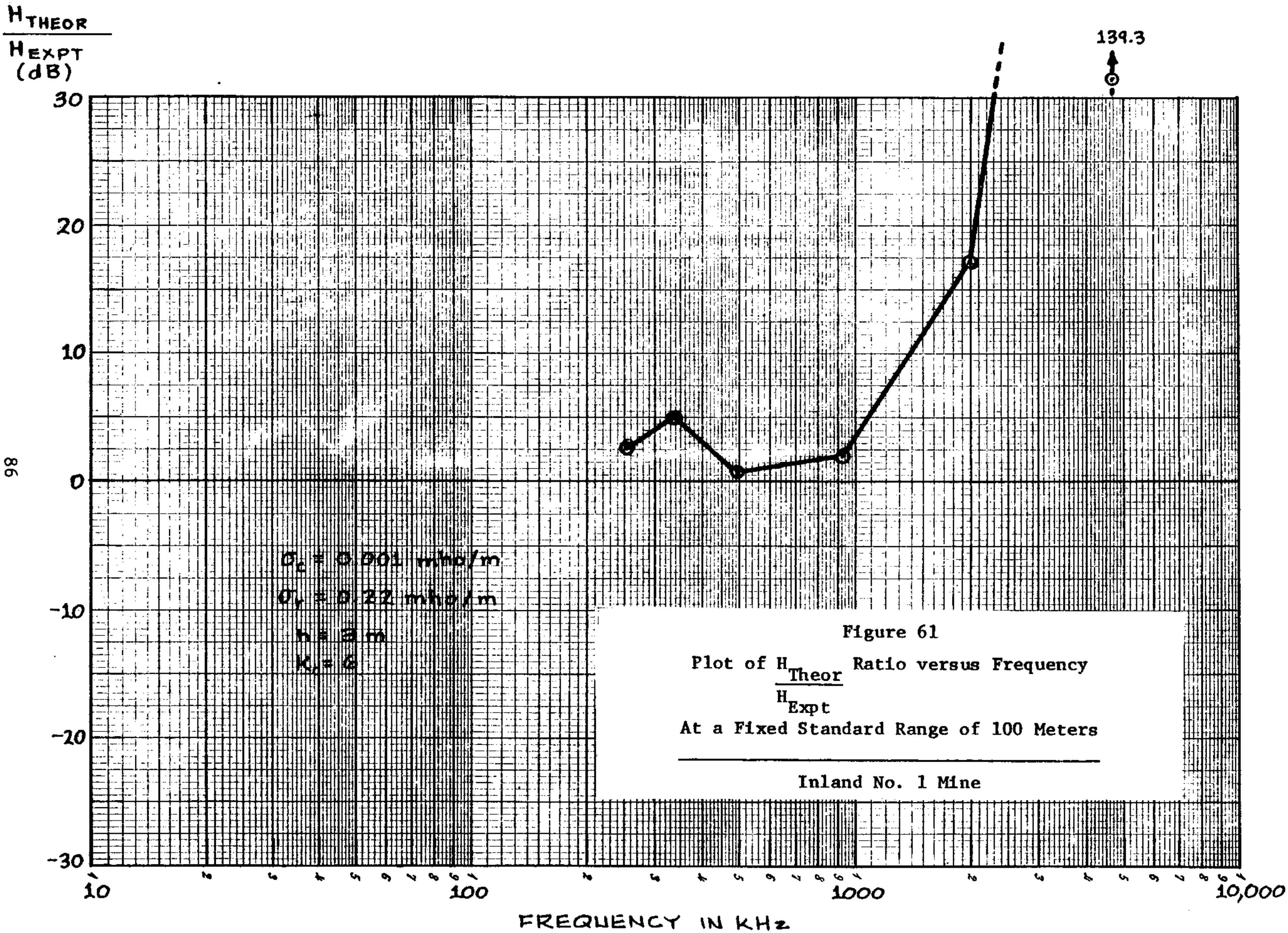


Figure 61

Plot of $\frac{H_{Theor}}{H_{Expt}}$ Ratio versus Frequency

At a Fixed Standard Range of 100 Meters

Inland No. 1 Mine

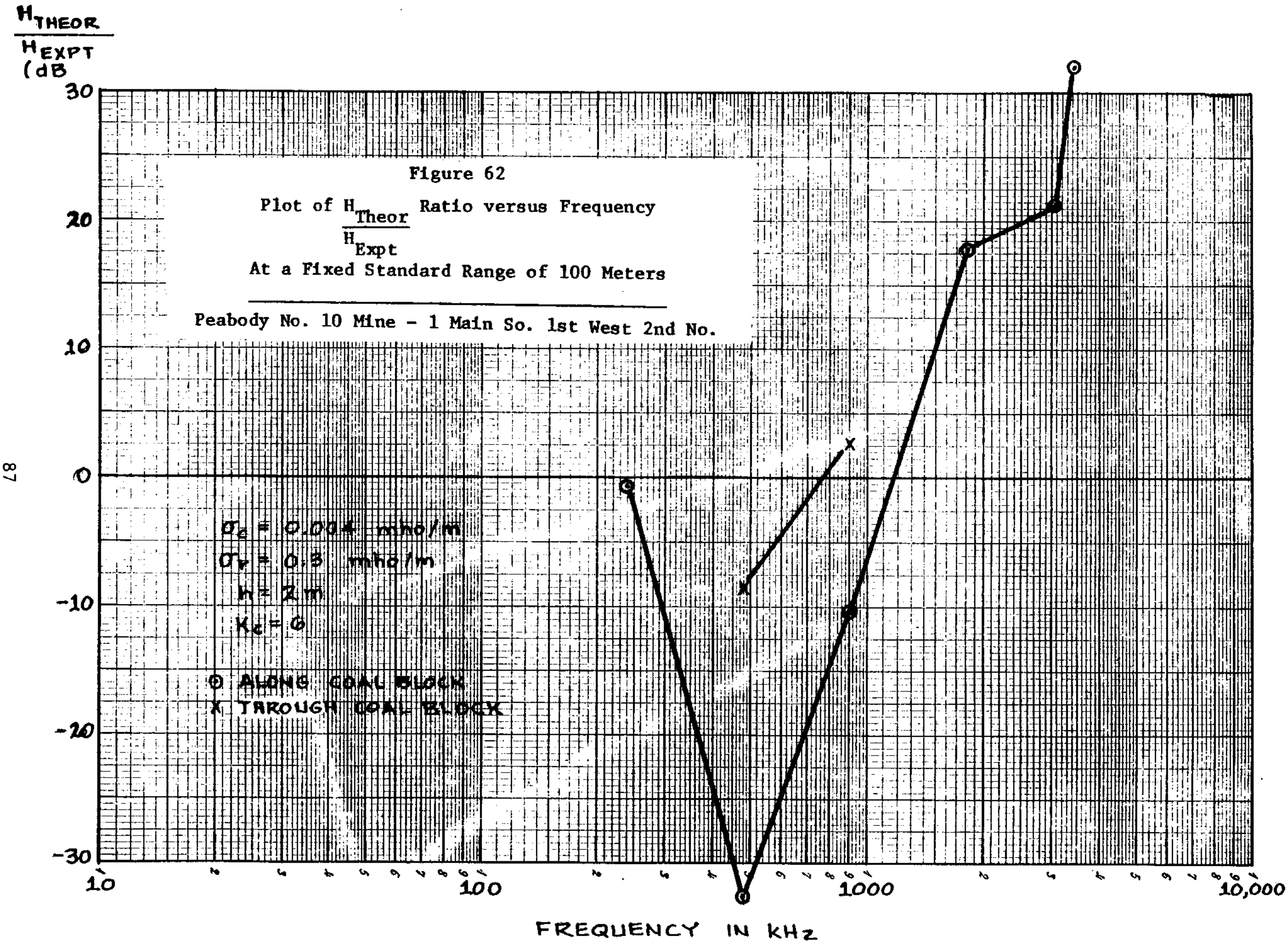


Figure 62

Plot of $\frac{H_{Theor}}{H_{Expt}}$ Ratio versus Frequency

At a Fixed Standard Range of 100 Meters

Peabody No. 10 Mine - 1 Main So. 1st West 2nd No.

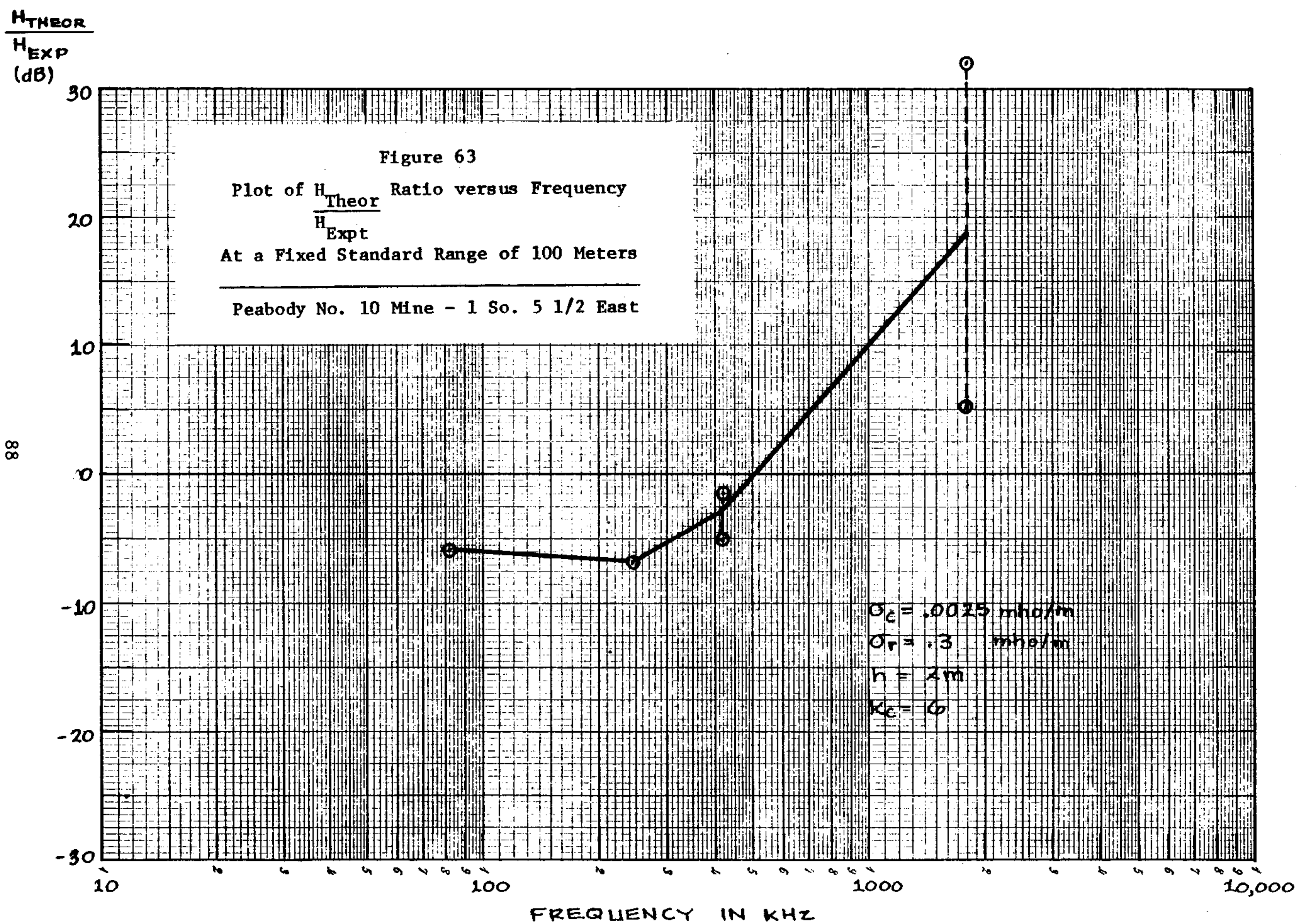


Figure 63

Plot of $\frac{H_{Theor}}{H_{Expt}}$ Ratio versus Frequency

At a Fixed Standard Range of 100 Meters

Peabody No. 10 Mine - 1 So. 5 1/2 East

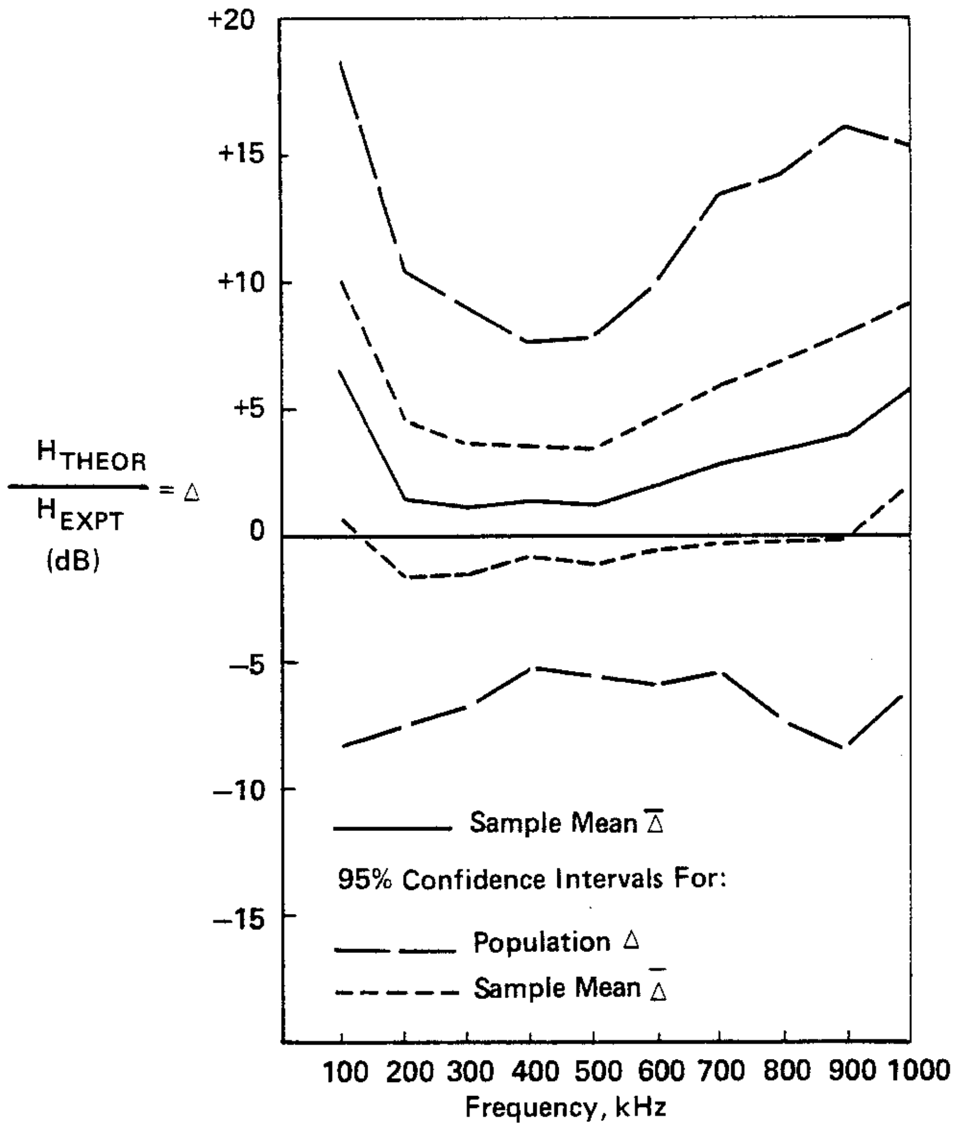


FIGURE 64 STATISTICAL SUMMARY OF H_{THEOR}/H_{EXPT} RATIOS IN dB

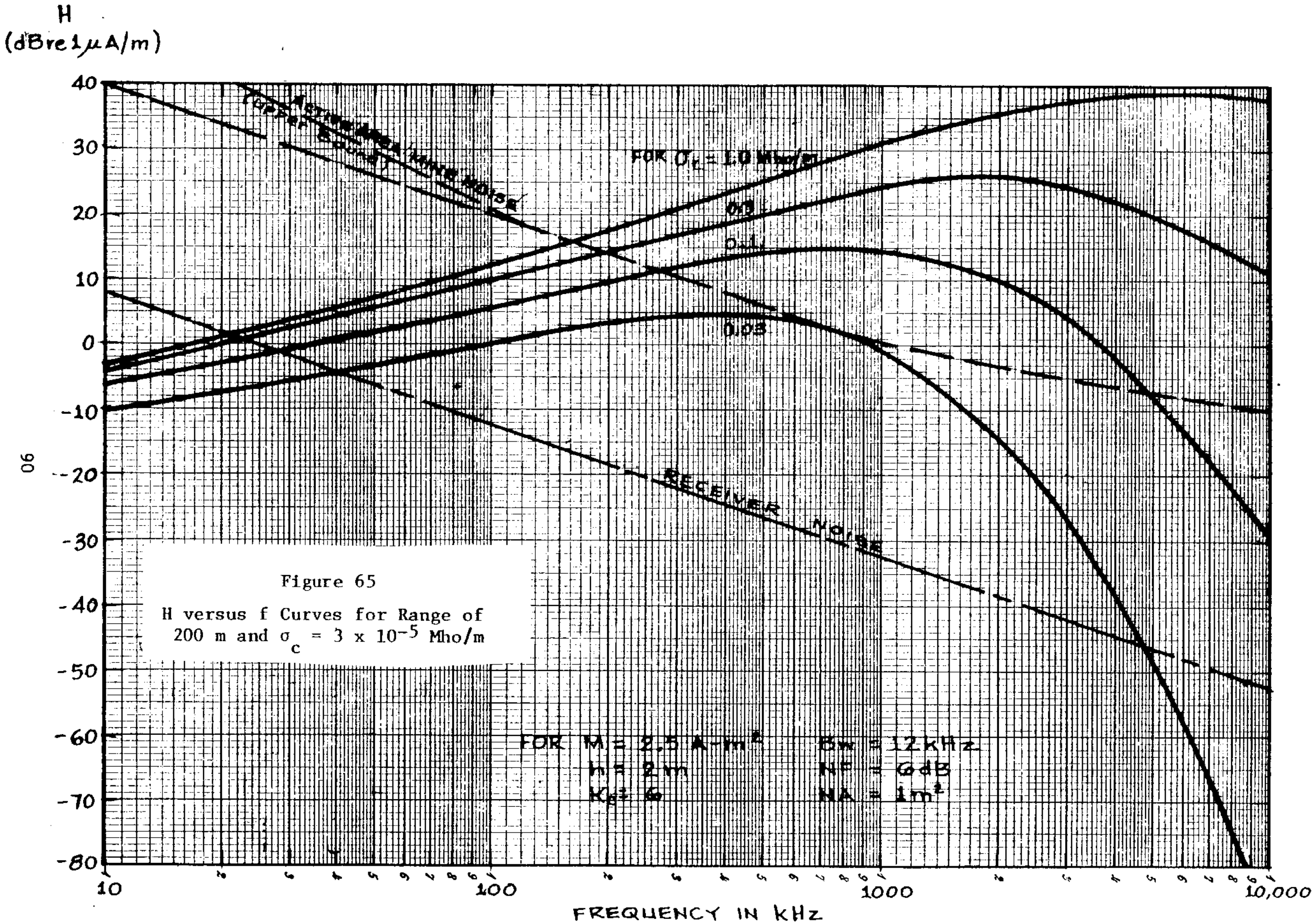


Figure 65

H versus f Curves for Range of 200 m and $\sigma_c = 3 \times 10^{-5}$ Mho/m

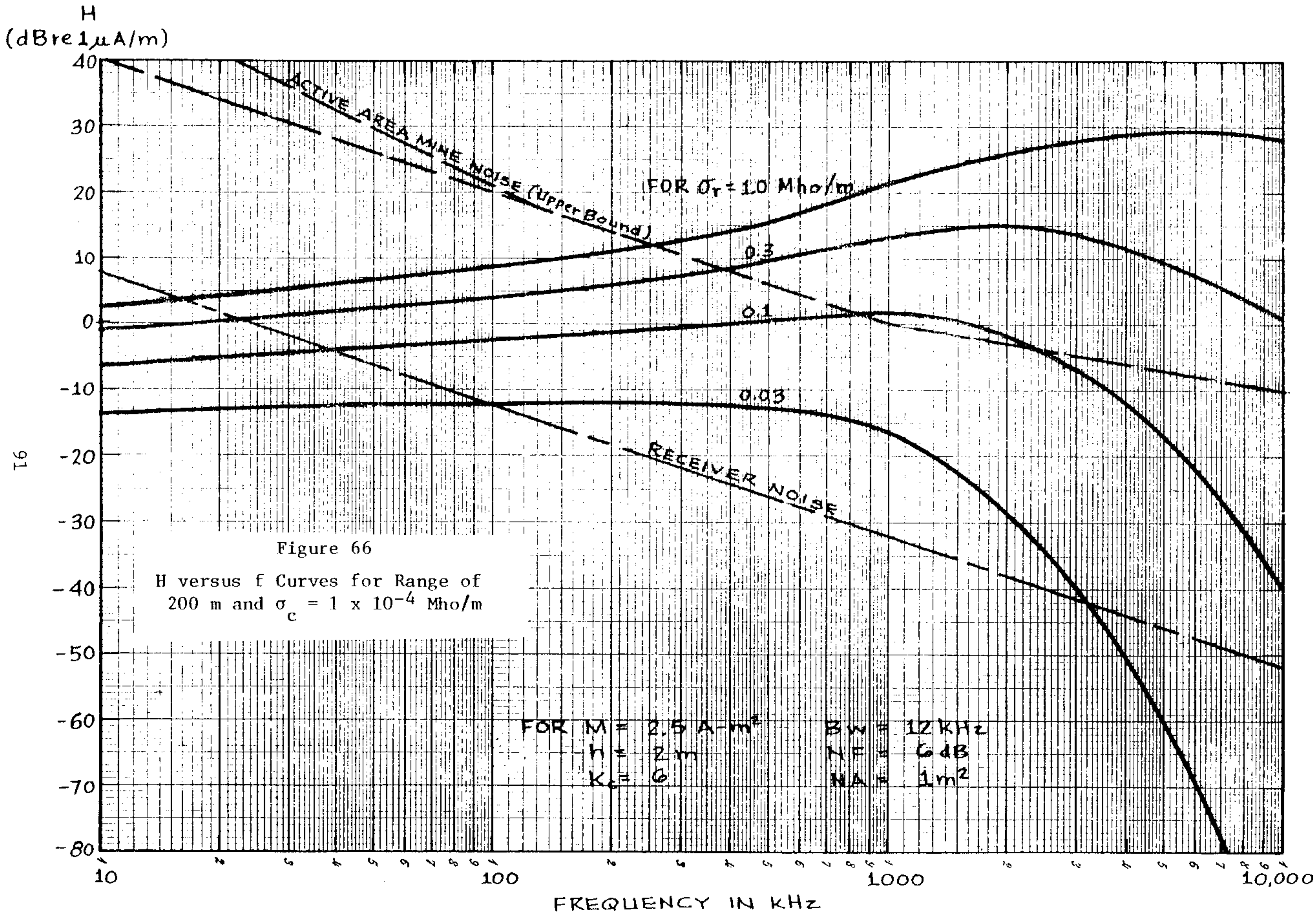


Figure 66

H versus f Curves for Range of 200 m and $\sigma_c = 1 \times 10^{-4}$ Mho/m

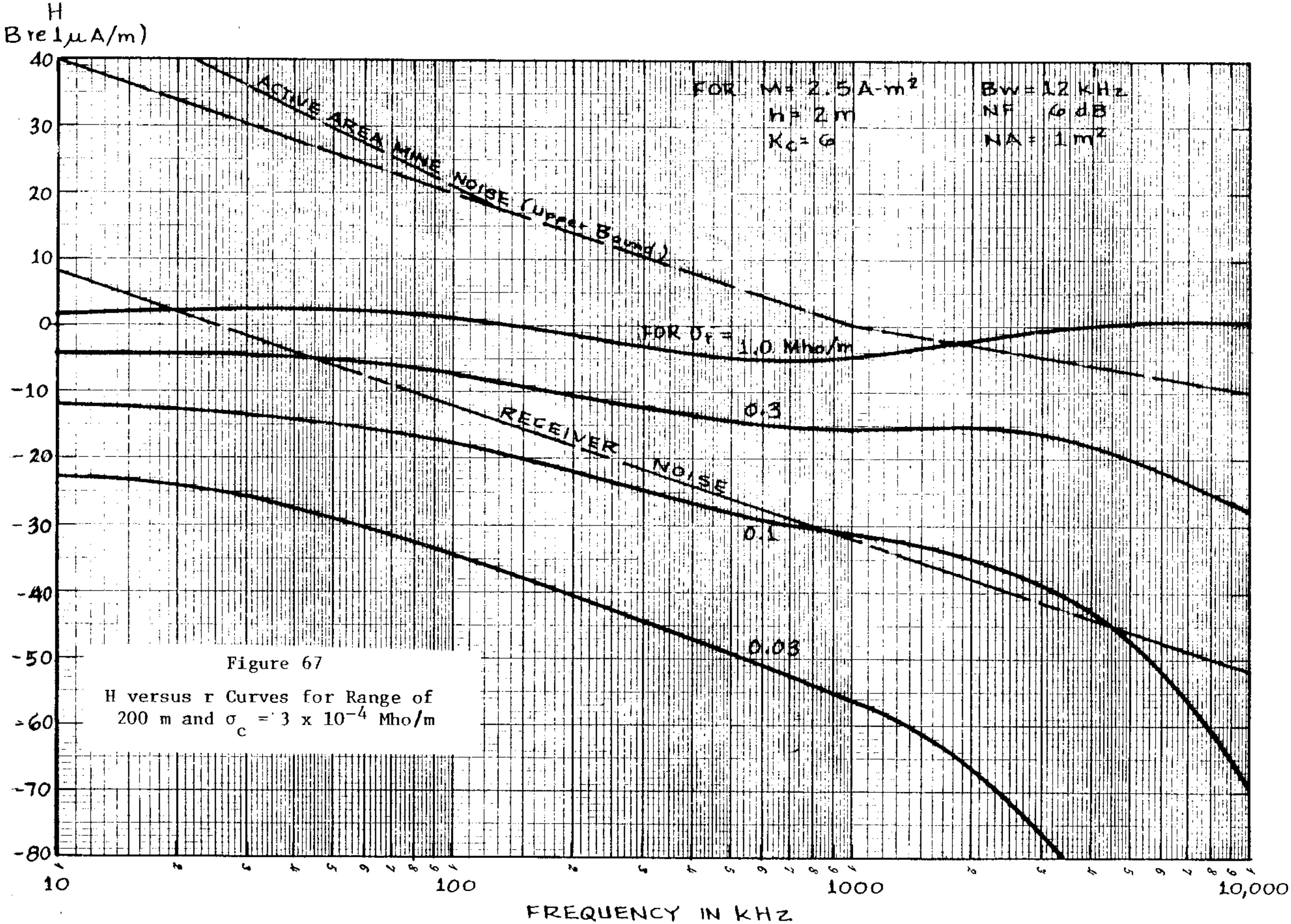


Figure 67

H versus r Curves for Range of 200 m and σ_c = 3 x 10^{-4} Mho/m

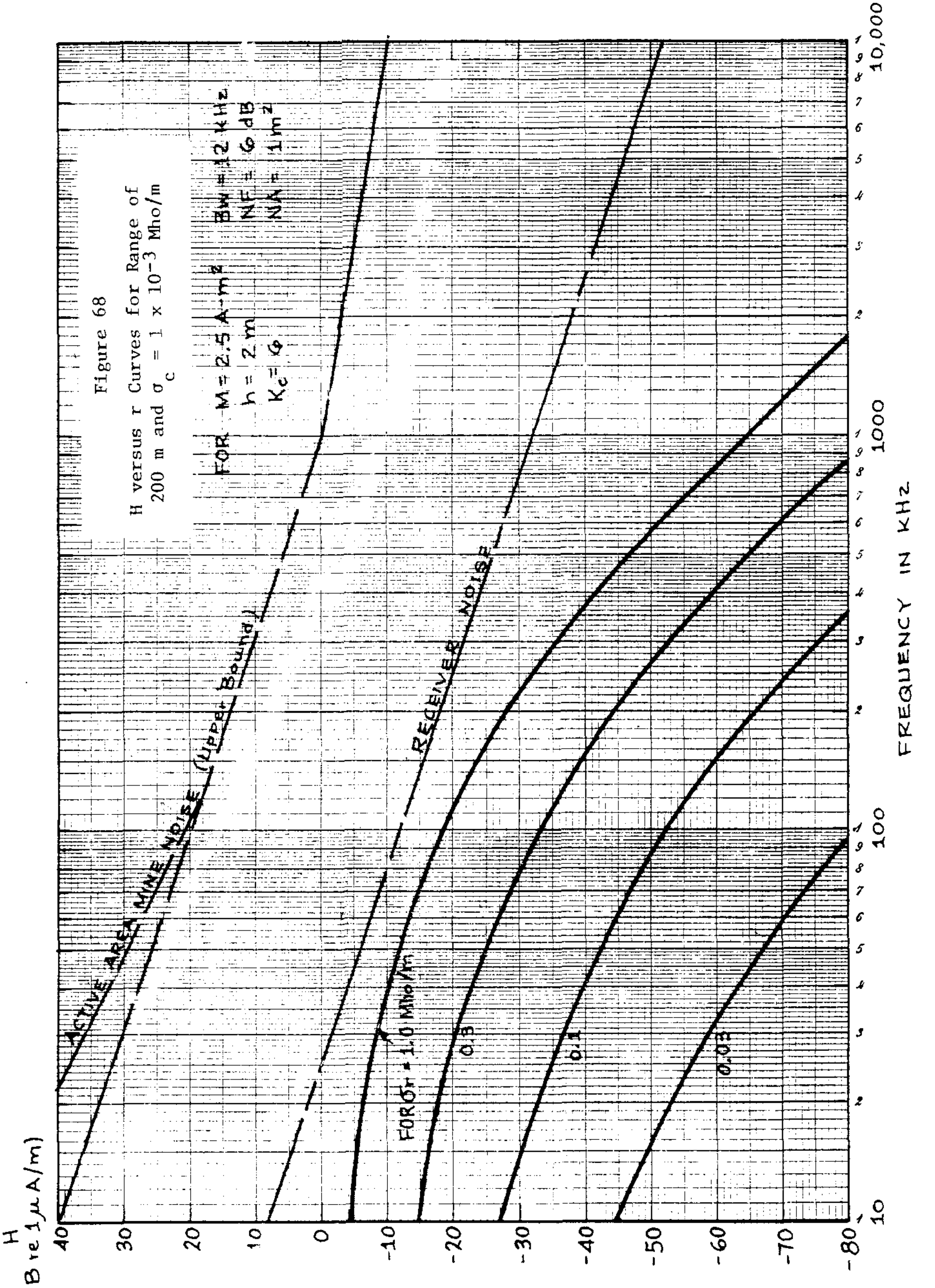


Figure 68

H versus r Curves for Range of 200 m and $\sigma_c = 1 \times 10^{-3}$ Mho/m

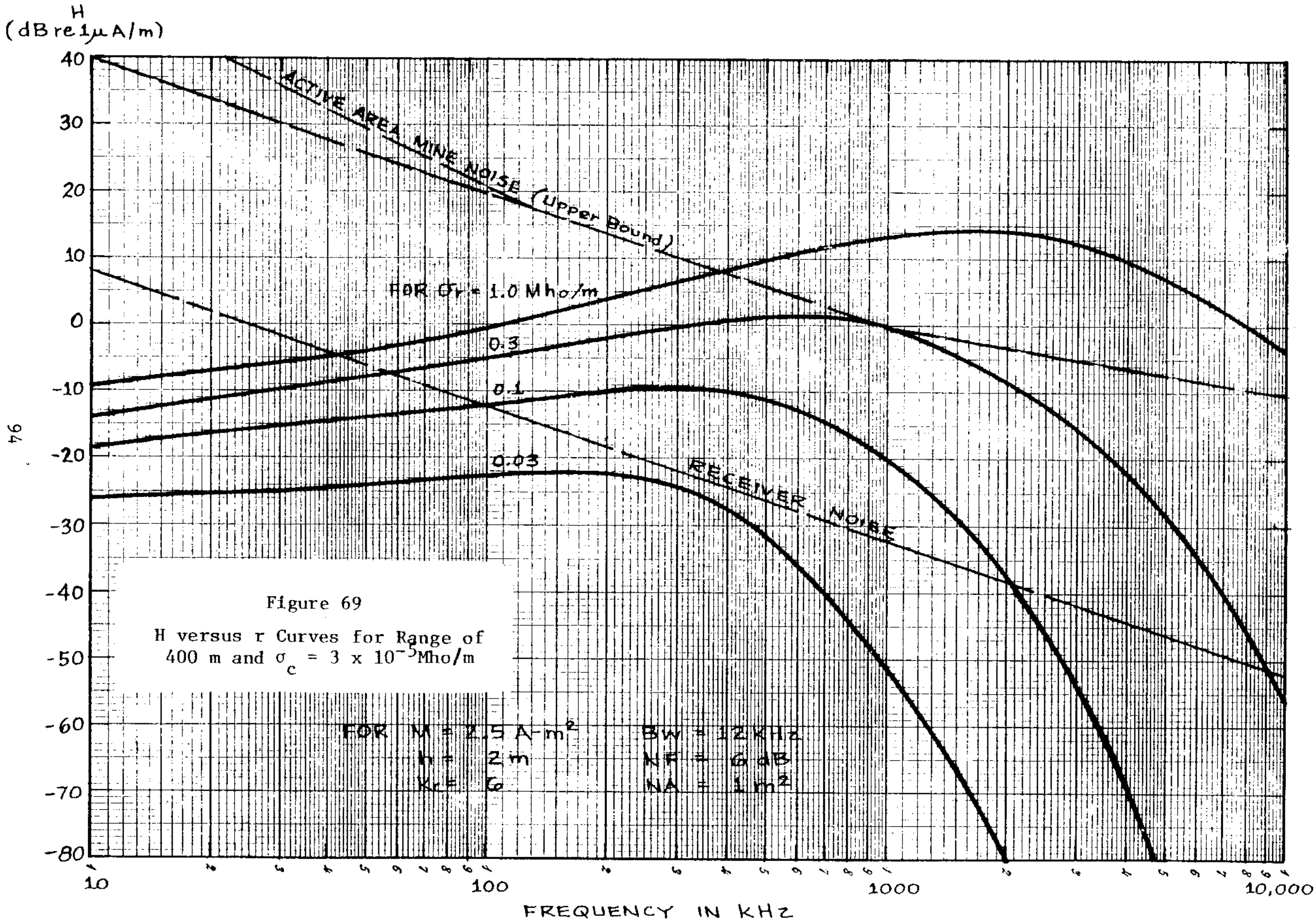


Figure 69

H versus r Curves for Range of 400 m and $\sigma_c = 3 \times 10^{-5}$ Mho/m

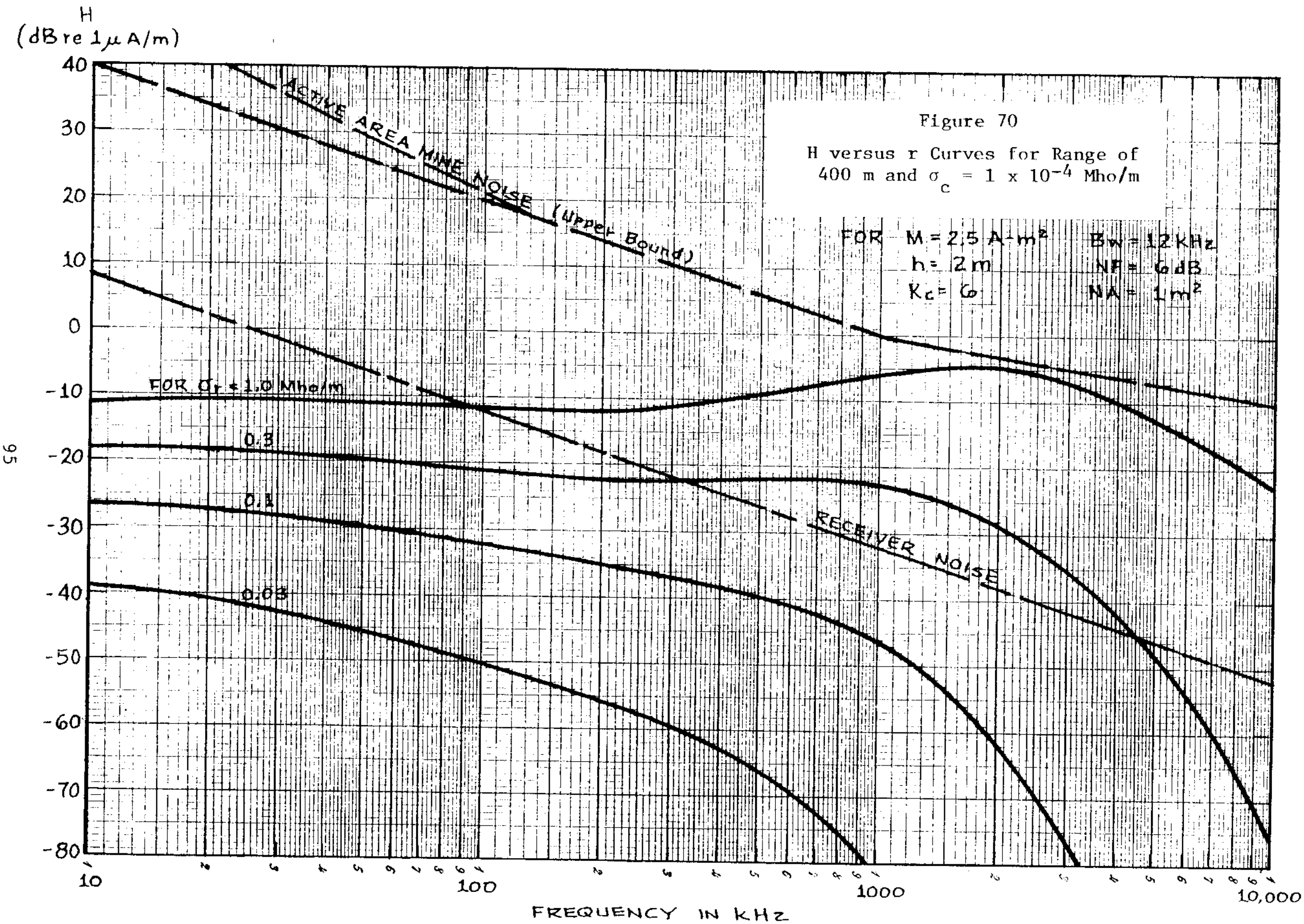
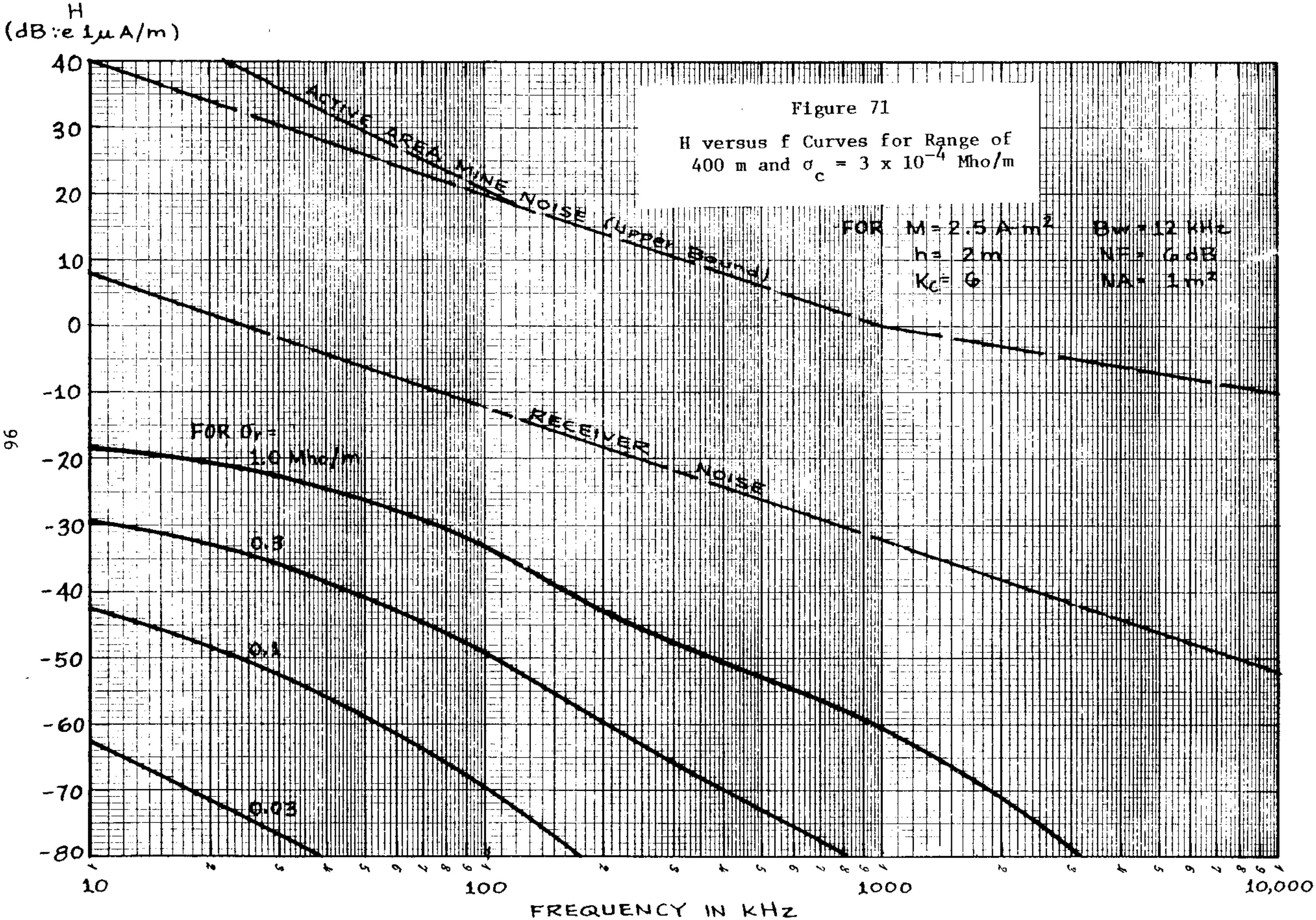


Figure 70

H versus r Curves for Range of 400 m and $\sigma_c = 1 \times 10^{-4}$ Mho/m

Figure 71

H versus f Curves for Range of 400 m and $\sigma_c = 3 \times 10^{-4}$ Mho/m



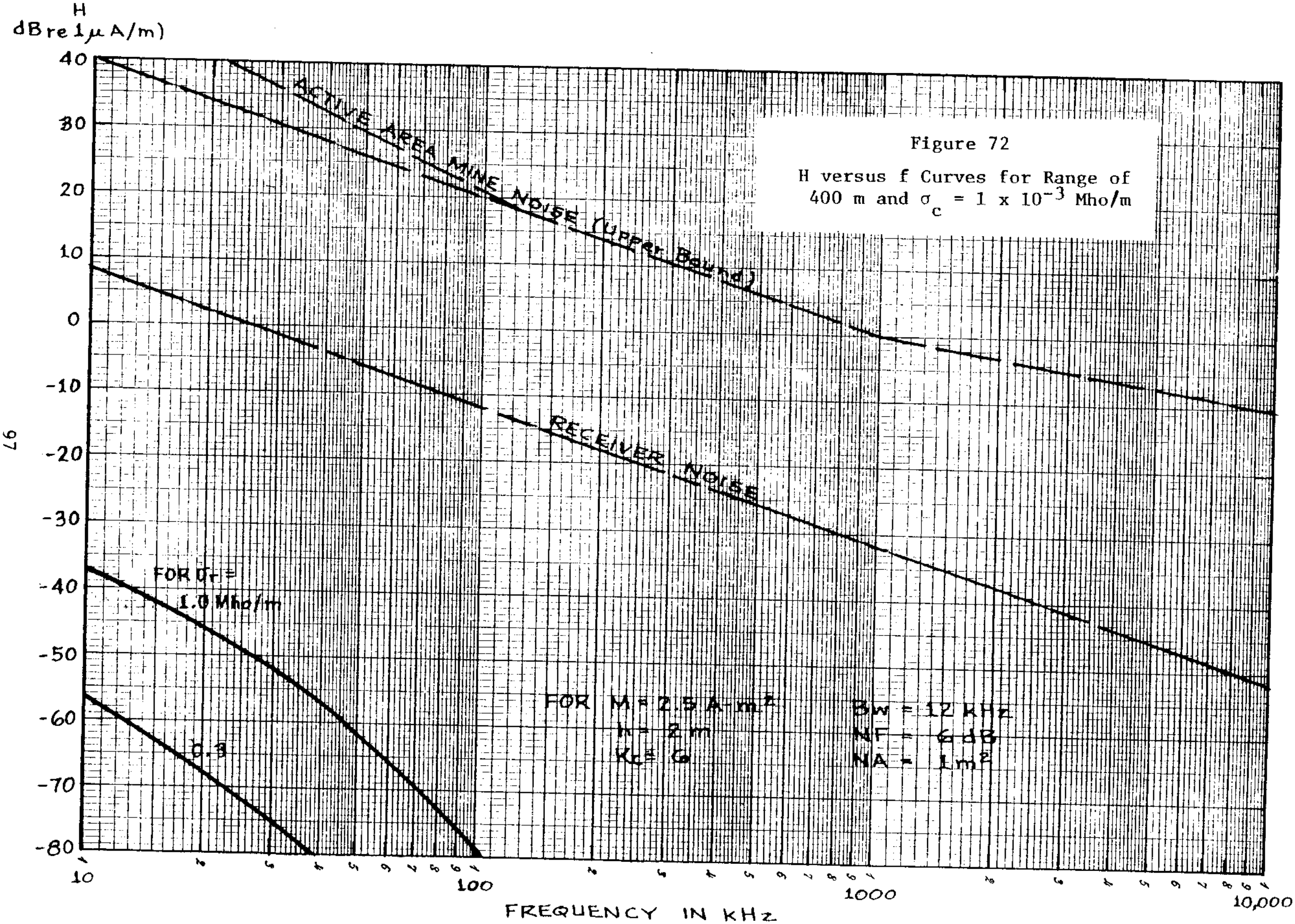
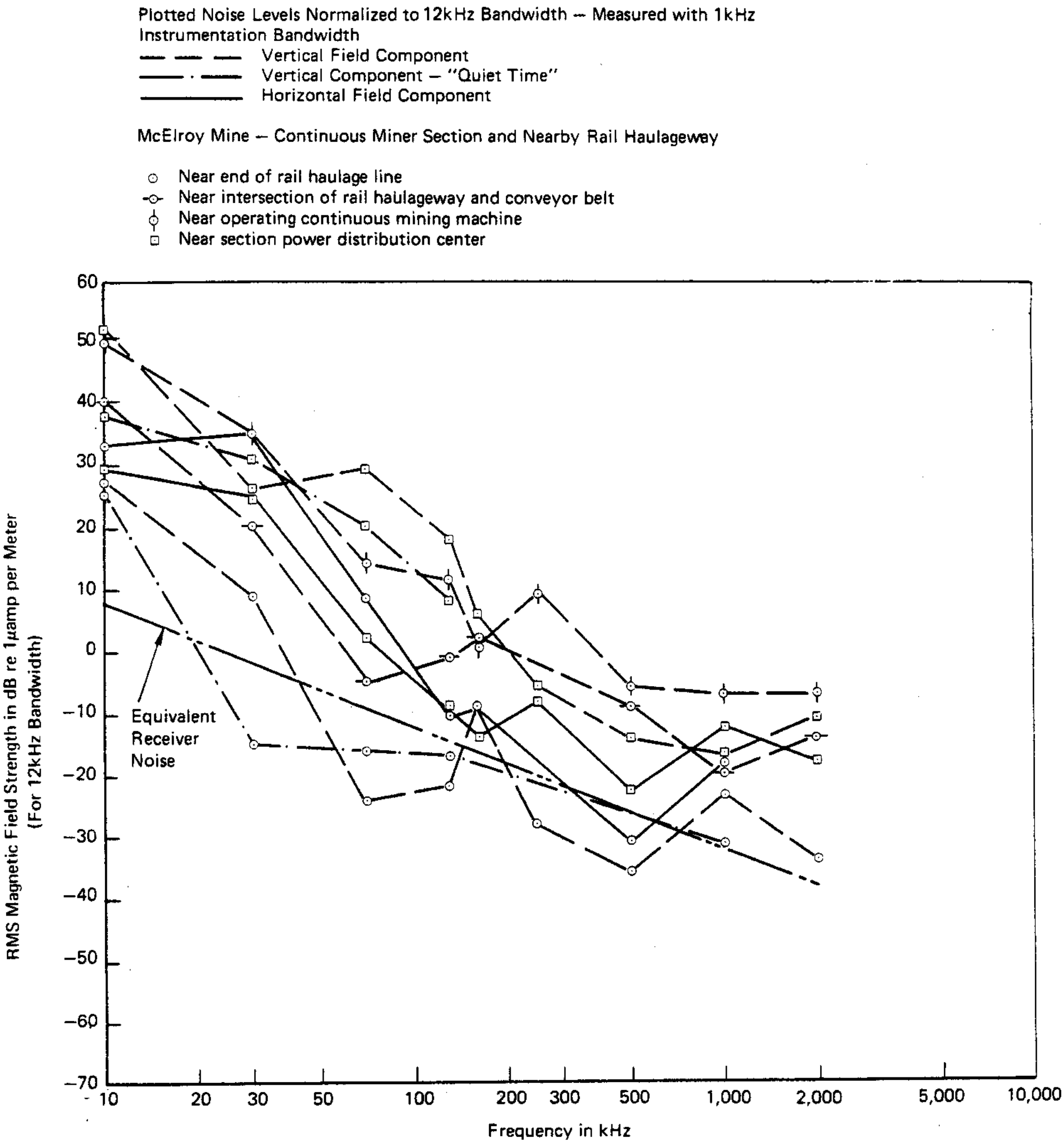


Figure 72

H versus f Curves for Range of 400 m and $\sigma_c = 1 \times 10^{-3}$ Mho/m



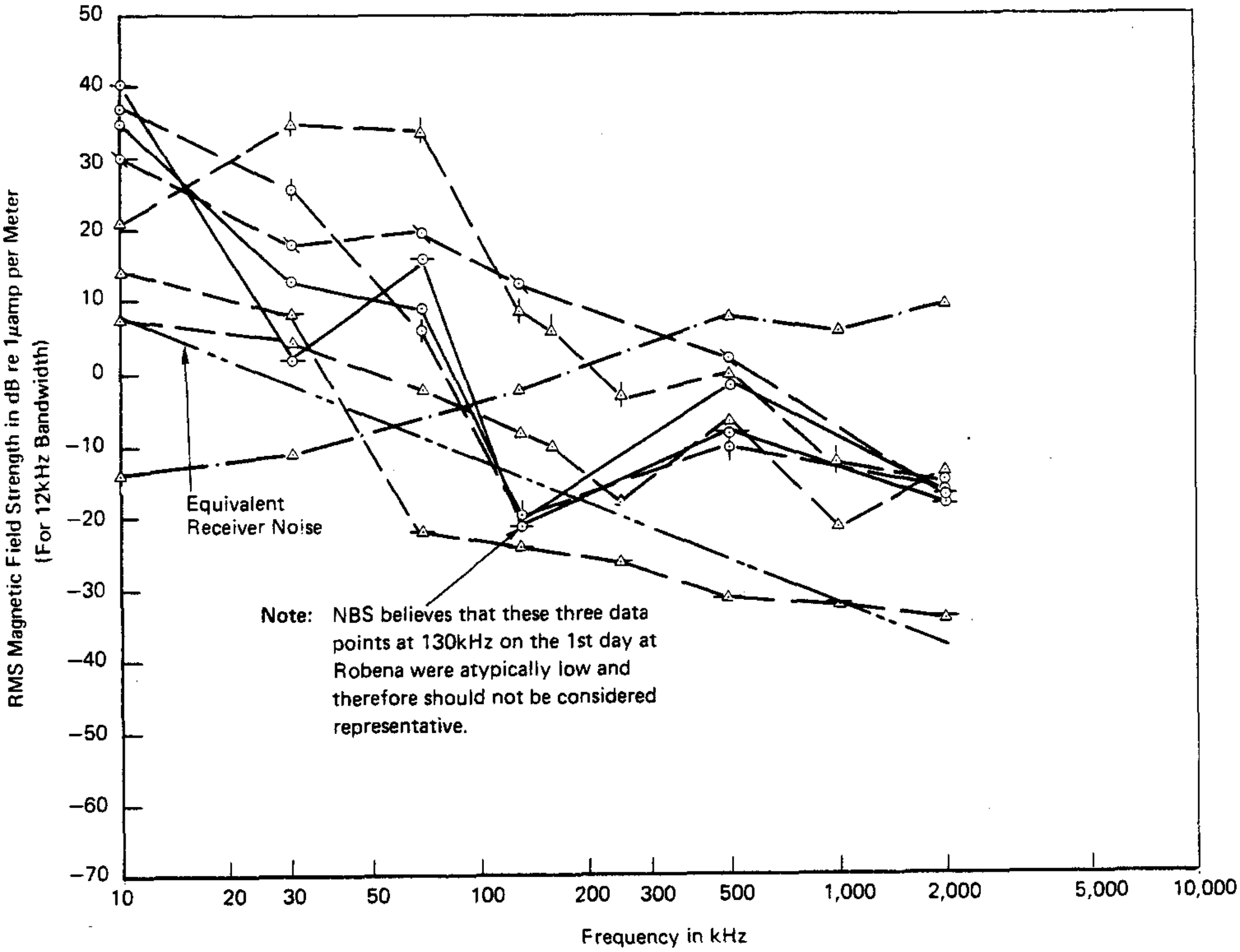
Source: National Bureau of Standards (Report NBSIR 74-389, June 1974)

FIGURE 73 REPRESENTATIVE RMS MAGNETIC FIELD NOISE LEVELS MEASURED IN THE McELROY COAL MINE

Plotted Noise Levels Normalized to 12kHz Bandwidth – Measured with 1kHz Instrumentation Bandwidth
— — Vertical Field Component
— · — Vertical Component – "Quiet Time"
——— Horizontal Field Component

Itmann Mine – Longwall Panels
- At longwall face head end – Farley panel
- 230 ft from longwall face – Farley panel
- At longwall face head end near main conveyor belt – Cabin Creek panel

Robena Mine – Rail Haulageway serving continuous miner section. All curves for same location approximately 300 meters from face area
- Horizontal (E-W) – 1st day
- Horizontal (N-S) – 1st day
- Vertical – 1st day
- Vertical – 2nd day



Source: National Bureau of Standards (Reports NBS Technical Note 654, April 1974 Robena; and NBSIR 74-390, June 1974, Itmann)

FIGURE 74 REPRESENTATIVE RMS MAGNETIC FIELD NOISE LEVELS MEASURED IN THE ROBENA AND ITMANN COAL MINES

APPENDIX

Detailed Description of the Statistical Analysis

Since all the analyses were performed at the 100 meter range, all the data were checked to insure the signal had actually traveled that far. Any mine in which the attenuation rate was so great that the signal did not reach 100 meters was eliminated from the analysis. The only exception was in the Peabody #10 mine where at one of the frequencies the signal was only measured to 94 meters. A straight line extrapolation was made for this data point.

Table A-I shows each mine, its seam, and the difference, $\Delta = H_{THEOR}/H_{EXPT}$ at 100 meters for the frequencies of 100 kHz to 1000 kHz. The differences Δ were obtained by taking straight line interpolations between the actual frequencies tested to derive values every 100 kHz. Below the raw data of Table A-I is the work sheet of computations used to obtain the average difference, $\overline{\Delta}$, the variance of $\overline{\Delta}$, and the variance of Δ.

Table A-II shows the same average, as well as the average for all mines, for the differences $\Delta = H_{THEOR} - H_{EXPT}$ in dB at 100 meters between 100 kHz and 1000 kHz. For the Herrin #6 seam at 100 kHz and 200 kHz the average is composed of one data point from one mine. The Pittsburgh seam average is composed of measurements at 4 locations from 3 mines; the Pocahontas seam has 3 locations from 1 mine; and the Herrin #6 has 2 locations, one each from 2 mines. The seam average values, $\overline{\Delta}$, from Table A-II are plotted in Figure A-1. This figure shows the differences to be homogeneous over all the mines. With the exception of 100 and 200 kHz, where the Herrin #6 seam had readings from only the Peabody #10 mine, there is only at the most a 2 dB difference between any of the graphs. Therefore, no information is lost by pooling all the data and studying the composite data rather than continuing the analysis on a seam basis. Conversely, the results of the analyses can then be applied back to all mine seams uniformly.

Figure A-2 is a graph of the variance of the differences, $S^2(\Delta)$, every 100 kHz. The population variance was neither very large, nor did it fluctuate widely, although it was of the same order of magnitude as the average difference between the model predictions and the experimentally recorded data.

Figure 64 in the body of the report is a graph of the Grand Mean, $\overline{\Delta}$, and 95% Confidence Intervals for the Δ and $\overline{\Delta}$. As noted before, the 95% Confidence Interval for $\overline{\Delta}$ is equivalent to a visual hypothesis test (t-test) that:

H_o: $H_{THEOR} = H_{EXPT}$

versus

H_1: $H_{THEOR} \neq H_{EXPT}$

at each frequency from 100 kHz to 1000 kHz. To visually interpret the test, one must only check to see if zero is included in the interval. Whenever the Confidence Interval contains zero, no significant difference between the theoretical model and the actual readings exists. This can be visually checked by looking at Figure 64. As an example, the actual hypothesis test (t-test) at 100 kHz and 200 kHz will be performed.

The hypothesis test is given below (a 1-sample t-test):

H_o: $E_o = 0$ ($H_{THEOR} = H_{EXPT}$)

H_1: $E_1 \neq 0$ ($H_{THEOR} \neq H_{EXPT}$)

The test statistic is:

$$\left| \frac{\overline{X} - E_o}{S/\sqrt{n}} \right|$$

and it is compared to a t-statistic on n-1 degrees of freedom at the $1-\alpha/2$ level; $t(n-1, 1-\alpha/2)$. For 100 kHz, $n = 8$ and $\alpha = 5\%$; and for 200 kHz, $n = 9$ and $\alpha = 5\%$. If the computed statistic is greater in absolute value than the t-statistic, then the null hypothesis is rejcted; i.e., the model does not fit the data. If the computed test statistic is less than the t-statistic, then the null hypothesis cannot be rejected. From this last case, based on the data given in Table A-I, we draw the conclusion that the model did, indeed, fit the data for the frequencies between 200 kHz and 900 kHz. For 100 kHz:

$$\left|\frac{\bar{X} - E_o}{S/\sqrt{n}}\right| = \qquad E_o = 0 \text{ since the null hypothesis } H_o \text{ is } \Delta$$

$$= H_{THEOR} - H_{EXPT}$$

$$= 0$$

$$\left|\frac{5.31}{5.72/\sqrt{8}}\right| =$$

$$\left|\frac{5.31}{2.02}\right| =$$

$$\left|\underline{2.628}\right| > t(n-1,\ 1-\alpha/2) = t(7,\ .975) = \underline{2.365}$$

The null hypothesis is rejected at the 5% level (95% chance of happening) and the model does not fit the data at 100 kHz.

For 200 kHz:

$$\left|\frac{\bar{X} - E_o}{S/\sqrt{n}}\right| = \left|\frac{1.5}{3.79/\sqrt{9}}\right| = \left|\frac{1.5}{1.34}\right| = \left|\underline{1.12}\right| < t(8,\ .975) = \underline{2.306}$$

The null hypothesis, H_o, cannot be rejected at the 5% level and we draw the conclusion that at 200 kHz the model fits the data.

Thus, the Grand Mean may be used in all analyses, and it may be used to represent the individual seam averages. Furthermore, the model fits the experimental data in the 200 kHz to 900 kHz frequency range at 100 meters. It did not fit the experimental data outside the range of those frequencies.

REFERENCES

Brownlee, K.A., Statistical Theory and Methodology in Science and Engineering, J. Wiley, N.Y., 1967.

Neter, J., and Wasserman, W., Applied Linear Statistical Models, Irwin, Honewood, Illinois, 1977.

TABLE A-I

$H_{THEORETICAL} - H_{EXPERIMENTAL}$ IN dB
AT 100 METERS

MINE	SEAM	100	200	300	400	500	600	700	800	900	1000
		FREQUENCY									
Ireland (I)	Pitt	12.50	2.50	- 2.00	- 3.00	- 4.50	- 5.50	- 6.00	- 6.50	- 7.00	---
Ireland (II)	Pitt	2.00	4.50	5.50	4.00	2.00	1.50	1.00	0.50	-0-	0.50
Federal #1	Pitt	8.00	4.00	4.00	5.50	6.50	6.00	6.00	6.00	6.00	6.00
Robinson Run	Pitt	6.00	1.00	1.00	2.00	2.00	6.00	8.50	10.50	12.50	14.00
Pocahontas #1 3 SO. Entry A	POC	6.00	1.50	1.00	1.50	2.00	2.00	2.50	3.00	3.00	3.00
Pocahontas #1 3 SO. Entry B	POC	3.50	- 0.50	- 1.50	1.00	- 2.50	3.50	4.50	5.00	6.00	6.00
Pocahontas #1 2 No. #1 Plow	POC	10.50	5.50	2.50	0.50	- 0.50	0.50	2.00	3.00	4.00	2.00
Inland #1	Herrin #6	---	---	4.00	3.00	1.00	1.00	1.50	1.50	2.00	3.50
Peabody #10 1 SO. 5.5 East	Herrin #6	- 6.00	- 6.50	- 5.50	- 3.00	- 0.50	2.50	4.50	6.50	8.50	10.00
	ΣX	42.50	12.00	10.00	11.50	10.50	17.50	24.50	29.50	35.00	45.00
	$\overline{X}$	5.31	1.50	1.10	1.28	1.17	1.94	2.72	3.28	3.89	5.63
	ΣX^2	454.75	118.50	105.00	78.75	82.25	128.25	198.25	276.25	362.50	393.50
	$(\Sigma X)^2/n$	225.78	---	---	--- (Not Listed on Table)	---	---	66.69	96.69	136.11	253.13
	Sum of Squares	228.97	---	---	---	---	---	131.56	179.56	226.39	140.37
	S^2 (Variance)	32.71	14.36	11.74	8.01	8.75	11.78	16.44	22.45	28.30	20.05
	S(Std. Deviation)	5.72	3.79	3.43	2.83	2.96	3.43	4.06	4.74	5.32	4.48
	tS	13.53	8.96	7.89	6.51	6.81	7.89	9.36	10.93	12.27	10.59
95% Population Confidence Interval		(-8.22, 18.84)	(-7.46, 10.46)	(-6.79, 8.99)	(-5.23, 7.79)	(-5.64, 7.98)	(-5.95, 9.83)	(-5.30, 13.42)	(-7.65, 14.21)	(-8.38, 16.16)	(-6.11, 15.08)
	$S/\sqrt{n}$	2.02	1.34	1.14	0.94	0.99	1.14	1.35	1.58	1.77	1.58
	$tS/\sqrt{n}$	4.78	3.17	2.63	2.17	2.27	2.63	3.12	3.64	4.09	3.74
95% Sample Mean Confidence Interval		(0.53, 10.09)	(-1.67, 4.67)	(-1.53, 3.73)	(-0.89, 3.45)	(-1.10, 3.44)	(-0.67, 4.57)	(-0.40, 5.84)	(-0.38, 6.92)	(-0.20, 7.98)	(-1.89, 9.37)

t (7.00, 0.95) = 2.365
t (8.00, 0.95) = 2.306

$$S^2 = \frac{\text{Sum of Squares}}{n - 1}$$

S = Sample Standard Deviation

TABLE A-II

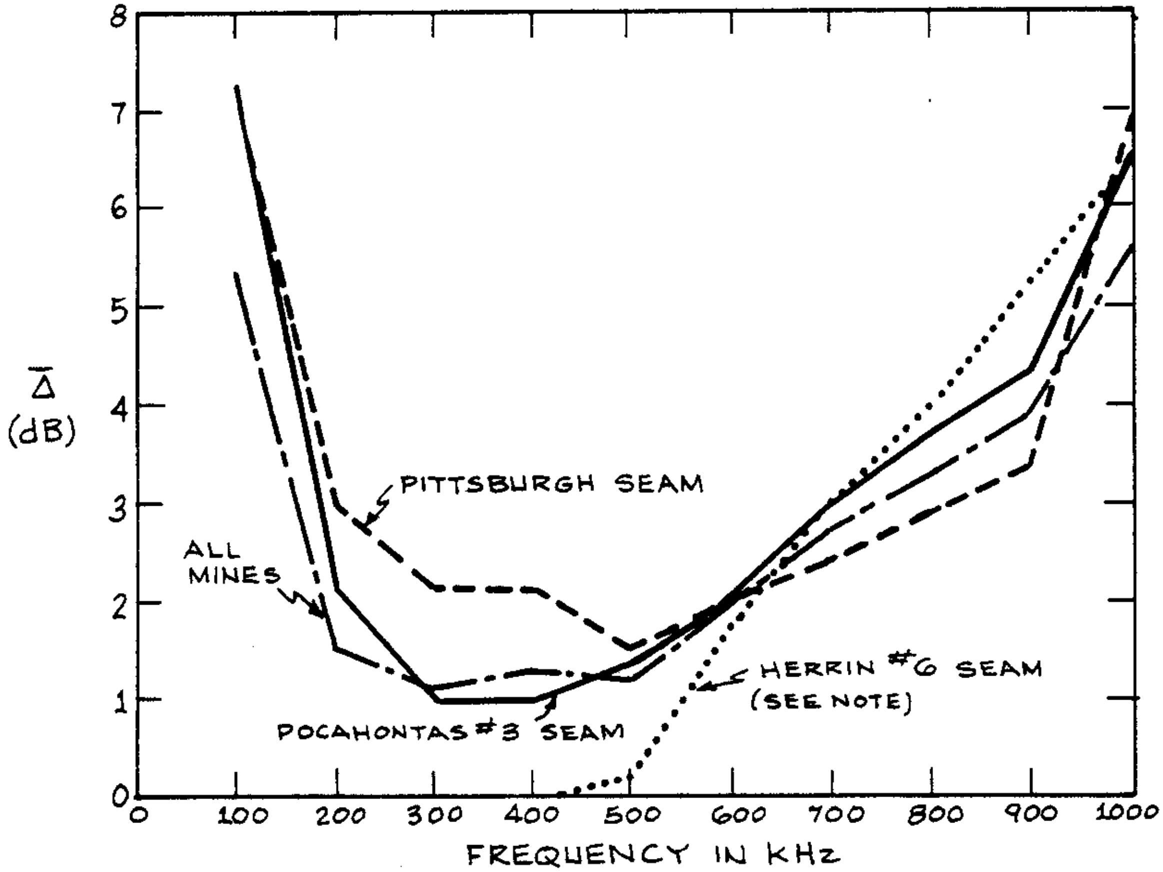
AVERAGE RATIO

$$\frac{H_{\text{Theoretical}}}{H_{\text{Experimental}}} \text{ in dB}$$

Frequency	All Mines	Pittsburgh Seam	Pocahontas Seam	Herrin #6 Seam
100	5.31	7.13	7.33	- 6.00*
200	1.50	3.00	2.17	- 6.50*
300	1.10	2.13	1.00	- 0.75
400	1.28	2.13	1.00	-0-
500	1.17	1.50	1.33	0.25
600	1.94	2.00	2.00	1.75
700	2.72	2.38	3.00	3.00
800	3.28	2.88	3.67	4.00
900	3.89	3.38	4.33	5.25
1000	5.63	6.83**	3.67	6.50

*Data from 1 mine, 1 location only

**Data from 3 mines, 3 locations, Pittsburgh Seam



NOTE: FREQ 100 & 200 = -6 , 300 = -0.75

Figure A-1 Seam Average Values $\overline{\Delta}$ (dB)

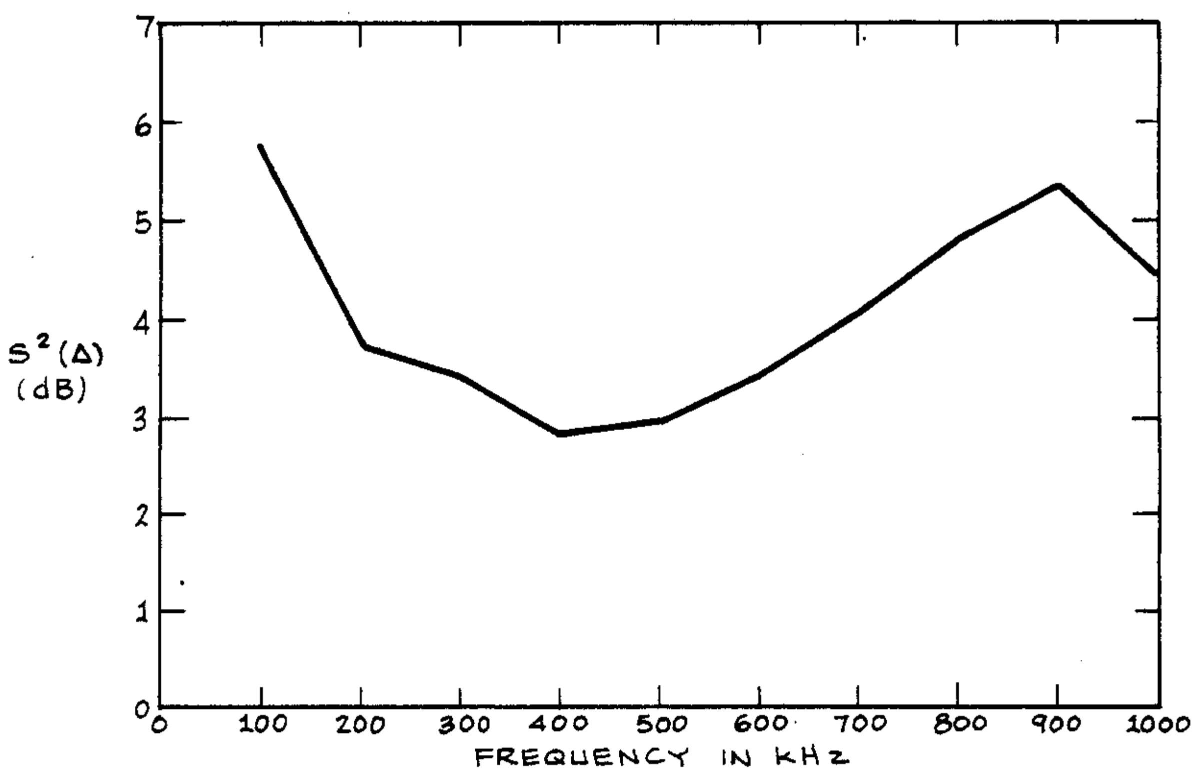


Figure A-2 Variance of the Differences $S^2(\Delta)$
(All Mines)

IV. ANALYSIS OF MF PROPAGATION DATA FROM MARGARET NO. 11, NANTY GLO, EHRENFELD, AND ADRIAN COAL MINES - Interim Report, May 1978

ANALYSIS OF MF PROPAGATION DATA FROM MARGARET NO. 11, NANTY GLO, EHRENFELD, AND ADRIAN COAL MINES

Robert L. Lagace -- Task Leader
Alfred G. Emslie

WORKING MEMORANDUM
On
Task Order No. 4
Contract No. H0346045

May 1978

C-78453

Arthur D. Little, Inc.
Cambridge, Massachusetts

TABLE OF CONTENTS

I. INTRODUCTION

Several improvements have been made in the analytical procedures applied to the data taken by T. S. Cory[1] at the four primarily low-coal mines examined in this memorandum. The mines are located in the Upper Freeport, Lower Freeport, and Lower Kittaning coal seams, thus bringing the number of seams sampled up to six.

The $H\sqrt{r}$ versus r method of plotting the data, to get a straight line graph from which the attenuation constant α can be obtained by inspection at each frequency f, is used in the same way as before.[2] The derivation of the coal and rock conductivities from the α versus f data is now, however, carried out by a convenient graphical scheme which determines those values of the two conductivities that produce a theoretical α versus f curve that gives a least square fit to the experimental α versus f data. Furthermore, the theoretical magnetic field signal levels derived from the conductivities are now compared with the corresponding experimental values by means of the respective coupling factors C_{theor} and C_{expt}. The experimental coupling factor, at each frequency, is defined as the intercept of the $H\sqrt{r}$ versus r straight line with the $H\sqrt{r}$ axis. The theoretical value is calculated as a function of frequency from the conductivities by means of the coal-seam mode magnetic field equation (1). This type of comparison is more fundamental than the previous method of comparing theoretical and experimental values of magnetic field at some standard range.

In addition to these improvements in analytical technique, we have worked out a theory of the coupling of the coal-seam mode to a cable. This theory, which was presented at the recent EM Guided Wave Workshop in Boulder, Colorado, makes use of image theory, Fourier analysis, and the principle of reciprocity. The theory was compared in a preliminary way with experimental results from the Margaret No. 11 mine. A more complete test requires experimental measurements, now in progress, of the effect of loop orientation on the degree of coupling to the cable.

A copy of the paper[3] describing the theory for coupling of the coal seam mode to a cable in a mine tunnel and its application to data taken at the Margaret No. 11 mine is included in the Appendix of this working memorandum. Also included is a copy of a paper[4] describing the three-layer theoretical model and its use in the analysis of the quasi-conductor-free area propagation data taken by T. S. Cory in the first six mines.

II. REDUCTION OF THE DATA

The coal-seam mode of propagation at medium frequencies is essentially a TEM transmission-line mode between parallel conducting plates, with the E field vertical and the H field horizontal. The conducting rock above and below the coal seam forms the "plates" while the much less conducting coal acts as the "lossy dielectric" layer between the plates. This mode can be excited by a vertical loop antenna, and the magnetic field H falls off with horizontal distance r from the antenna, in the plane containing the loop, according to the formula[1]

$$H = C \frac{e^{-\alpha r}}{\sqrt{r}} , \qquad (1)$$

where C is a coupling factor, and α is the attenuation constant. This formula is valid when r is greater than $1/\alpha$.

Eq (1) can be written in the form

$$20\mathrm{Log}(H\sqrt{r}) = 20\mathrm{Log}C - 8.686\alpha r \qquad (2)$$

which shows that a plot of $H\sqrt{r}$ (in dB) versus r (in meters) will be a straight line with slope 8.686α and intercept C (in dB). Plotting the experimental values of H versus r in this way therefore provides a very simple way to obtain both α and C directly from the data. Since the experimental results give H in dB re 1 μA/m versus r in meters, the following simple conversion of the data must first be carried out:

$$(H\sqrt{r})_{\mathrm{dB\ re\ 1\mu A/\sqrt{m}}} = (H)_{\mathrm{dB\ re\ 1\mu A/m}} + 10\mathrm{Log}(r) \qquad (3)$$

Figure 1 shows the original data at 890 kHz for the fresh air entry in the 5-Cross Area of the Nanty Glo mine. Figure 2 shows the same data transformed by means of Eq (3). It is seen that the effect of this transformation is to straighten the curve, as expected, in support of Eq (1).

The slope of the straight line drawn through the data points in Figure 2 gives $\alpha = 0.0600\ m^{-1}$. The intercept gives, for the coupling

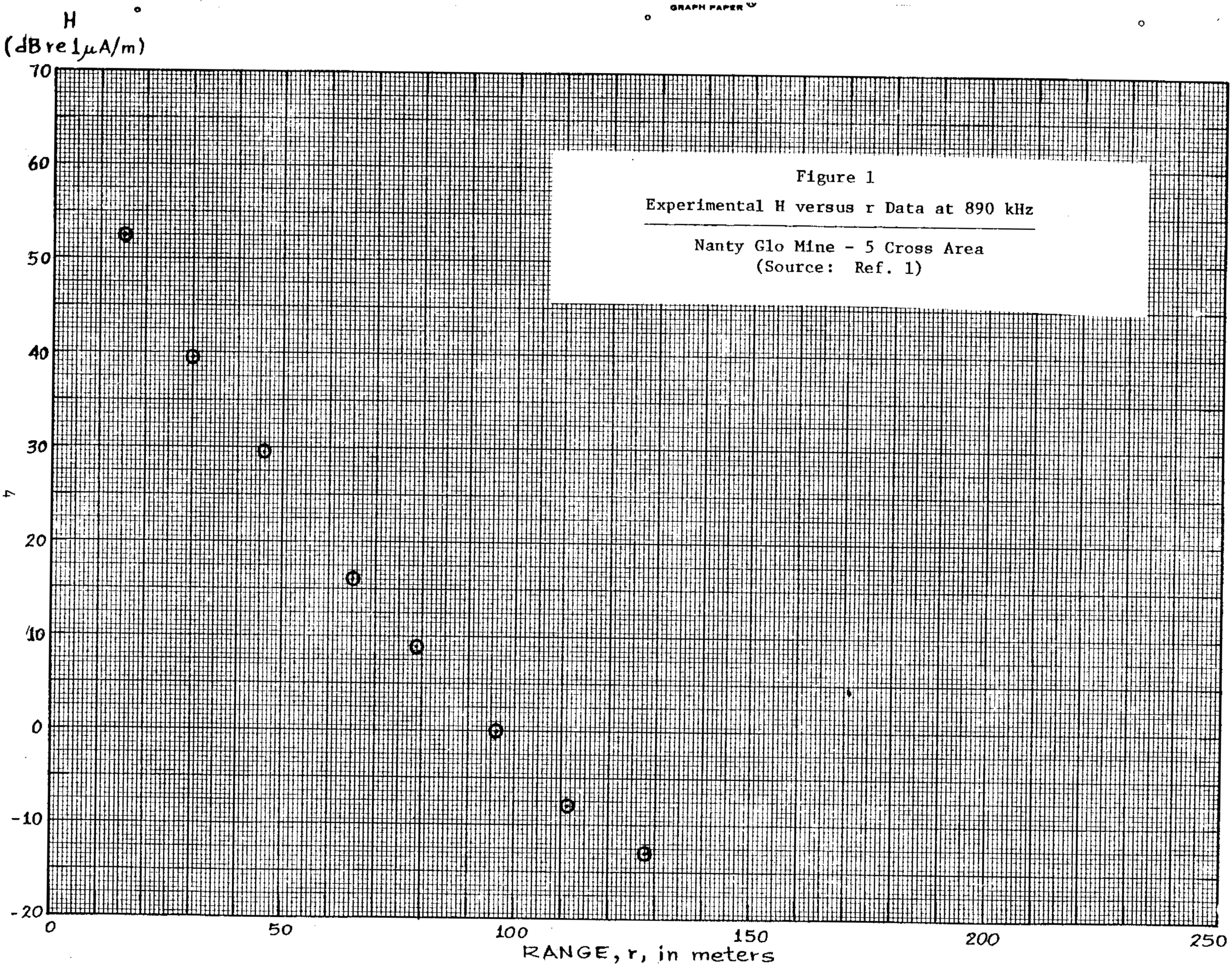


Figure 1

Experimental H versus r Data at 890 kHz

Nanty Glo Mine - 5 Cross Area
(Source: Ref. 1)

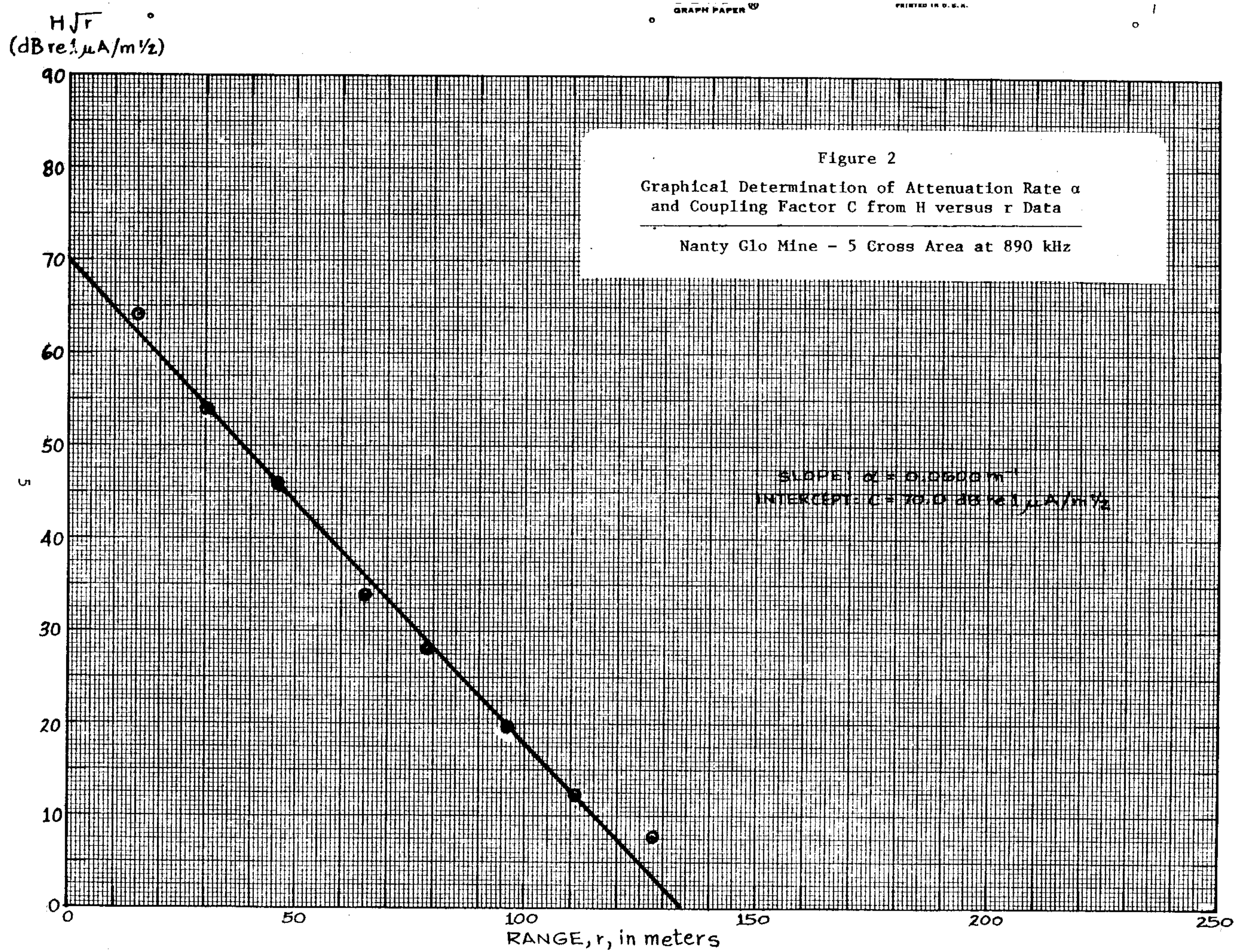


Figure 2

Graphical Determination of Attenuation Rate α and Coupling Factor C from H versus r Data

Nanty Glo Mine - 5 Cross Area at 890 kHz factor, $C = 70.0$ dB re $1\mu A/m^{1/2}$. The first data point lies within the distance $1/\alpha = 16.7$ m, and was therefore disregarded in drawing the straight line. The last data point was also disregarded, since it is close to the noise level. The remaining six points lie on a reasonably straight line. Since the straight line in Figure 2 is completely specified by α and C, these two parameters represent all the data taken at 890 kHz.

On carrying out the same procedure for all the other frequencies, we can make plots of α and C versus frequency, as shown in Figures 3 and 4. These two plots summarize the MF characteristics of the particular propagation path under consideration, as determined directly from the experimental measurements.

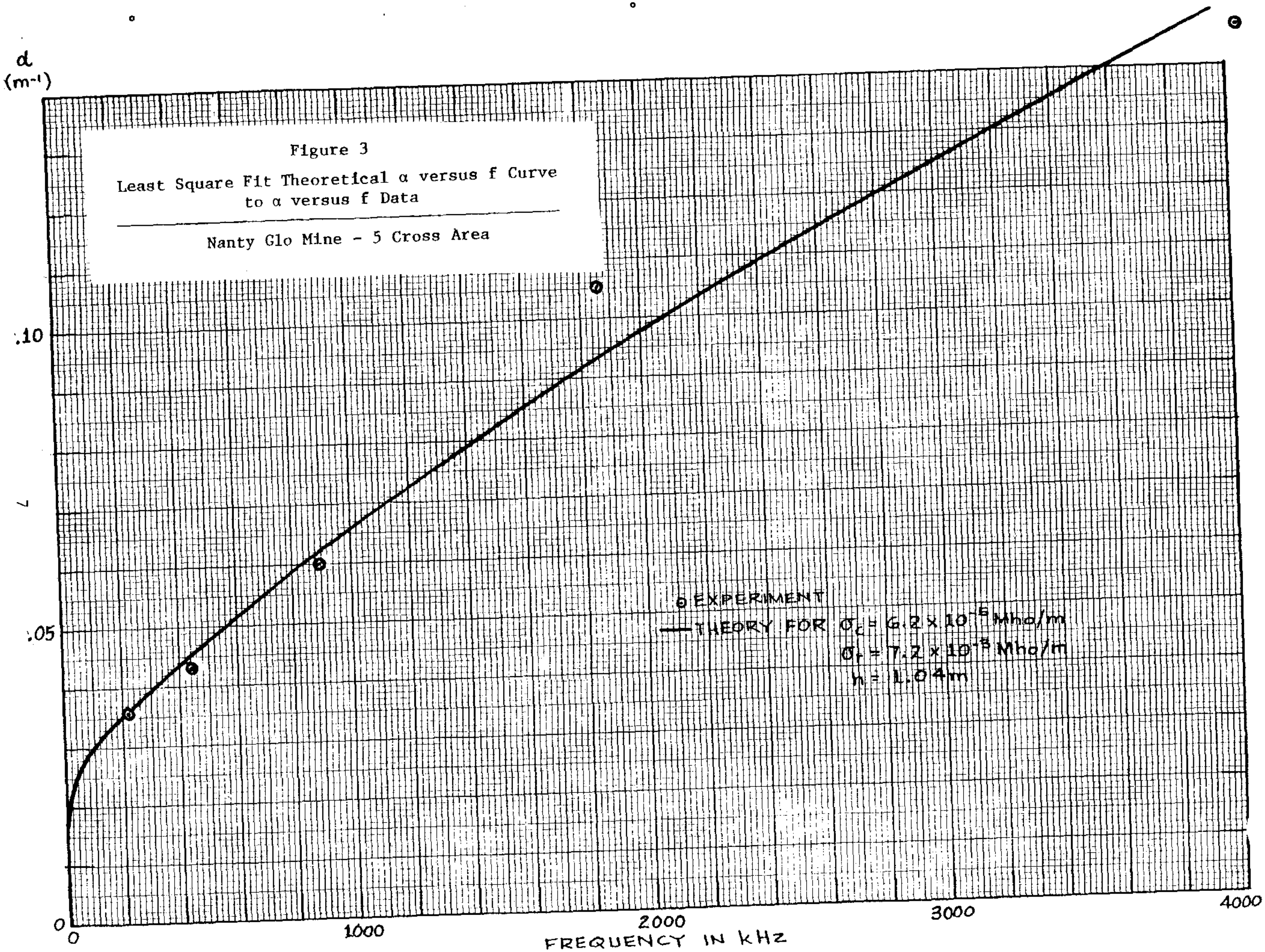


Figure 3

Least Square Fit Theoretical α versus f Curve to α versus f Data

Nanty Glo Mine - 5 Cross Area

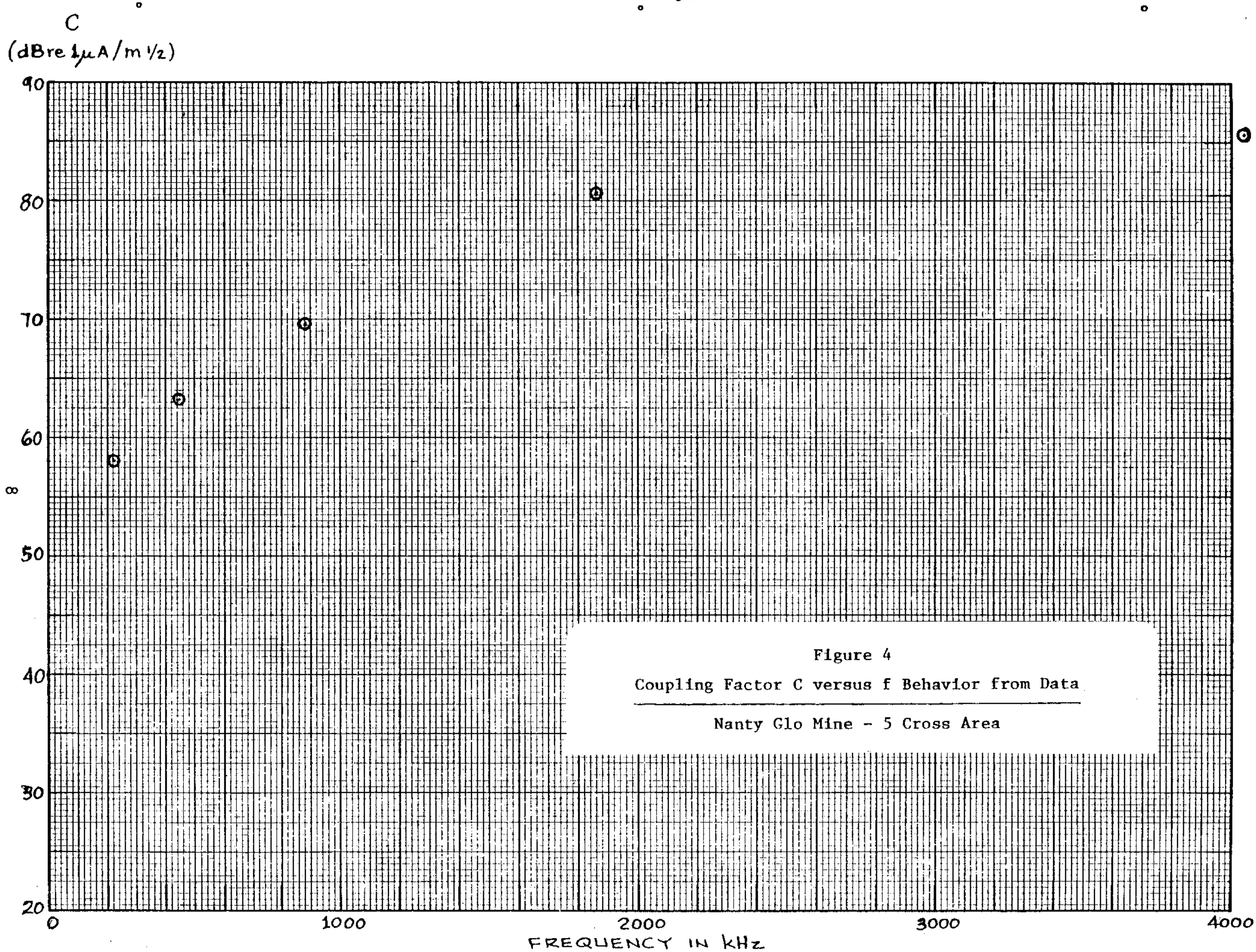


Figure 4

Coupling Factor C versus f Behavior from Data

Nanty Glo Mine - 5 Cross Area

III. DETERMINATION OF α VERSUS f PLOTS AND THE CONDUCTIVITIES

An experimental plot of the α versus f data, such as in Figure 3, contains enough information for the determination of the conductivities σ_c and σ_r of the coal and rock, respectively. The connection between α and the conductivities is given by the transmission-line formula[1,2]

$$\alpha + i\beta = \sqrt{\left(\frac{2Z_s}{h} + i\omega\mu_o\right)\left(\sigma_c + i\omega K_c \varepsilon_o\right)} \quad , \tag{3}$$

where Z_s, the surface impedance of the rock, is given by

$$Z_s = \frac{1+i}{\sigma_r \delta_r} \tag{4}$$

where δ_r, the skin depth in the rock, is given by

$$\delta_r = \sqrt{\frac{2}{\omega\mu_o\sigma_r}} \quad , \tag{5}$$

and h is the height of the coal seam, ω is $2\pi f$, K_c is the dielectric constant of the coal which we assume has the value 6, and μ_o and ε_o have their usual free space values.

The problem is to find values of σ_c and σ_r which produce a theoretical α versus f curve that gives a least square fit to the experimental α versus f plot in Figure 3. For given values of σ_c, σ_r, f, and h, one can calculate a theoretical value α by taking the real part of Eq (3). This can be done for each of the experimental frequencies f_i, and the set of theoretical and experimental α's can be used to calculate a sum-of-squares error given by

$$E(\sigma_c,\sigma_r) = \sum_{i=1}^{N} \left(\alpha_{expt} - \alpha_{theor}\right)_i^2 \quad , \tag{6}$$

where N is the number of frequencies at which experimental data were taken. We have found it convenient to use a programmable hand calculator such as the HP67 for this calculation. This calculator is capable of carrying out the calculation of $E(\sigma_c, \sigma_r)$ for 5 frequencies in 40 seconds, including both Eq (3) and Eq (6).

We search for the minimum E on a σ_c, σ_r diagram by the straightforward strategy shown in Figure 5, for the experimental data in Figure 3, with h = 1.04 m and N = 5. We start by making a traverse, labeled A, starting at the point $\sigma_c = 12 \times 10^{-5}$, $\sigma_r = 10 \times 10^{-3}$ and proceeding from right to left at constant, σ_r. The calculated values of 10^6 E are entered on the diagram at evenly spaced intervals in σ_c. It is seen that a subsidiary minimum of $E = 303 \times 10^{-6}$ occurs at $\sigma_c = 9 \times 10^{-5}$, $\sigma_r = 10 \times 10^{-3}$ Mho/m. It has been found, for the 100 to 1 scale ratio between σ_r and σ_c, that the E-topography usually has a deep valley from the upper right to the lower left. We therefore expect to find minima at $(10 \times 10^{-5}, 11 \times 10^{-3})$ and $(8 \times 10^{-5}, 9 \times 10^{-3})$, but we do not know which is the lower. To find out, we next try traverse B which has a higher minimum than for traverse A. We therefore do traverse C, followed by D and E and find continually decreasing minima, which are indicated by circles. For traverse F, however, the minimum rises again. We have therefore narrowed the search for the absolute minimum of E to a small area around the point $(6 \times 10^{-5}, 7 \times 10^{-3})$.

To obtain higher precision, we expanded the scale and continued the procedure as shown in Figure 6. The absolute minimum is found, to two-figure accuracy, to be at $\sigma_c = 6.2 \times 10^{-5}$ Mho/m, $\sigma_r = 7.2 \times 10^{-3}$ Mho/m with $E = 168.1 \times 10^{-6}$ m^{-2}. The root mean square value of the error in α is

$$(\Delta\alpha)_{rms} = \sqrt{\frac{168.1 \times 10^{-6} \ m^{-2}}{5}} = 0.0058 \ m^{-1}.$$

From the least-squares conductivity values, we can return to Eq (3) and calculate a theoretical α versus f curve. This curve is shown, in comparison with the experimental α versus f data plot, in Figure 3. The goodness of fit indicates that the simple transmission line equation (3), which is based on a three layer model, is valid over a wide range of frequencies. It further suggests that the experimental method used is an excellent way to determine the coal and rock conductivities.

Figure 5

Search Procedure for Calculating σ_c and σ_r for Least Square Fit, E_{min}, to α versus f Data-Coarse Grind

Nanty Glo Mine - 5 Cross Area

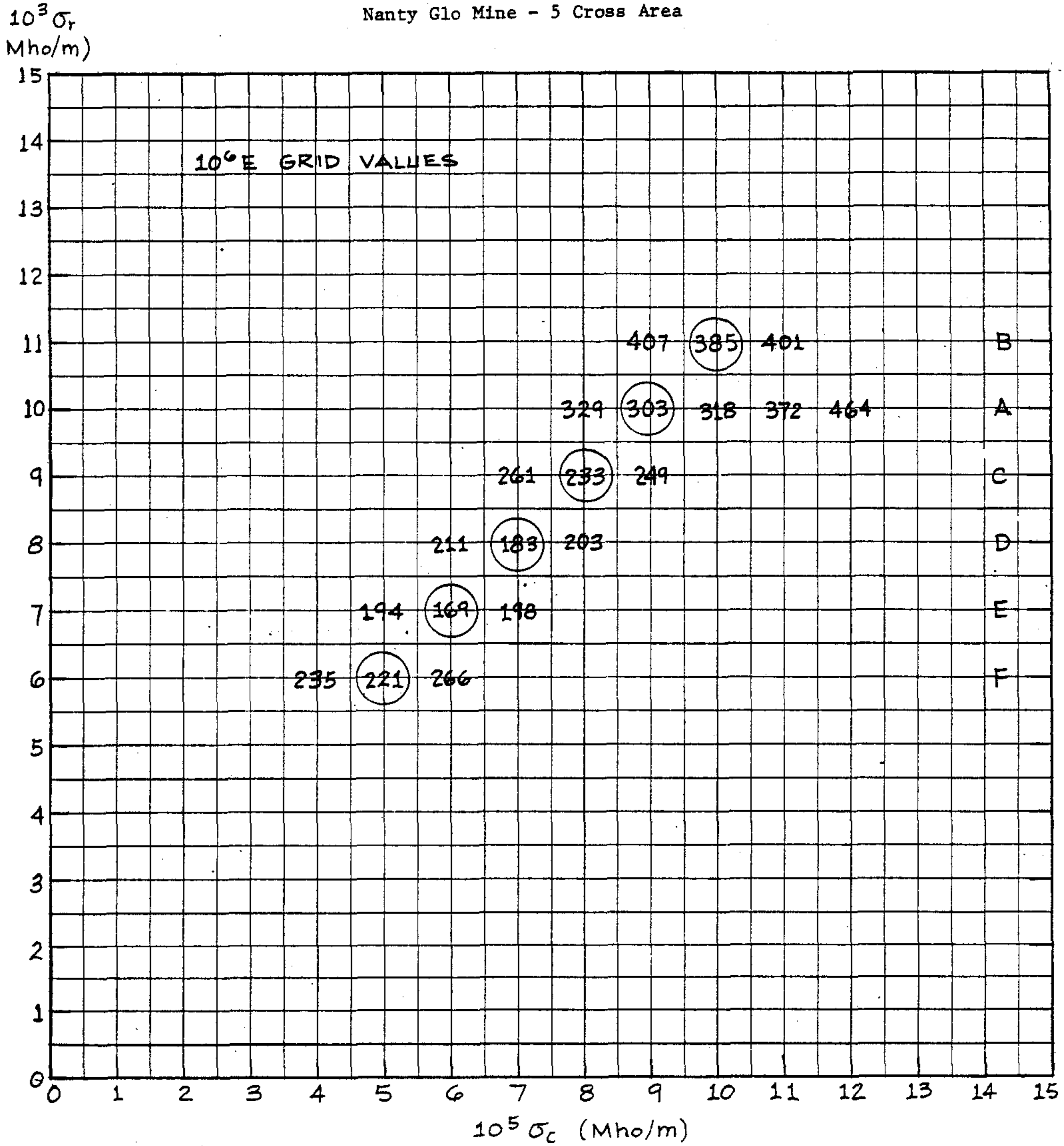


Figure 6

Search Procedure for Calculating σ_c and σ_r for Least Square Fit, E_{min}, to α versus f Data-Fine Grind

Nanty Glo Mine - 5 Cross Area

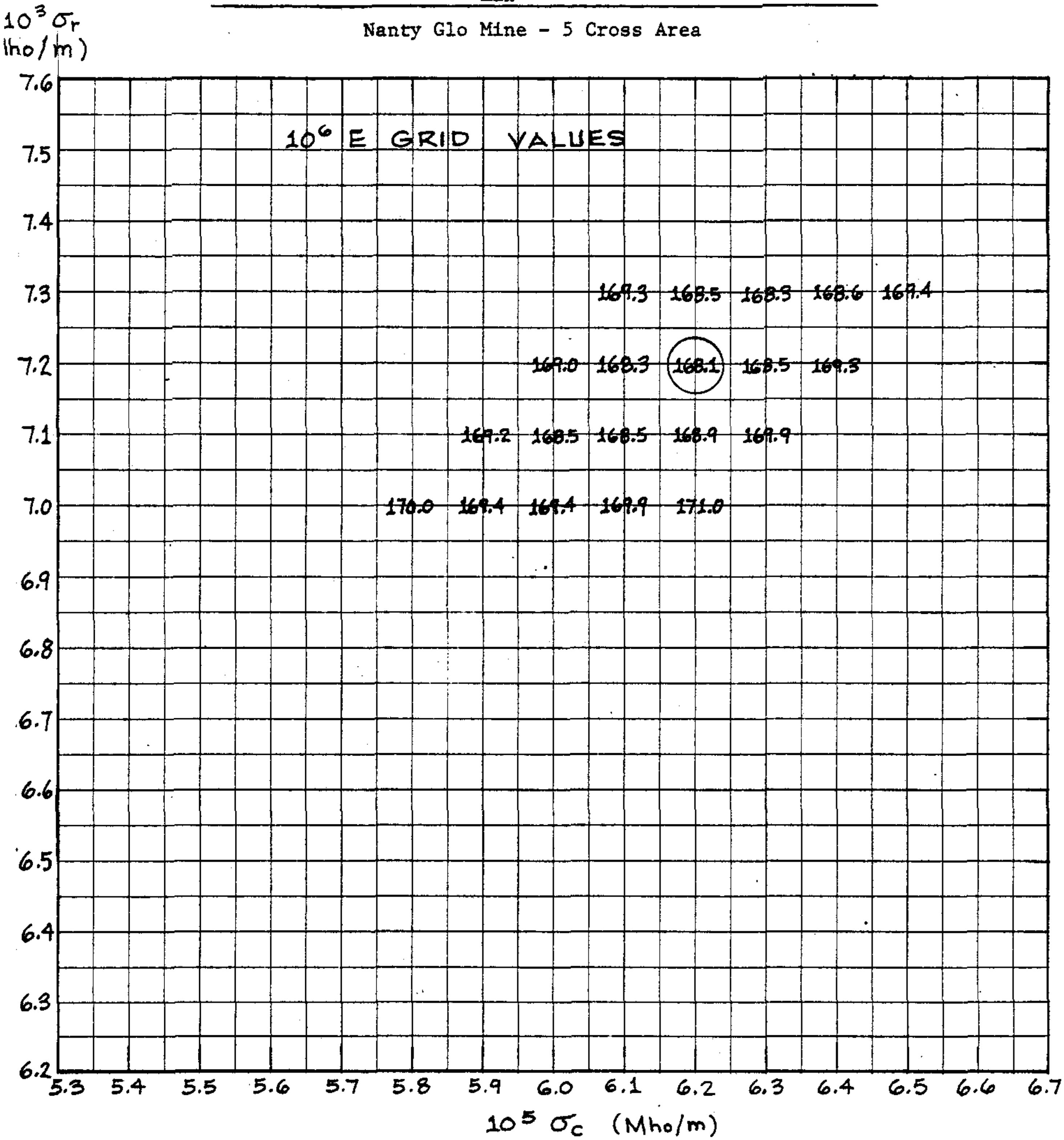


Figure 7 shows α versus f results for an entry in the Main-N area of the Nanty Glo mine located 16 miles from the 5-Cross area. Considerable heaving of the floor is present in this entry, which causes partial blockage of the tunnel cross-section. Comparison of the experimental plots of Figures 3 and 7 shows that the low frequency results are comparable in the two areas, whereas the values of α at the two highest frequencies are much lower in Figure 7 than in Figure 3. This may be due in some way to the floor heaving in the Main-N area. However, it may instead be due to the fact that the batteries began to run down during the Main-N measurements. We have therefore calculated least-square conductivities and theoretical α versus f curves for the Main-N case for the four lowest frequencies, as well as for all six frequencies. The Main-N results for four frequencies agree approximately with those for the 5-Cross Area, while the results by using all six frequencies are much larger than those for the 5-Cross Area.

Figures 8 to 11 show α versus f plots, obtained in the same way, for the Ehrenfeld, Adrian, and Margaret No. 11 mines. As before, the theoretical curves derived from Eq (3) can be made to agree well with the shapes of the experimental data plots for properly chosen values of the conductivities. In the case of the Adrian mine (Figure 9) the fit is exact since only two experimental points are available. In Figure 12, the α versus f curves for these four mines have been added to the composite plot of α versus f curves for the first six mines measured, taken from reference (1). Examination of Figure 12 reveals that the attenuation rates for the mines in all three new seams fall between those for the high loss Herrin No. 6 seam and the moderate loss Pocahontas No. 3 seam. The Upper Freeport seam in Pennsylvania exhibits the highest attenuation rate behavior among the three seams, falling close to values found for the Herrin No. 6 seam, but it has significantly different values than the Upper Freeport seam in West Virginia. On the other hand, the Lower Freeport and Lower Kittaning seams in Pennsylvania exhibit nearly similar behavior which lies close to that found in the Pocahontas No. 3 seam in Virginia below about 500 kHz, and

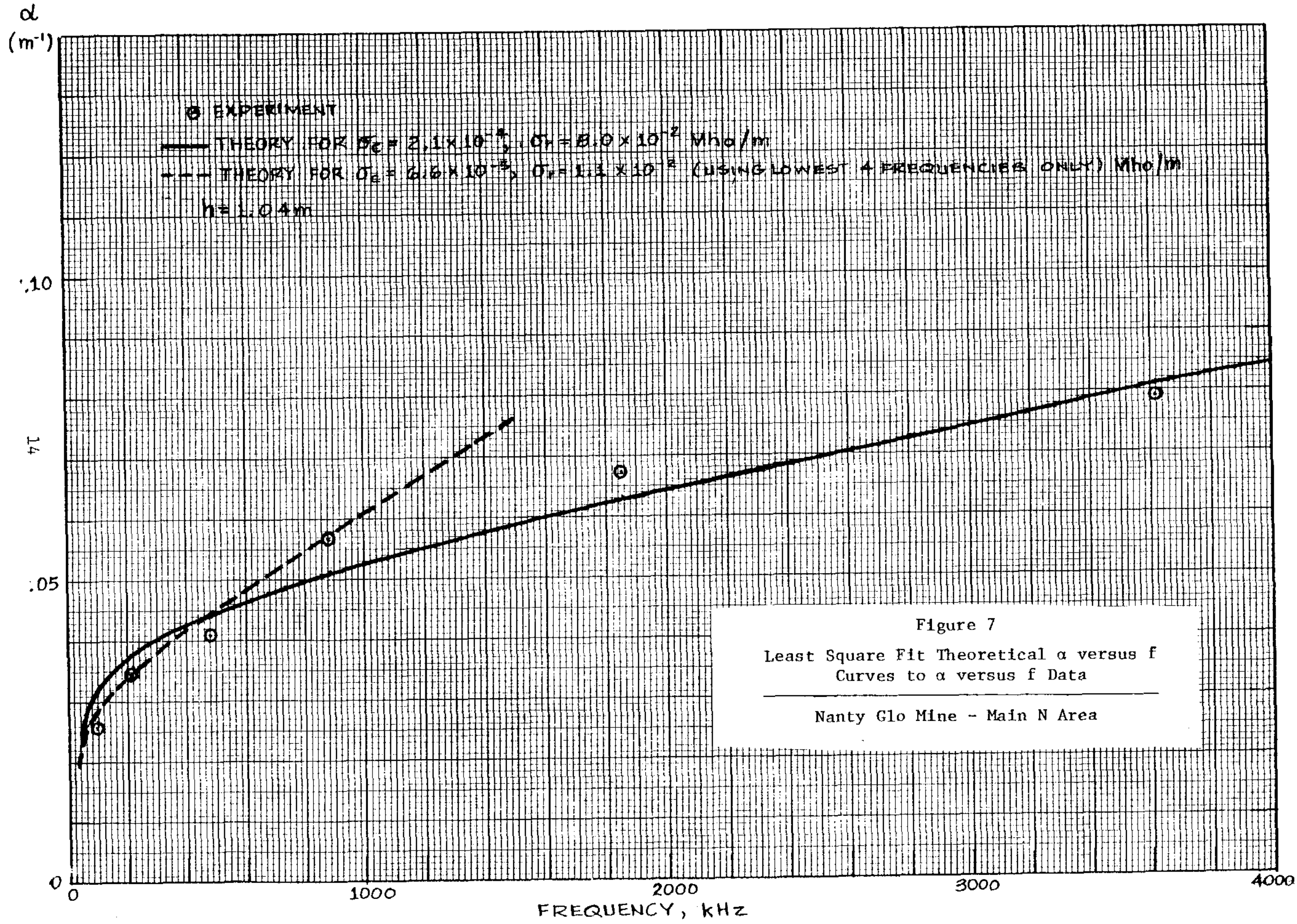


Figure 7

Least Square Fit Theoretical α versus f Curves to α versus f Data

Nanty Glo Mine - Main N Area

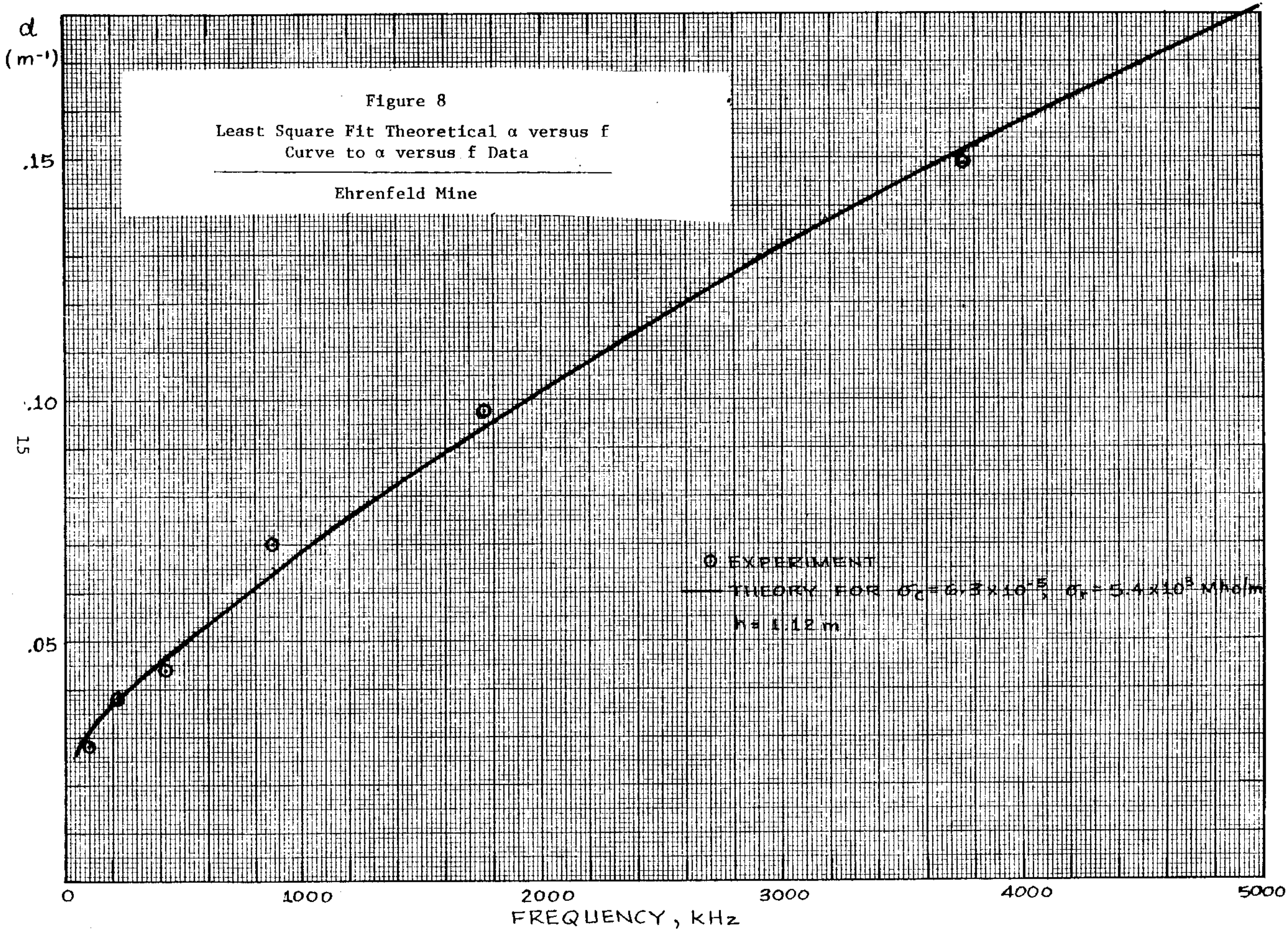


Figure 8

Least Square Fit Theoretical α versus f Curve to α versus f Data

Ehrenfeld Mine

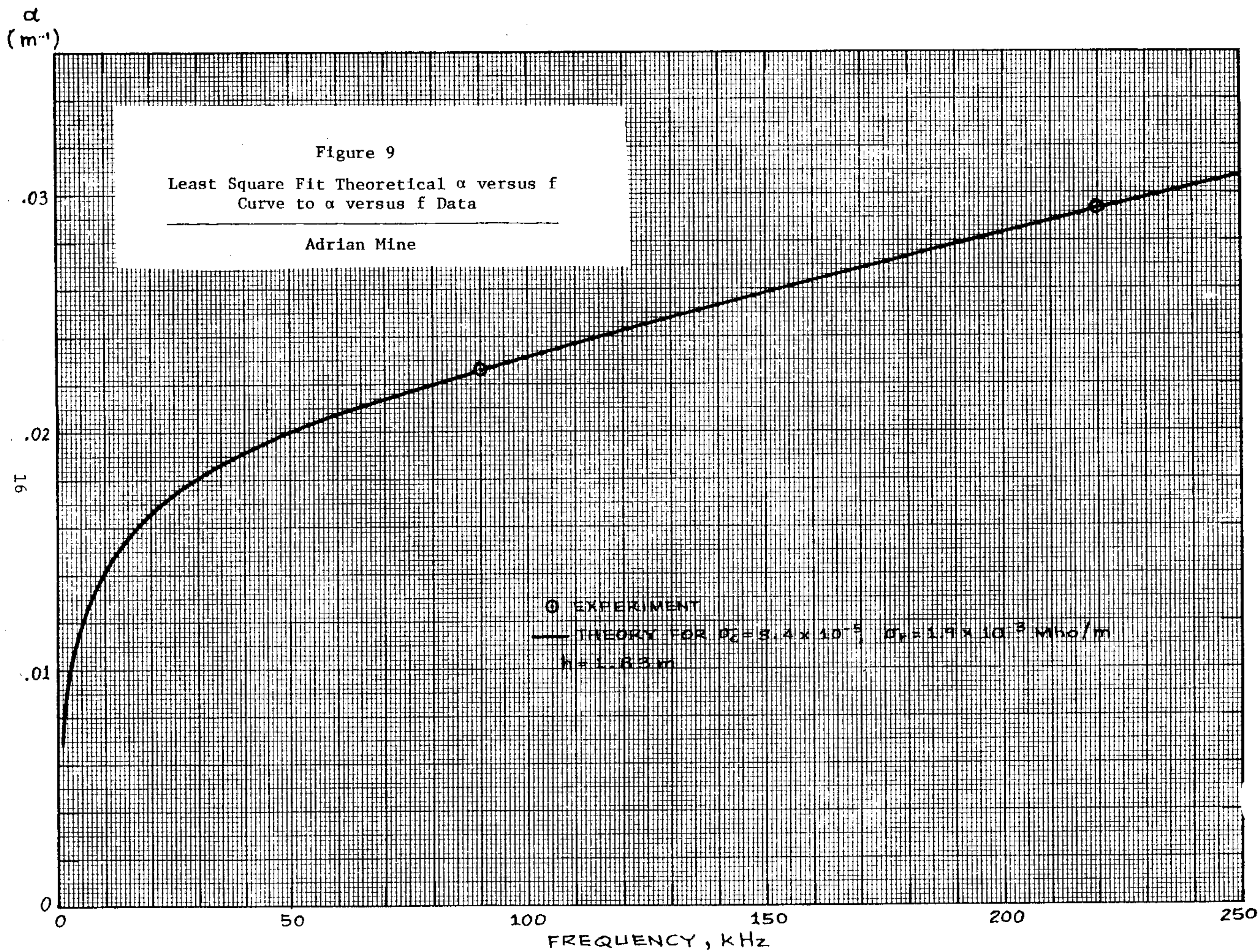


Figure 9

Least Square Fit Theoretical α versus f Curve to α versus f Data

Adrian Mine

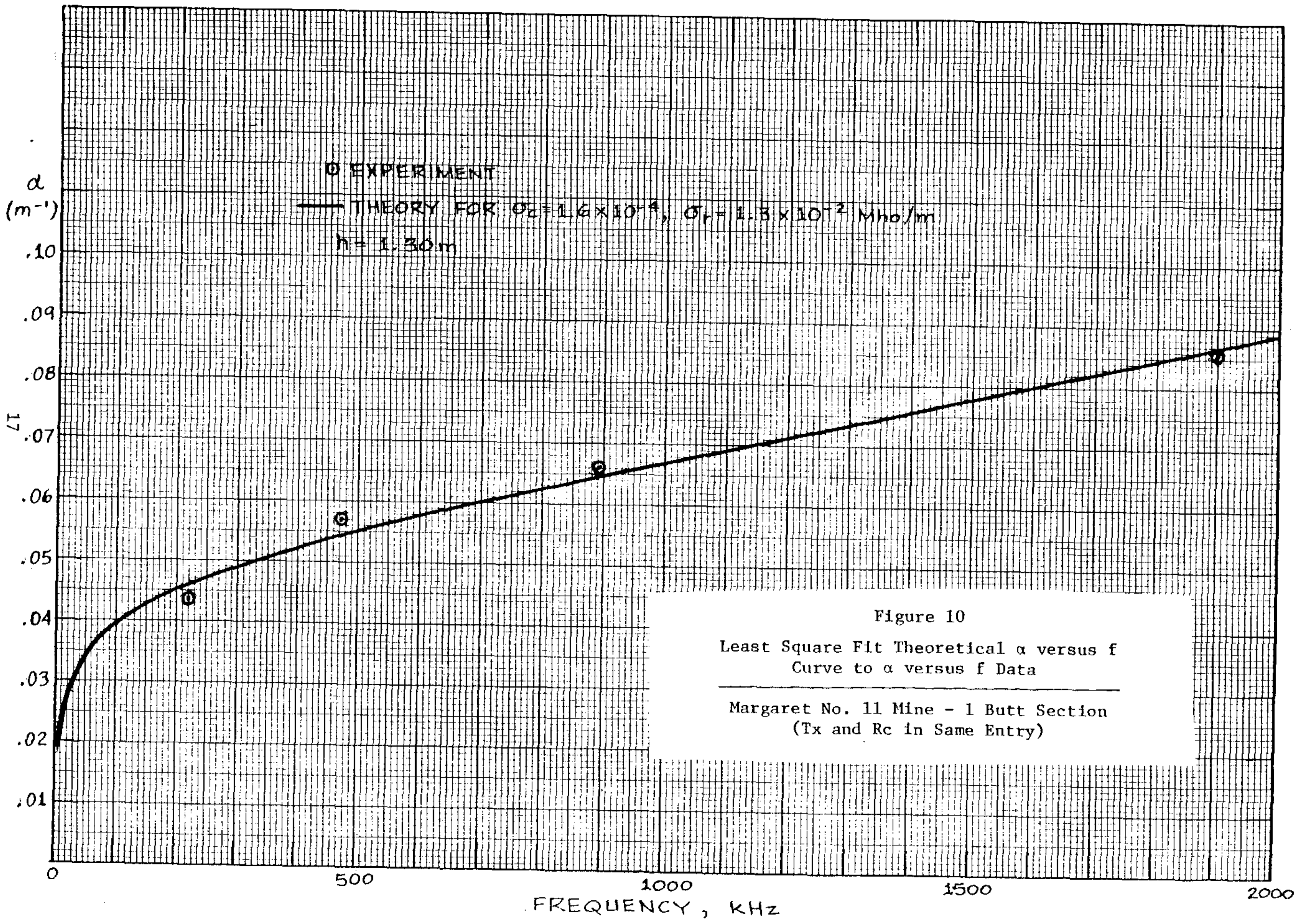


Figure 10

Least Square Fit Theoretical α versus f Curve to α versus f Data

Margaret No. 11 Mine - 1 Butt Section (Tx and Rc in Same Entry)

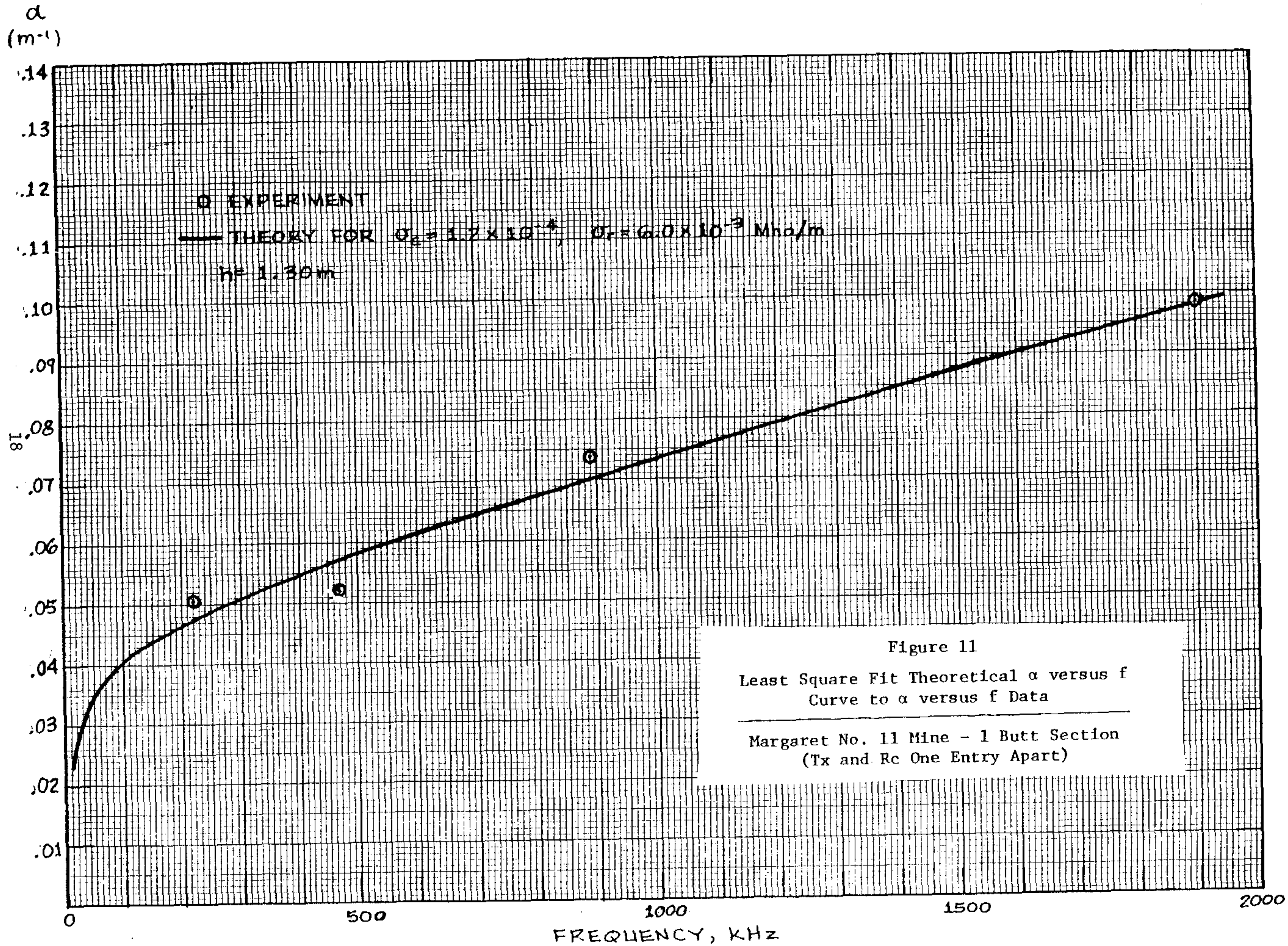


Figure 11

Least Square Fit Theoretical α versus f Curve to α versus f Data

Margaret No. 11 Mine - 1 Butt Section (Tx and Rc One Entry Apart)

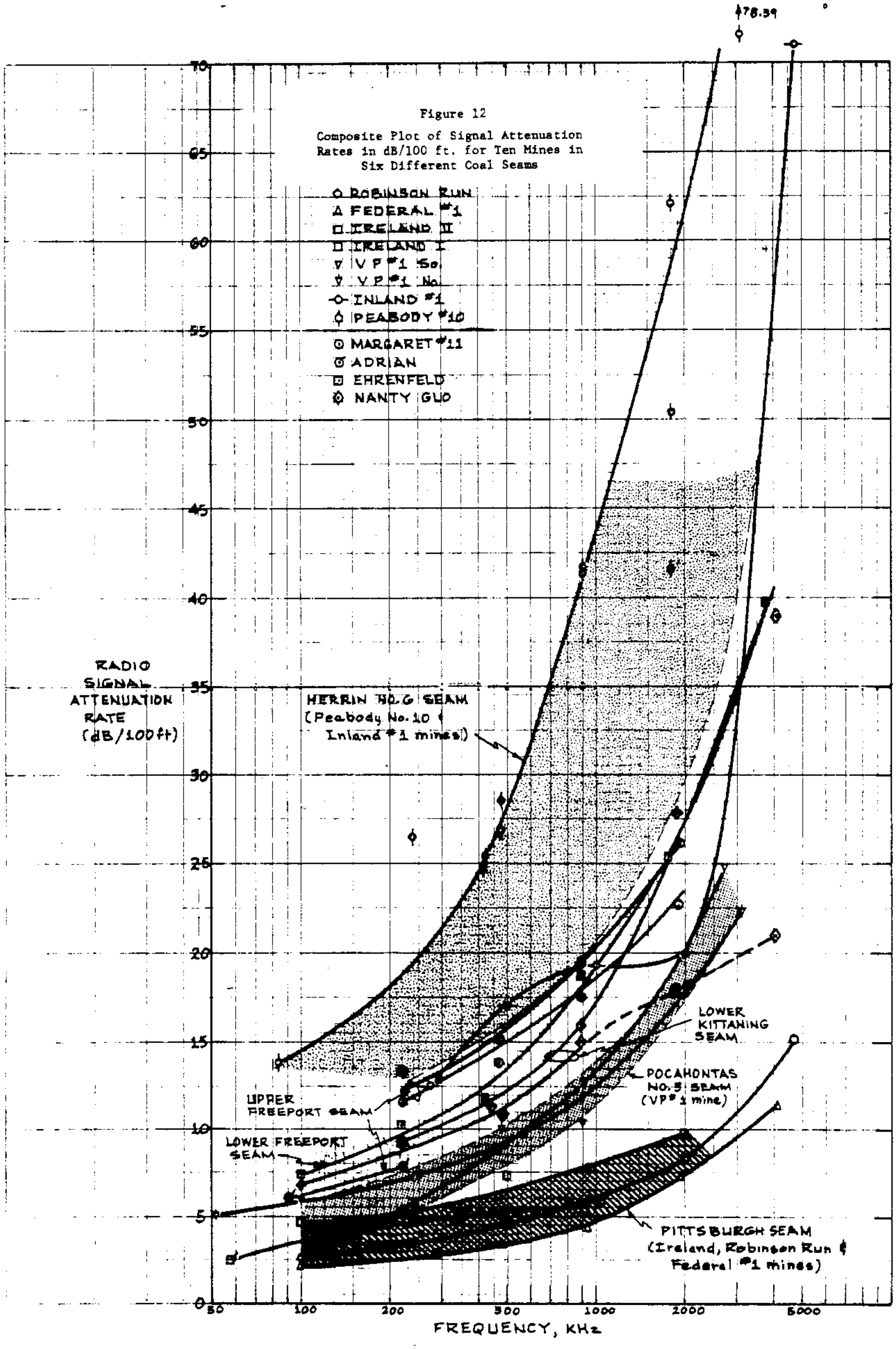


Figure 12
Composite Plot of Signal Attenuation Rates in dB/100 ft. for Ten Mines in Six Different Coal Seams
ROBINSON RUN
FEDERAL #1
IRELAND II
IRELAND I
V P #1 So.
V P #1 No.
INLAND #1
PEABODY #10
MARGARET #11
ADRIAN
EHRENFELD
NANTY GLO
RADIO SIGNAL ATTENUATION RATE (dB/100ft)
FREQUENCY, KHz
HERRIN NO.6 SEAM (Peabody No. 10 & Inland #1 mines)
UPPER FREEPORT SEAM
LOWER FREEPORT SEAM
LOWER KITTANING SEAM
POCAHONTAS No. 3 SEAM (VP #1 mine)
PITTSBURGH SEAM (Ireland, Robinson Run & Federal #1 mines)
78.59
0
5
10
15
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100
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500
1000
2000
5000

which approaches that found in the Herrin No. 6 seam in Illinois above 1 MHz. As mentioned previously, the high frequency results for the Nanty Glo Main-N area (dashed part of curve) are unreliable.

Table I gives a comparison of the conductivities obtained for the four mines in their respective coal seams. It is seen that the coal and rock conductivities differ by a factor of about 100. It is this large contrast between rock and coal conductivities that makes the MF coal-seam mode of propagation possible. However, it is seen that the coal and rock conductivities do not differ significantly from each other from mine to mine and seam to seam, with the possible exception of the Adrian mine results which were derived from measurements at only two frequencies. These coal and rock conductivities can be compared with those derived from the mines in the first three seams measured,[1] shown in Table II. We find that the Table I values are most similar in value to those obtained for the Pocahontas No. 3 seam in Virginia.

In summary, the signal attenuation rates for most of the seams examined to date fall in the moderate to high loss category, and it appears that the low losses found in the Pittsburgh seam may be the exception rather than the rule, unfortunately. The reasons for this are not yet apparent. However, enough propagation data may now be available to determine whether any correlation exists between the electrical properties of the coal and its chemical composition. Since chemical analyses of the coal are generally available for each mine, statistical regression analyses of these chemical and electrical data appear to be both practical and desirable.

TABLE I

DERIVED COAL AND ROCK CONDUCTIVITIES FOR FOUR MINES

(For $K_c = 6$)

Coal Mine	Seam Height h(m)	σ_{Coal} (Mho/m)	σ_{Rock} (Mho/m)	Coal Seam	County, State
Nanty Glo					
5-Cross Area	1.04	6.2×10^{-5}	7.2×10^{-3}	Lower Kittaning	Cambria, Pa.
Main-N Area (lowest 4 frequencies)	1.04 (to .61)	6.6×10^{-5}	11×10^{-3}	Lower Kittaning	Cambria, Pa.
Ehrenfeld	1.12	6.3×10^{-5}	5.4×10^{-3}	Lower Freeport	Cambria, Pa.
Margaret No. 11, 1 Butt Sec.					
Tx, Rx in same entry	1.30	16×10^{-5}	13×10^{-3}	Upper Freeport	Armstrong, Pa.
Tx, Rx one entry apart	1.30	12×10^{-5}	6×10^{-3}	Upper Freeport	Armstrong, Pa.
Adrian (Only 2 frequencies)	1.83	3.4×10^{-5}	1.9×10^{-3}	Upper Freeport	Upshur, W. Va.

TABLE II

CONDUCTIVITIES DERIVED FROM THE α VERSUS f PLOTS

Coal Mine	h (m)	K_c	σ_{coal} (Mho/m)	σ_{rock} (Mho/m)	Coal Seam
Robinson Run	1.5	6	0.3×10^{-4}	0.085	Pittsburgh
Federal No. 1	2	6	0.26×10^{-4}	0.084	Pittsburgh
Ireland "II"	2	6	1.0×10^{-4}	0.054	Pittsburgh
Ireland "I"	2	6	2.0×10^{-4}	1.09	Pittsburgh
			1.4×10^{-4}	0.3	Pittsburgh
Pocahontas No. 1					
3 South Area Entry A	1.37	6	3×10^{-5}	0.01	Pocahontas No. 3
3 South Area Entry B	1.37	6	3×10^{-5}	0.0077	Pocahontas No. 3
2 North No. 1 (Plow Area)	1.19	6	6×10^{-5}	0.017	Pocahontas No. 3
Inland No. 1	3	6	1.0×10^{-3}	0.22	Herrin No. 6
Peabody No. 10					
1 Main South 1st West 2nd North	2	6	4×10^{-3}	0.3	Herrin No. 6
1 South 5-1/2 East/ 1 South Jct.	2	6	2.5×10^{-3}	0.3	Herrin No. 6

IV. THE COUPLING FACTOR

The factor C in Eq (1) is given theoretically by the expression[1]

$$C = \frac{M(\alpha^2 + \beta^2)^{3/4}}{(8\pi)^{1/2}\left[(h + \delta_r)^2 + \delta_r^2\right]^{1/2}} \tag{7}$$

where M is the transmitter mangetic moment. From the conductivities, we can calculate α, β, and δ_r as functions of frequency by means of Eqs (3), (4), and (5). Therefore a theoretical curve of C versus f can be derived from Eq (7). Such a curve is shown for the Nanty Glo mine in Figure 13, in comparison with the experimental intercept values of Figure 3 obtained from the $H\sqrt{r}$ versus r plots for this mine. The agreement is seen to be fairly good. Similar coupling factor comparisons for the other mines are shown in Figures 14 to 18. It is seen that the theory generally underestimates the experimental values below about 1 MHz and overestimates them above 1 MHz.

Figure 14 for the Main-N area of the Nanty Glo mine shows that the experimental values of C for the two highest frequencies are considerably out of line, due probably to the effect of considerable floor heaving in this tunnel. We have therefore included in Table I only the conductivity values derived from the experimental data taken at the four lowest frequencies for this case.

The comparison of theoretical and experimental values of the coupling factor, defined by the $H\sqrt{r}$ axis intercept at $r = 0$, is more fundamental than the comparison of theoretical and experimental values of magnetic field at some standard range. Therefore, we recommend that the ratio C_{theor}/C_{expt} expressed in dB be analyzed statistically, instead of H_{theor}/H_{expt} (@ 100 m), to assess the goodness of fit between the three-layer model and the data as a function of frequency.

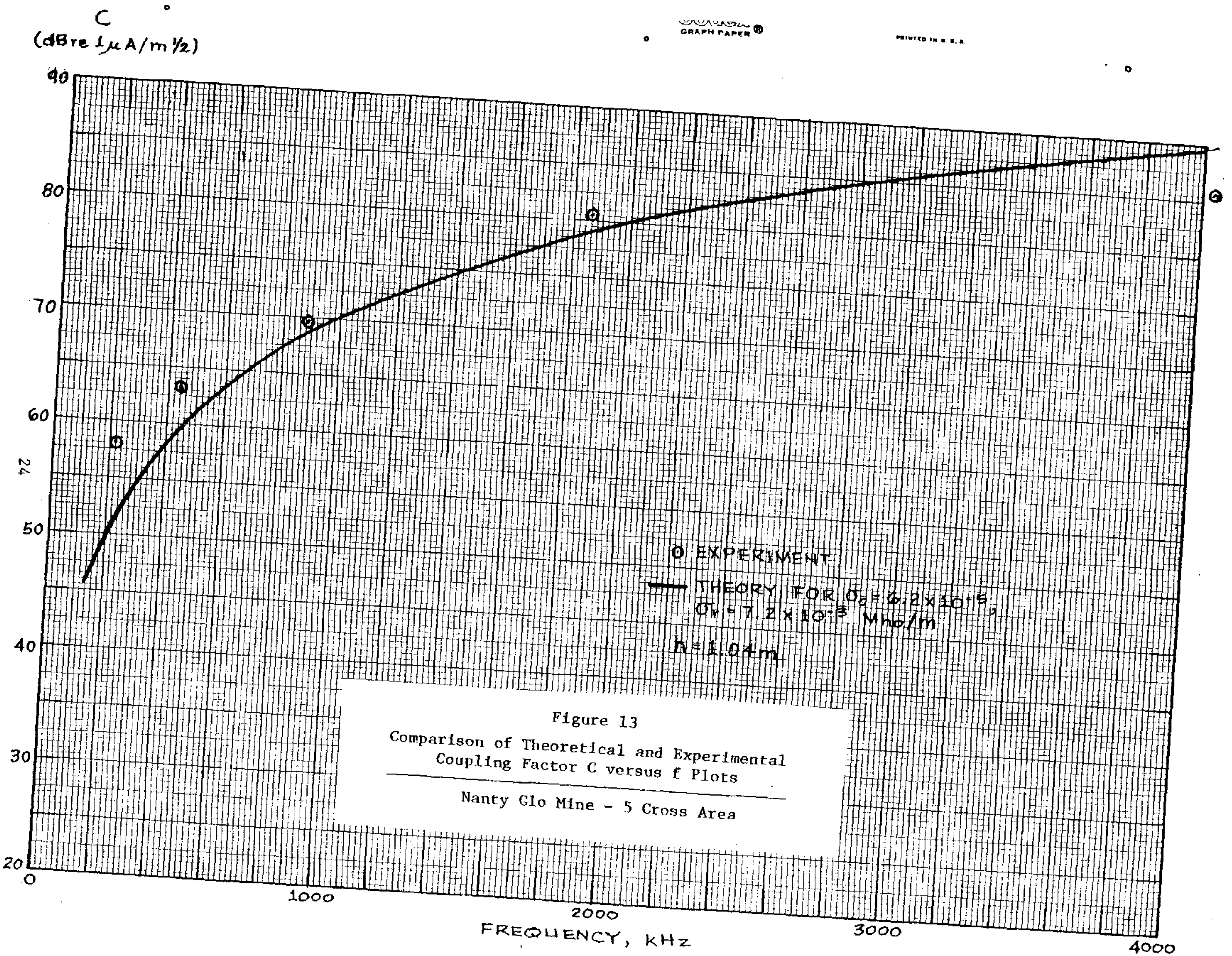

Figure 13

Comparison of Theoretical and Experimental Coupling Factor C versus f Plots

Nanty Glo Mine - 5 Cross Area

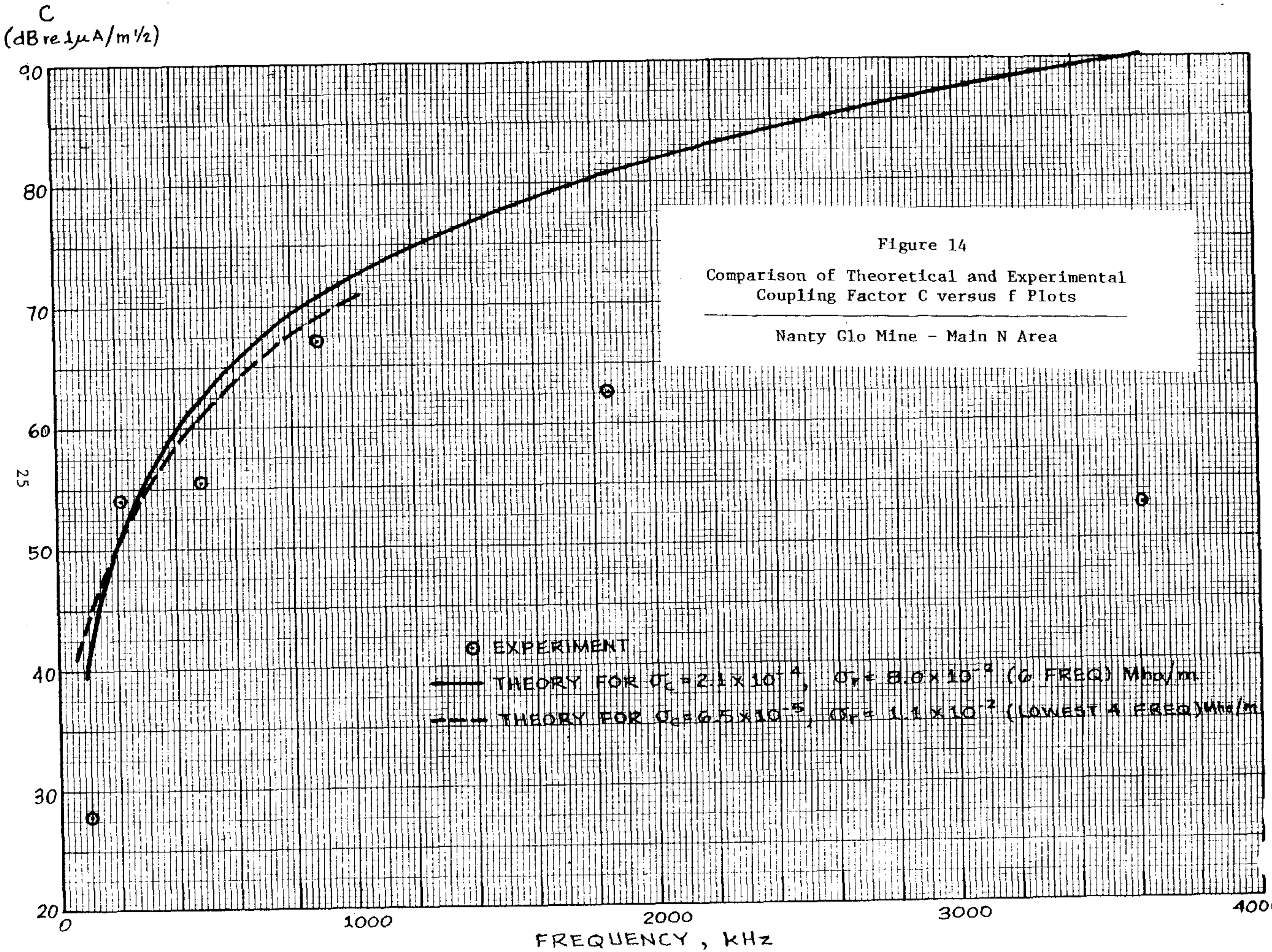

Figure 14

Comparison of Theoretical and Experimental Coupling Factor C versus f Plots

Nanty Glo Mine - Main N Area

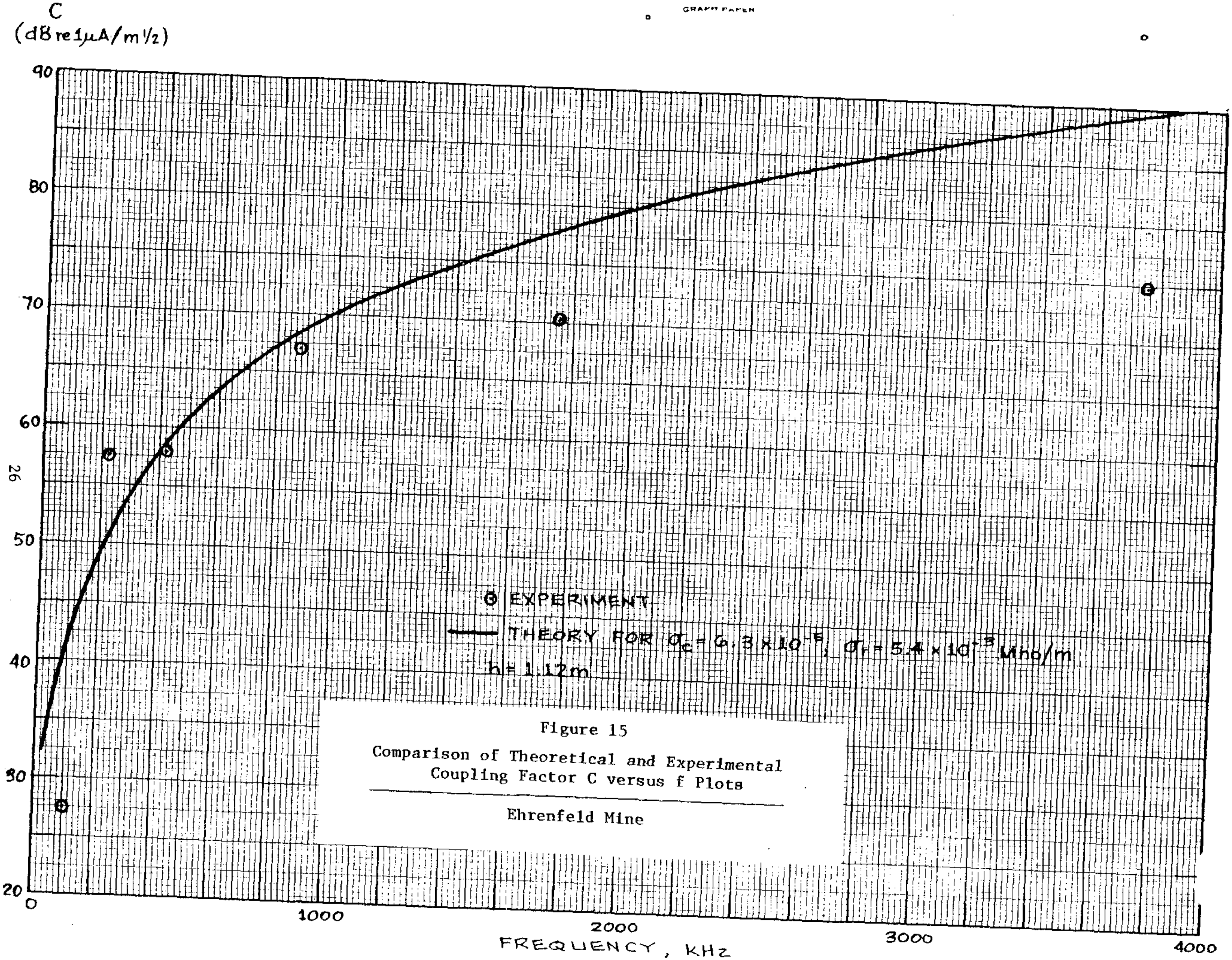

Figure 15

Comparison of Theoretical and Experimental Coupling Factor C versus f Plots

Ehrenfeld Mine

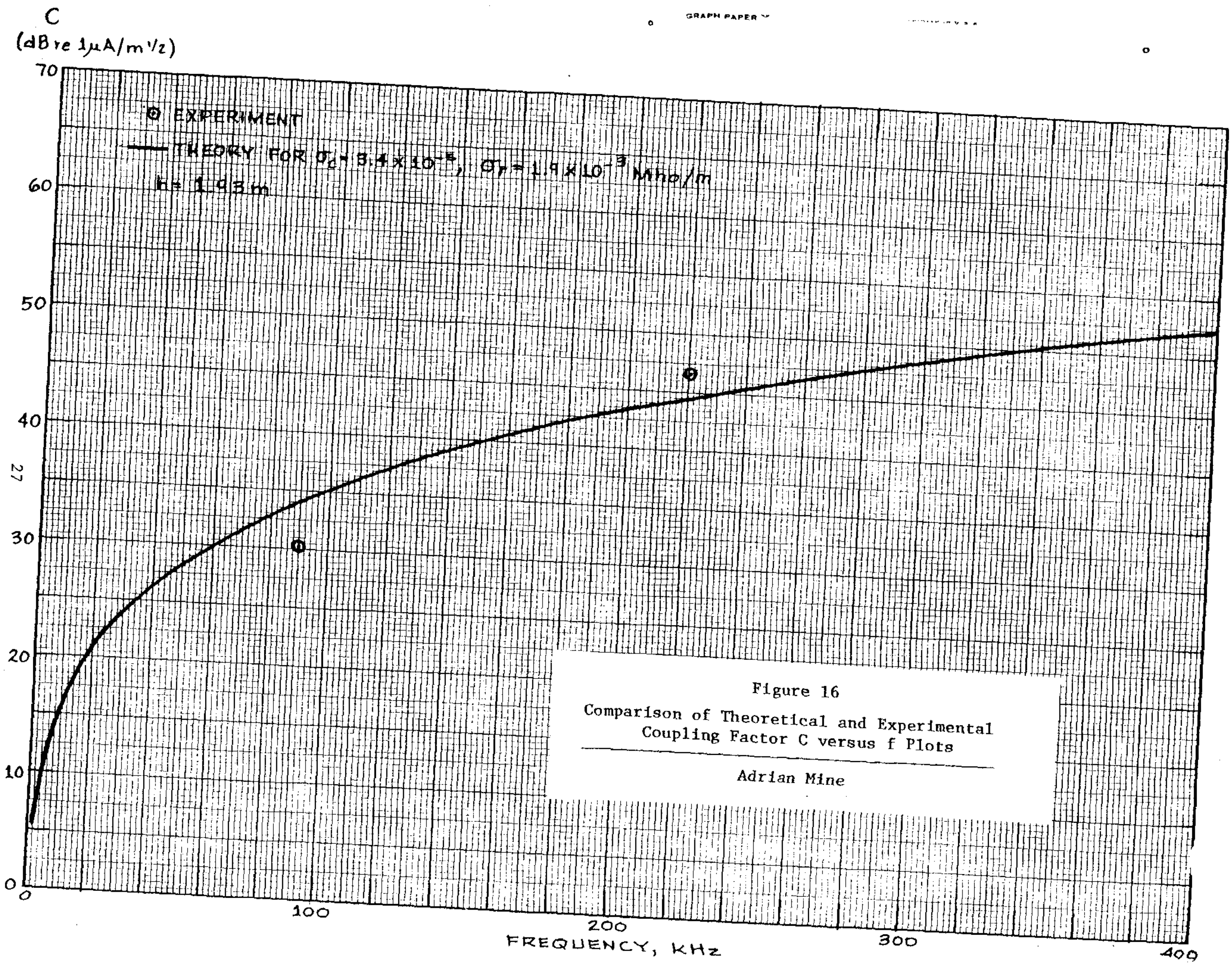

Figure 16

Comparison of Theoretical and Experimental Coupling Factor C versus f Plots

Adrian Mine

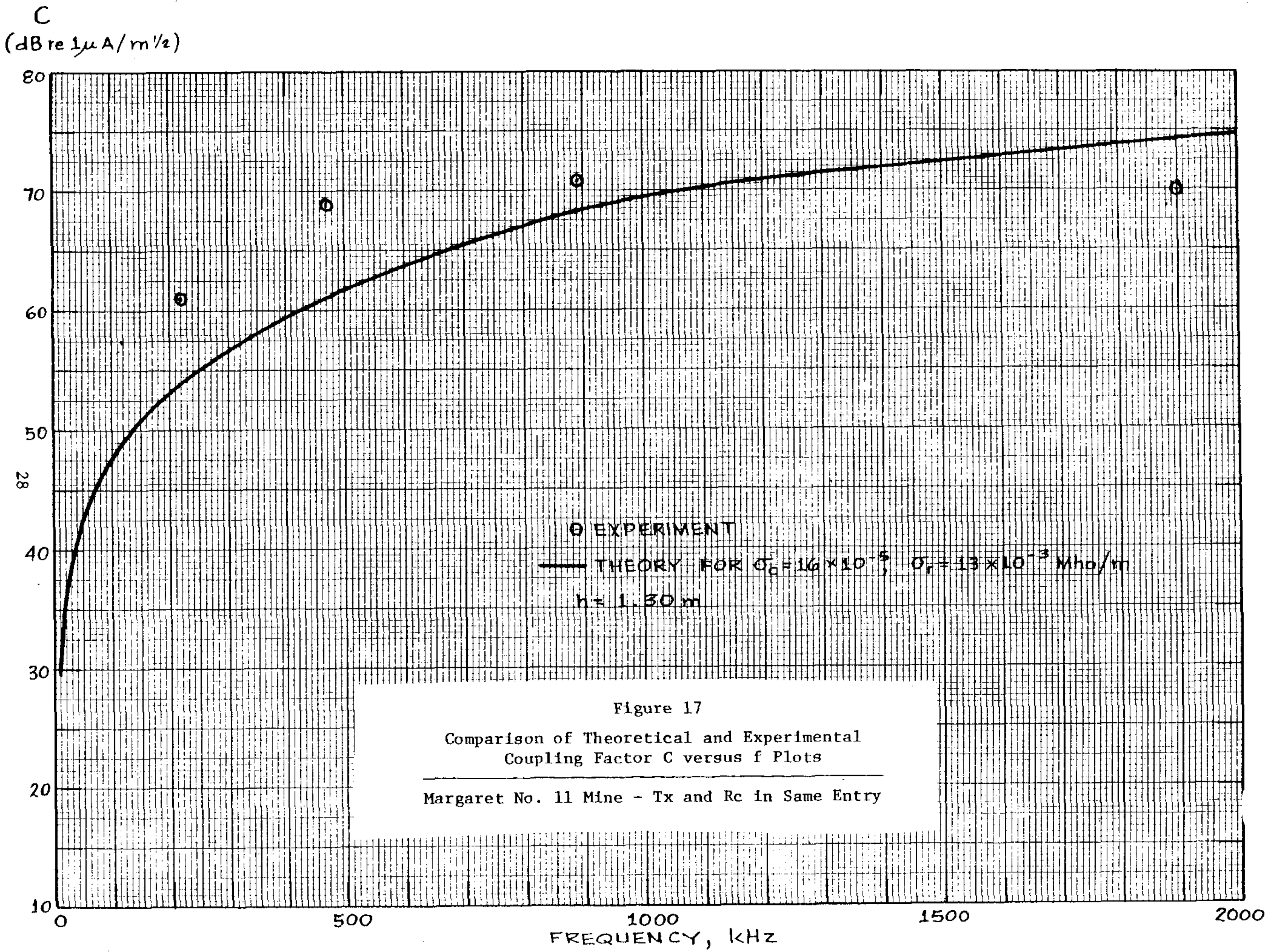

Figure 17

Comparison of Theoretical and Experimental Coupling Factor C versus f Plots

Margaret No. 11 Mine - Tx and Rc in Same Entry

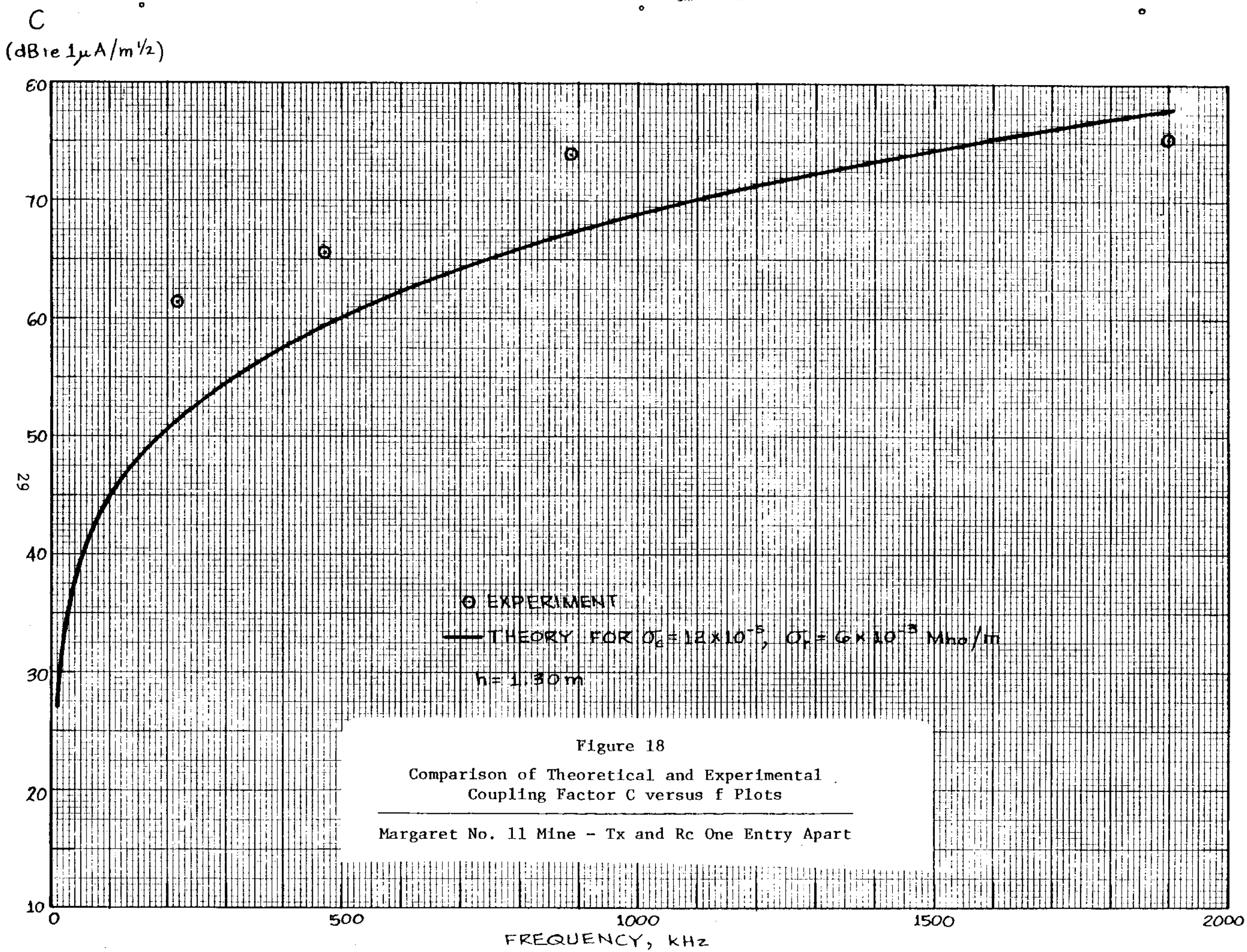

Figure 18

Comparison of Theoretical and Experimental Coupling Factor C versus f Plots

Margaret No. 11 Mine - Tx and Rc One Entry Apart

V. EFFECT OF SEAM HEIGHT ON α AND C

It is of interest to know how the attenuation constant α and the coupling factor C depend on the seam height h if all other parameters are kept constant. Figures 19 and 20 show what would happen if the seam height of the Nanty Glo mine were 2.08 m instead of 1.04 m. It is seen from Figure 19 that α is markedly reduced, especially at the higher frequencies. This would result in a considerable increase in range of communication. On the other hand, Figure 20 shows that the coupling factor is decreased by about 5 dB at all frequencies. This loss of coupling in the high coal case would by no means nullify the larger gain in signal strength caused by the decrease in α. Thus, MF radio communication will be more favorable in high coal than low coal seam waveguides having the same electrical properties.

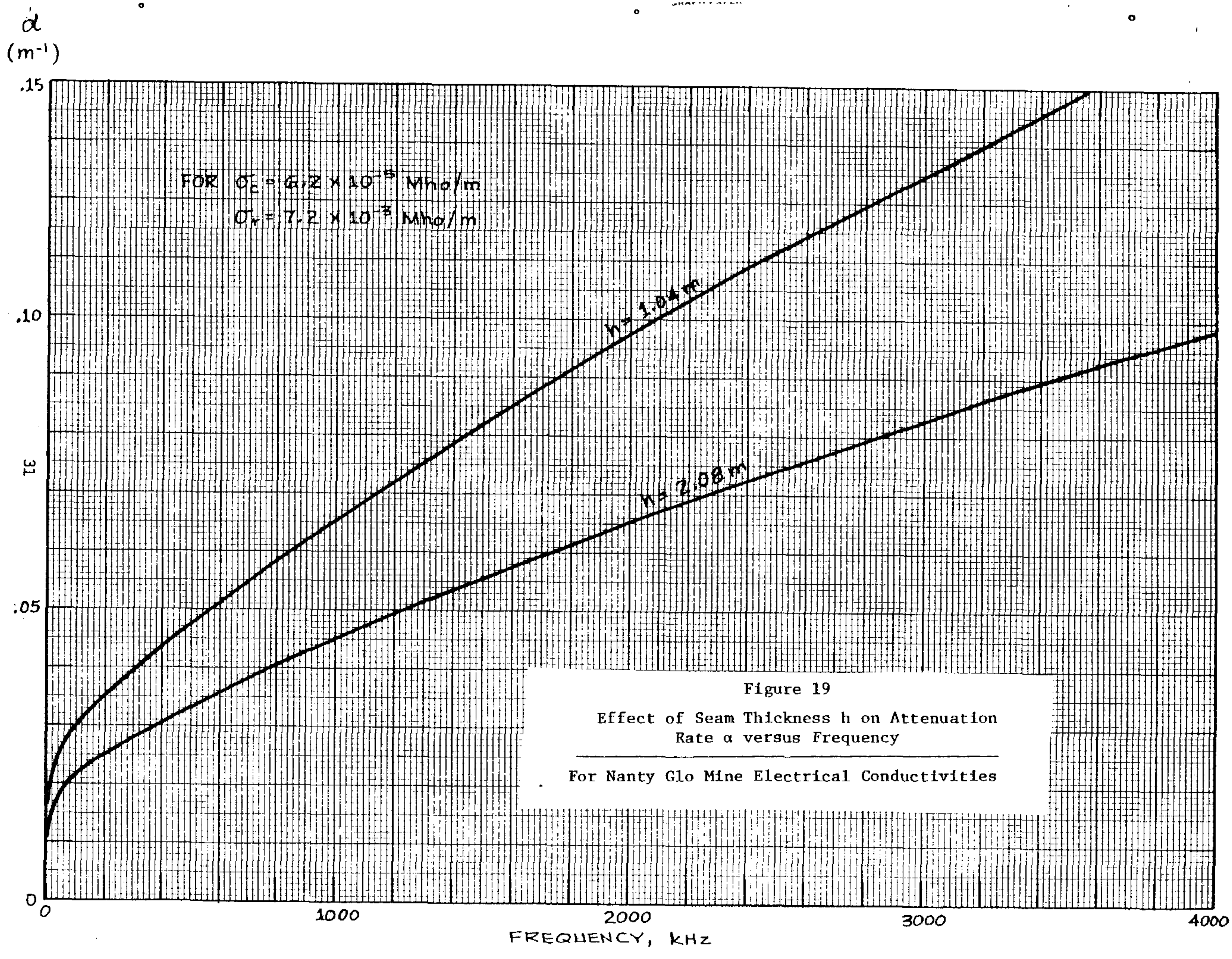

Figure 19

Effect of Seam Thickness h on Attenuation Rate α versus Frequency

For Nanty Glo Mine Electrical Conductivities

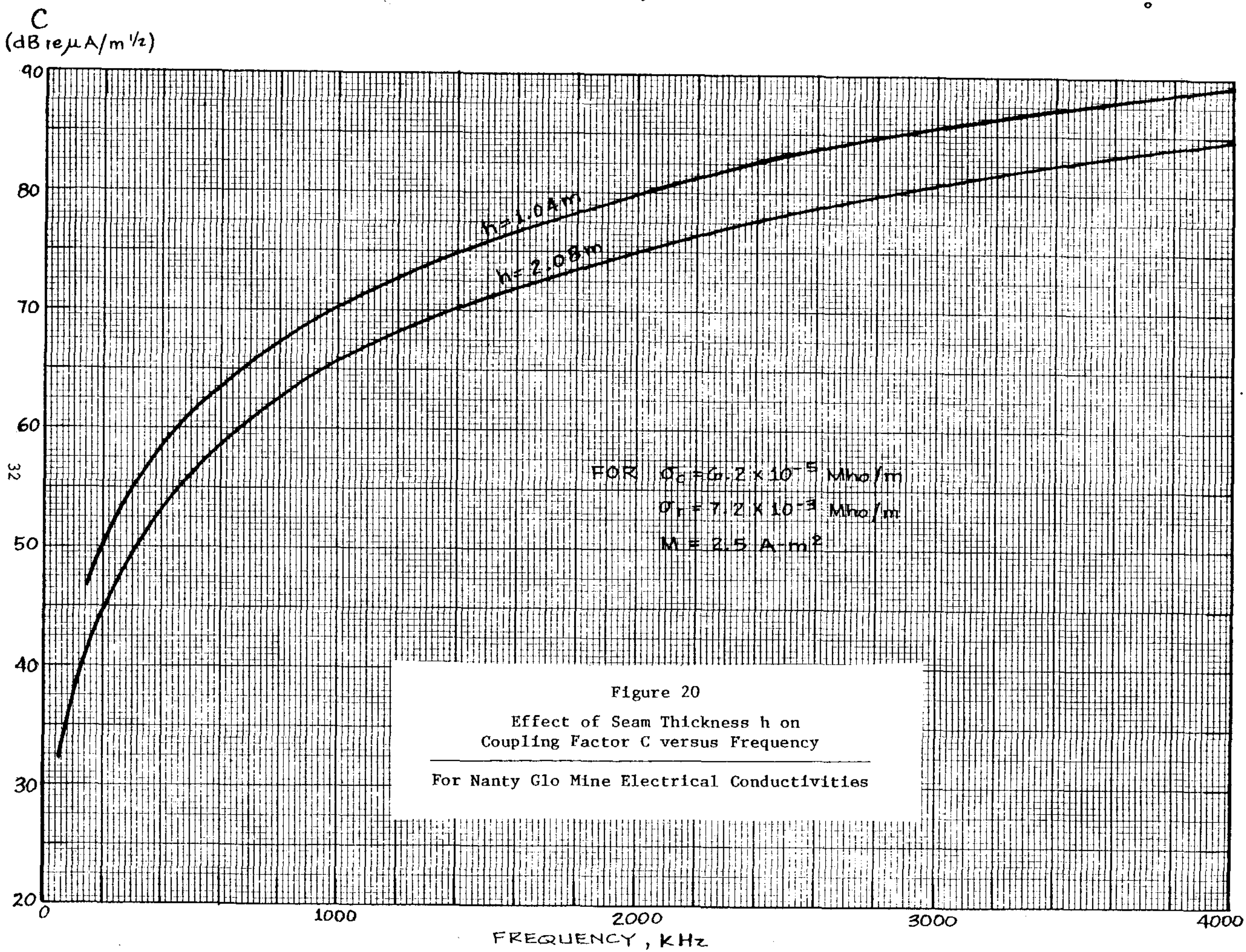

Figure 20

Effect of Seam Thickness h on
Coupling Factor C versus Frequency

For Nanty Glo Mine Electrical Conductivities

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APPENDIX

COUPLING OF THE COAL-SEAM MODE TO A CABLE IN A TUNNEL AT MEDIUM RADIO FREQUENCIES

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INTRODUCTION

The lowest order coal-seam mode is a parallel-plate TEM transmission-line type of propagation[1] of medium frequency radio waves in a conducting coal seam which is bounded above and below by more conductive rock, with the electric field vertical and the magnetic field horizontal. This mode can be excited by a vertical loop antenna placed in a tunnel in the coal seam. In a conductor-free region of the coal mine the magnetic field falls off with distance with a cylindrical spreading factor multiplied by an exponential loss factor. However, when a conductor, such as a power cable, is present in a parallel tunnel, the field is found experimentally[2] to level off to a much lower rate of decay after a certain fairly well defined distance.

The effect can be attributed to coupling of the coal-seam mode to a low attenuation mode guided by the cable. Experiment shows[2] that a slowly decaying current is indeed present in the cable. The purpose of this paper is to investigate the nature of the coupling. The method is to start with a current in the cable, calculate the magnetic field produced by this current at the location of the loop antenna, determine the voltage induced in the loop by this field, and finally use the reciprocity principle to determine the current induced in the cable when the loop acts as a transmitter.

MAGNETIC FIELD DUE TO CURRENT IN CABLE

Figure 1 shows the cable at a distance y = d from the center of the coal seam. The cable carries a current I which produces an infinite set of images[3] with current

$$I_n = (-1)^n I \tag{1}$$

located at the (complex) positions:

$$y_n = n\,(h + \delta_r - i\delta_r) + (-1)^n d \tag{2}$$

where $\delta_r = (\pi\mu_0\, f\sigma)^{-1/2}$ is the skin depth in the rock. The images, including the cable itself, form a periodic distribution of current of period:

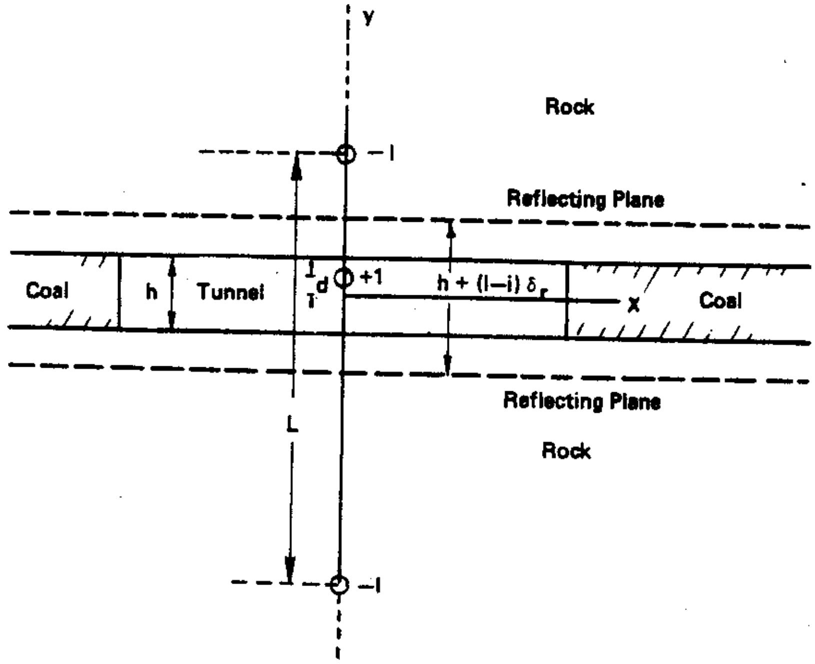
$$L = 2(h + d - i\delta_r) \tag{3}$$

To calculate the magnetic field due to the set of images it is convenient to represent the discrete currents by a Fourier series:

$$I(y) = \sum_{1}^{\infty} \left(A_p \cos \frac{2\pi p y}{L} + B_p \sin \frac{2\pi p y}{L} \right) \tag{4}$$

This work was supported by the U.S. Department of the Interior, Bureau of Mines, Pittsburgh Mining and Safety Research Center, under USBM Contract HO346045.

FIGURE 1
CABLE WITH CURRENT (+ I) IN
COAL MINE TUNNEL WITH IMAGES (– I) IN ROCK



which contains no constant term since the total current in cable and rock is zero. For the currents defined by (1) and (2) the Fourier series takes the form:

$$I(y) = \frac{4I}{L}\left(\cos\frac{2\pi d}{L}\cos\frac{2\pi y}{L} + \sin\frac{4\pi d}{L}\sin\frac{4\pi y}{L} + \cos\frac{6\pi d}{L}\cos\frac{6\pi y}{L} + \sin\frac{8\pi d}{L}\sin\frac{8\pi y}{L} + \text{-----}\right) \quad (5)$$

The magnetic fields corresponding to the first harmonic of the yz current sheet, for a wave propagating along the cable, are readily found to be:

$$H_x = \frac{ik_y}{k_x}\frac{2I_o}{L}\cos k_y d e^{-ik_x x} e^{-ik_z z} \sin k_y y \quad (6)$$

$$H_y = \frac{2I_o}{L}\cos k_y d\, e^{-ik_x x} e^{-ik_z z} \cos k_y y \quad (7)$$

$$H_z = 0 \quad (8)$$

$$k_y = \frac{2\pi}{L} \quad (9)$$

where I_o is the current in the cable at $z = 0$.

For the second harmonic, the field is:

$$H_x = -\frac{ik_y}{k_x}\frac{2I_o}{L}\sin k_y d e^{-ik_x x}e^{-ik_z z}\cos k_y y \tag{10}$$

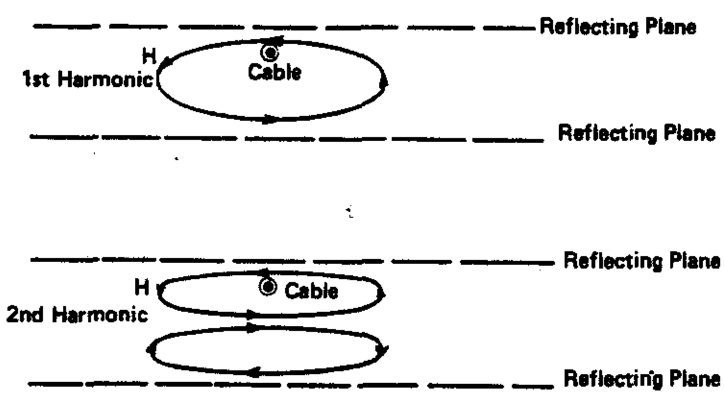
$$H_y = \frac{2I_o}{L}\sin k_y d e^{-ik_x x}e^{-ik_z z}\sin k_y y \tag{11}$$

$$H_z = 0 \tag{12}$$

$$k_y = \frac{4\pi}{L} \tag{13}$$

The magnetic field lines for the two harmonics are shown in Figure 2.

FIGURE 2
MAGNETIC FIELD LINES FOR TWO HARMONICS



The k's are related by the formula:

$$k_x^2 + k_y^2 + k_z^2 = k_o^2 \tag{14}$$

where k_o is the free-space propagation constant and k_z is the z-directed propagation constant for the cable-guided wave. For medium frequencies, k_z is not very different from k_o[4,5] ($\sim .75k_o$) and both are small in magnitude compared with k_y. Therefore, Equation (14) can be written to a good approximation as:

$$k_x \cong -ik_y . \tag{15}$$

If we make the further approximation that $|k_y d| \ll 1$, and let y = 0, we obtain the simple results:

$$\left|\frac{H_x}{I_o}\right|_1 = 0 \tag{16}$$

$$\left|\frac{H_y}{I_o}\right|_1 = \frac{1}{\sqrt{(h+\delta_r)^2 + \delta_r^2}}\; e^{-\frac{\pi (h+\delta_r) x}{(h+\delta_r)^2 + \delta_r^2}} \tag{17}$$

$$\left|\frac{H_x}{I_o}\right|_2 = \frac{2\pi d}{(h+\delta_r)^2 + \delta_r^2}\; e^{-\frac{2\pi (h+\delta_r) x}{(h+\delta_r)^2 + \delta_r^2}} \tag{18}$$

$$\left|\frac{H_y}{I_o}\right|_2 = 0 \tag{19}$$

where the subscripts 1 and 2 refer to first and second harmonics, respectively.

EXCITATION OF THE CABLE BY A TRANSMITTING LOOP ANTENNA

By the principle of reciprocity, we can use the above results to find the current I_c induced in the cable by a loop antenna situated at a distance x from the cable. The result is:

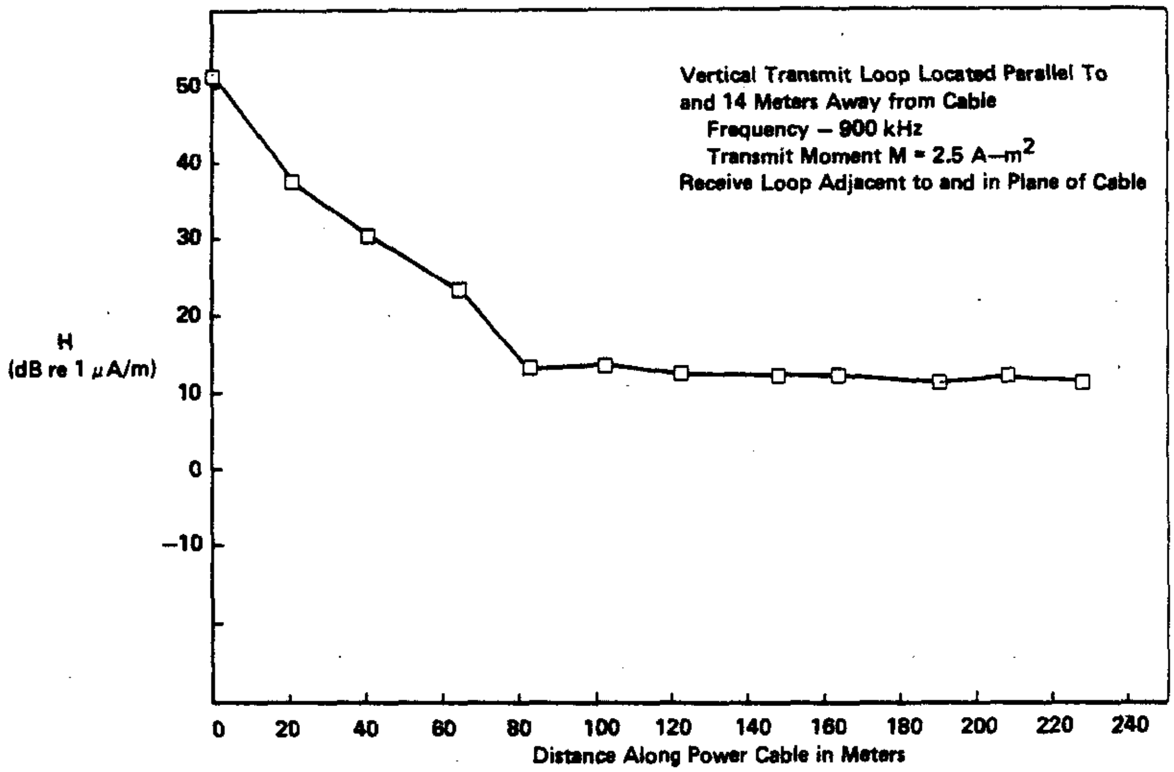
$$I_c = \frac{\omega\mu_o M}{2Z_o} \frac{H}{I_o} \tag{20}$$

where M is the magnetic moment of the loop, Z_o is the characteristic impedance of the cable transmission line, and (H/I_o) is the appropriate ratio from Equations (16 – 19).

Measurements by T.S. Cory[2] in the Helvetia Coal Co. Margaret No. 11 mine with a vertical transmit loop parallel to, and placed at a distance of 14 meters from, a power cable are shown in Figure 3. The first part of the magnetic field plot represents the decay of the incident field of the coal-seam mode. Beyond about 80 m along the cable, the measured field is due to the current induced in the cable. This current is estimated from the data, and from the size of the receiving loop located adjacent to and in the plane of the cable, to be about 6×10^{-6} A. From other measurements taken in a conductor-free area of the same mine, we can infer that the conductivity of the rock, σ_r, is in the range 0.01 to 0.02 Mho/m. For σ_r = 0.01 Mho/m, the skin depth in the rock is δ_r = 5.3 m.

If the transmitting loop is oriented vertically, so as to generate the TEM coal-seam mode with the magnetic field horizontal, it is seen from (16) and (18) that coupling to the cable occurs only via the second and higher-order even harmonics. Using the above value of skin depth, δ_r, and the experimental values d = 0.45 m, h = 1.3 m, and x = 14 m, theoretical estimates of the current induced in the cable are obtained from Equation (18) for the second harmonic. Equation (18) gives $|H_x/I_o|_2 = 1.2 \times 10^{-5}\ m^{-1}$. Equation (20), with M = 2.5 A - m² and Z_o = 300 Ω, then gives $I_c = 1.4 \times 10^{-7}$ A. Thus, the predicted current value for a vertically oriented transmit loop is about 50 times less than the experimentally determined value.

FIGURE 3
MAGNETIC FIELD VS. DISTANCE
ALONG POWER CABLE
MARGARET NO. 11 MINE, FREEPORT SEAM



This disagreement implies that the excitation of the cable-guided mode is not brought about by the TEM coal-seam mode. Rather, it is brought about by a higher-order mode, below cutoff in the coal seam at MF frequencies, which has circular lines of E about a vertical axis and an H field with both radial and vertical components. This type of mode is generated by a horizontally oriented transmitting loop which couples to the cable via the first harmonic which produces a nonzero y-component of magnetic field. Equation (17), which applies for this case, gives $|H_y/I_0|_1 = 2.06 \times 10^{-3}$. Equation (20) then gives $I_c = 6.1 \times 10^{-5}$ A, which is 10 times larger than the experimental value obtained for a vertical antenna. An accidental tilt of the antenna of about 6 degrees away from the vertical would therefore make theory and experiment agree.

An alternative explanation of the coupling of a vertical loop to the cable is that the rock conductivity above the coal seam is appreciably different from that below the seam. Under these conditions the two reflecting planes are not symmetrically located with respect to the coal seam. In that case, as shown in Figure 4, a vertical loop now couples to the first harmonic of the cable field. A vertical displacement of the loop with respect to the center of the tunnel, with symmetrically placed reflecting planes, also gives coupling to the first harmonic.

FIGURE 4
VERTICAL LOOP COUPLING TO 1ST HARMONIC WHEN COAL
SEAM NOT CENTERED BETWEEN REFLECTING PLANES

COMMUNICATION BETWEEN HORIZONTAL LOOP ANTENNAS IN THE PRESENCE OF CONDUCTORS

The foregoing analysis suggests that horizontally oriented loop antennas may provide an efficient communication system in areas where conductors such as power lines, trolley lines, and rails are present. The vertical component of magnetic field at a distance x_2 from a cable due to a horizontal transmitting loop at a distance x_1 from the same cable is from Equation (17) (used twice) and Equation (20),

$$H = \left(\frac{\omega\mu_0 M}{2Z_0}\right)\left\{\frac{1}{(h+\delta_r)^2+\delta_r^2}\right\} e^{-\frac{\pi(h+\delta_r)(x_1+x_2)}{(h+\delta_r)^2+\delta_r^2}} \tag{21}$$

Figures 5 and 6 show graphs of H versus $x_1 + x_2$ for various frequencies, for rock conductivities of 0.01 and 0.1 Mho/m. The horizontal bar on each line indicates the intrinsic receiver noise level at that frequency for a 12 kHz bandwidth. It is seen that the maximum value of $x_1 + x_2$ depends strongly on the conductivity and is 38 m for $\sigma_r = 0.01$ Mho/m, but only 18 m for $\sigma_r = 0.1$ Mho/m. The optimum frequencies are 300 kHz and 100 kHz, respectively. No allowance has been made for loss along the cable itself. The results are not valid for very small values of either x_1 or x_2.

FIGURE 5
VERTICAL MAGNETIC FIELD AT DISTANCE X_2 FROM CABLE DUE TO HORIZONTAL TRANSMIT LOOP AT DISTANCE X_1
(Rock Conductivity σ_r = 0.01 Mho/m)

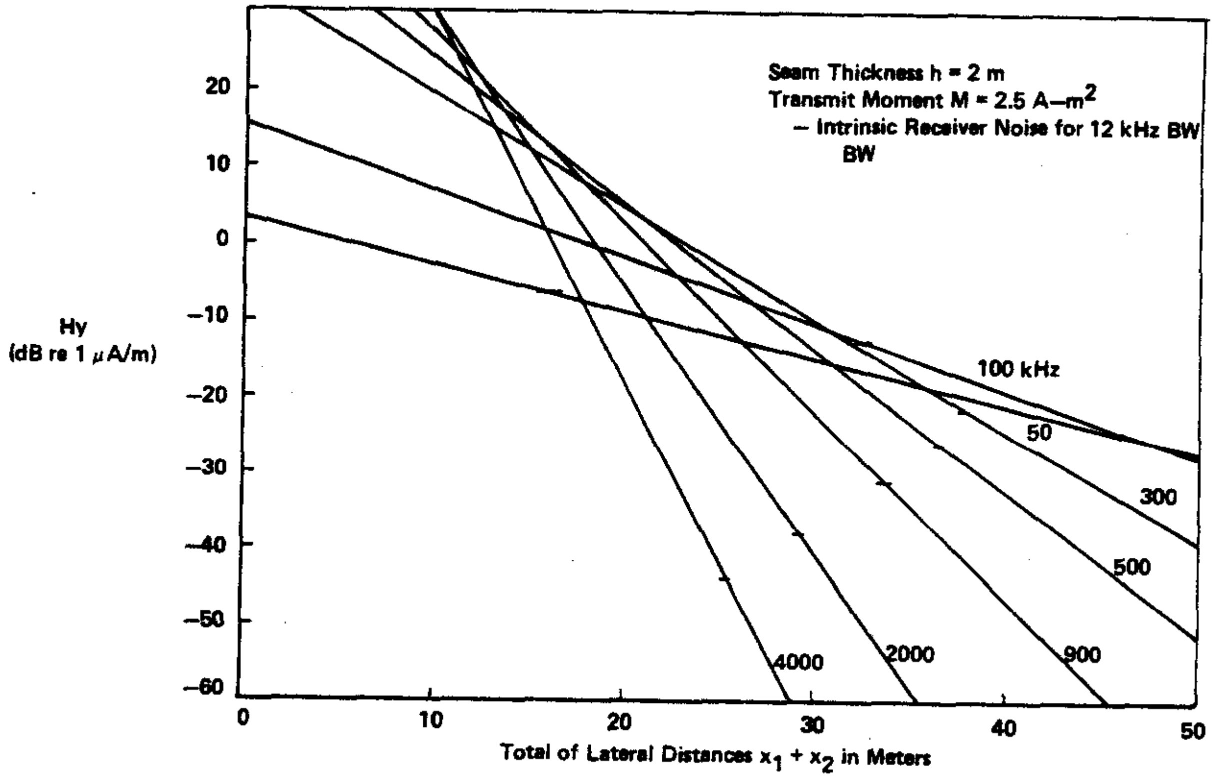
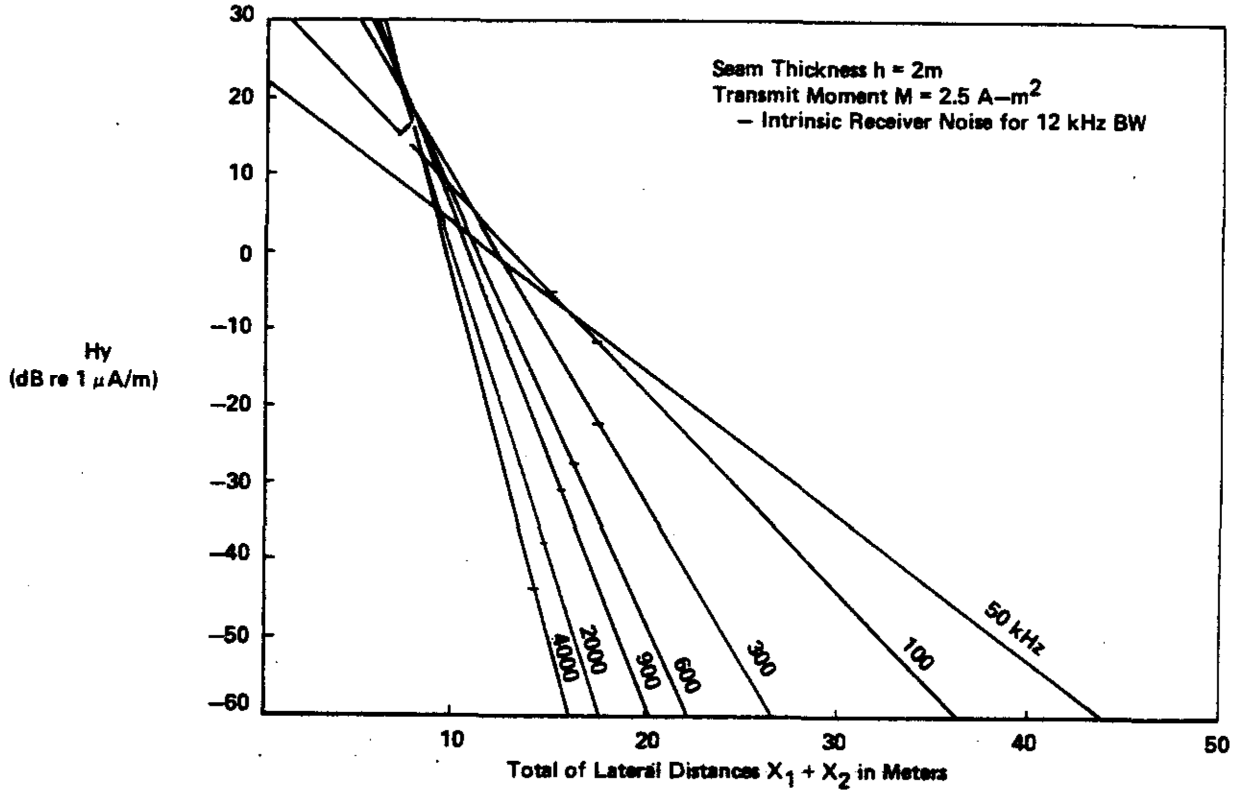


FIGURE 6
VERTICAL MAGNETIC FIELD AT DISTANCE X_2
FROM CABLE DUE TO HORIZONTAL TRANSMIT
LOOP AT DISTANCE X_1
(Rock Conductivity σ_r = 0.1 Mho/m)



Figures 7 and 8 show similar plots, derived from (17) and (20), for the field at the cable itself, (as measured by a square coil of edge 0.67 m held with one edge alongside the cable) due to a horizontal transmitter loop at a distance x from the cable. The maximum distances for the two values of rock conductivities are 57 m and 22.5 m, and they occur at 100 kHz and 50 kHz, respectively.

CONCLUSION

A theoretical model for predicting the coupling behavior between loop antennas and conducting cables in coal mine tunnels is currently under development, and the results are comparing favorably with the limited amount of experimental in-mine data taken to date. Further refinements of this theoretical model, together with comparisons with more comprehensive data from two additional coal mines, will be performed in the near future.

FIGURE 7
MAGNETIC FIELD AT THE CABLE DUE TO HORIZONTAL TRANSMIT LOOP AT DISTANCE X FROM THE CABLE
(Rock Conductivity σ_r = 0.01 Mho/m)

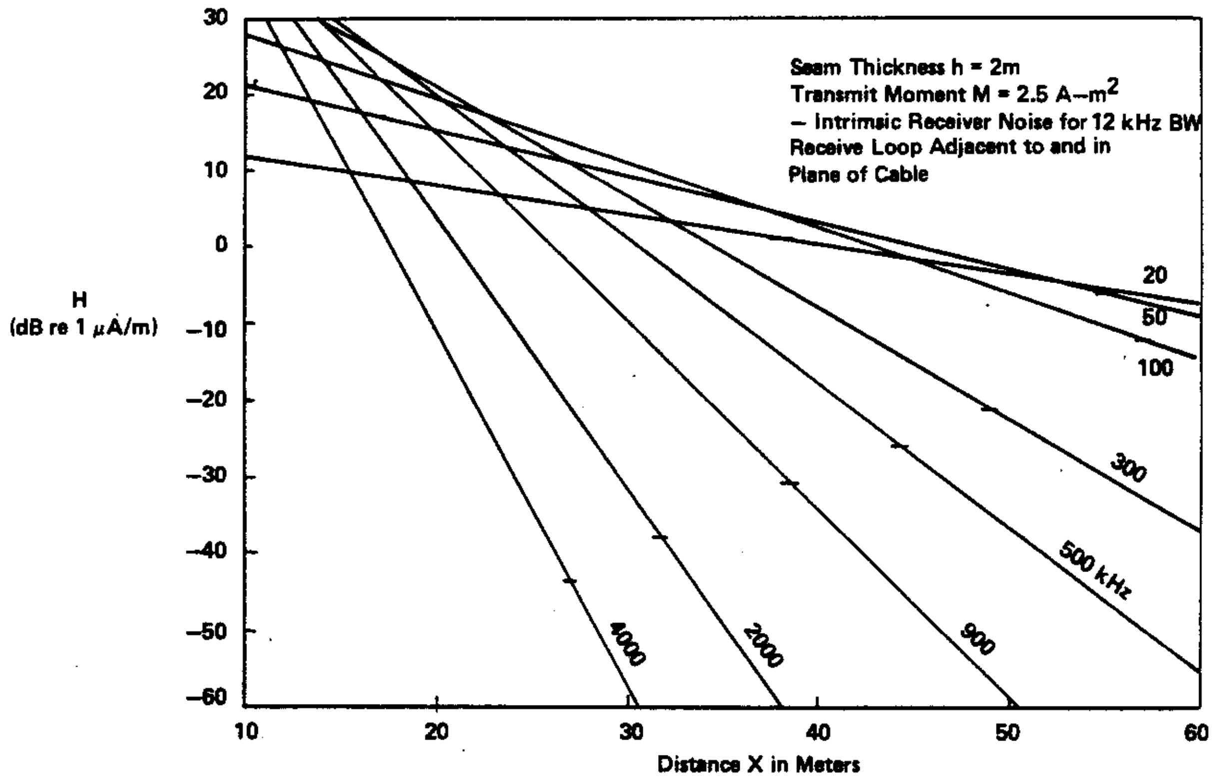
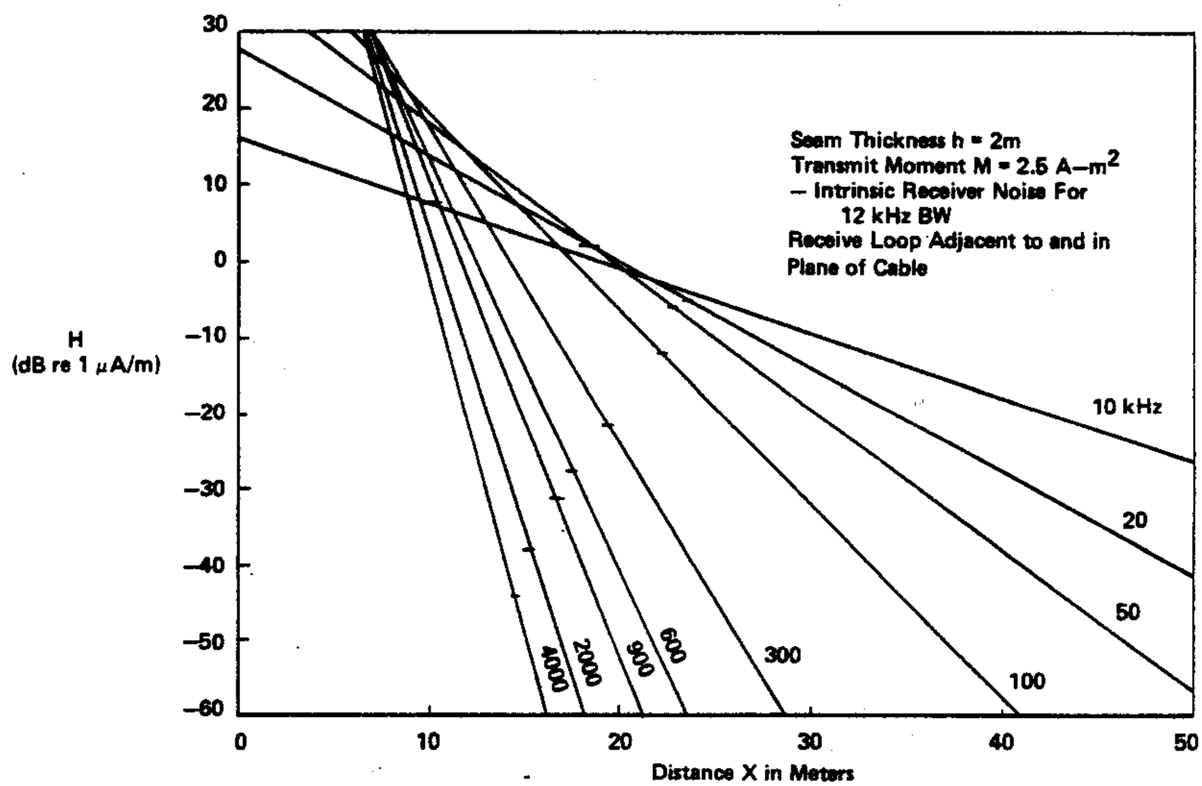


FIGURE 8
MAGNETIC FIELD AT THE CABLE DUE TO HORIZONTAL TRANSMIT LOOP AT DISTANCE X FROM THE CABLE
(Rock Conductivity σ_r = 0.1 Mho/m)



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MEDIUM FREQUENCY RADIO PROPAGATION AND COUPLING IN COAL MINES

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EXCITATION OF THE COAL-SEAM MODE IN A CONDUCTOR-FREE REGION

Medium frequency waves can propagate in a conducting coal seam, bounded above and below by more conductive rock, in an approximate TEM transmission line mode with the electric field vertical and the magnetic field horizontal.[1] The magnetic field components produced by a transmitting loop antenna located at the center of the coal seam in a vertical plane are, in terms of cylindrical coordinates with the origin at the center of the loop, the z-axis vertical, and the loop in the r-z plane:

$$H_\phi = \frac{imk}{4} \cos\phi \frac{d}{dr} \left\{ H_1^{(2)}(kr) \right\} \tag{1}$$

$$H_r = -\frac{imk}{4} \sin\phi \cdot \frac{1}{r} \cdot H_1^{(2)}(kr)\,. \tag{2}$$

$H_1^{(2)}$ is the first order Hankel function for outgoing waves, k is the propagation constant of the coal-seam mode, and m is the effective magnetic moment per unit length, distributed along the z-axis, that is equivalent to the magnetic moment M of the loop antenna located in the coal seam waveguide.

The effects of the currents induced in the rock by the transmitting loop can be represented by an infinite set of uniformly spaced loop images, each of magnetic moment M distributed along the z-axis with complex spacing[2]

$$D = h + (1-i)\,\delta_r, \tag{3}$$

where h is the thickness of the coal seam and δ_r is the skin depth in the rock. The magnetic moment density m, which couples to the TEM coal seam mode, is the zero-order component of the Fourier series that represents the set of magnetic moment images and is given by:

$$m = \frac{M}{D} = \frac{M}{h + (1-i)\,\delta_r} \tag{4}$$

The higher order Fourier series components couple to higher order coal-seam modes which are highly damped, and can therefore be ignored.

This work was supported by the U.S. Department of the Interior, Bureau of Mines, Pittsburgh Mining and Safety Research Center, under USBM Contract HO346045.

The propagation constant k is given by

$$k = \beta - i\alpha \tag{5}$$

where α and β can be calculated by means of the usual parallel plate transmission line formula:

$$\alpha + i\beta = \sqrt{(R + i\omega L)(G + i\omega C)} \tag{6}$$

which in this case takes the form:

$$\alpha + i\beta = \sqrt{(2Z_s + i\omega\mu_o h)\left(\frac{\sigma_c}{h} + \frac{i\omega\epsilon_c}{h}\right)}. \tag{7}$$

Z_S is the surface impedance of the rock, given by

$$Z_S = \frac{1+i}{\sigma_r \delta_r} \tag{8}$$

where

$$\delta_r = \sqrt{\frac{2}{\omega\mu_o \sigma_r}} \quad , \tag{9}$$

and σ_r, σ_c are the rock and coal conductivities, ϵ_c is the coal permittivity, and ω is the angular frequency. The permittivity of the rock ϵ_r is ignored since $\omega\epsilon_r \ll \sigma_r$ for the frequencies of interest here.

On taking the asymptotic form of the Hankel function, we find for the direction $\phi = 0$, in the plane of the loop, that the magnitude of the azimuthal component of magnetic field is:

$$|H| \simeq \frac{M(\alpha^2 + \beta^2)^{3/4}}{(8\pi)^{1/2}\,[(h+\delta_r)^2 + \delta_r^2]^{1/2}} \cdot \frac{e^{-\alpha r}}{\sqrt{r}} \tag{10}$$

This expression is approximately valid at ranges for which $\alpha r > 1$.

ATTENUATION RATE VERSUS FREQUENCY

Medium frequency transmission measurements have been made by T.S. Cory[3] in six coal mines. From a communications point of view, one can make a very meaningful comparison of the various mines directly from the experimental data, by plotting the attenuation constant α versus the frequency f. For this purpose, Equation (10) shows that if, for a given frequency, the experimental values of $H\sqrt{r}$, expressed in decibles, are plotted against r, a straight line of slope proportional to α should be obtained.

Figure 1 shows such a plot of $H\sqrt{r}$ versus r for Consolidation Coal Company's Robinson Run Mine (No. 95) at a frequency of 477 kHz. It is seen that the experimental points plotted in this way do indeed conform to Equation (10). The slope of the best straight line drawn through the plotted points gives an attenuation constant $\alpha = .01253\ m^{-1}$. It is to be noted that the range r has, for convenience, been divided by an arbitrary standard range of 100 m in the derivation of $H\sqrt{r}$ from the data. The value H = 24.0 dB re 1 μA/m on the straight line at this standard range, along with the slope $\alpha = 0.01253\ m^{-1}$, completely specify the experimental data at this frequency.

On repeating this procedure for the data at each frequency used in the experiments, we obtain the α versus f plot shown in Figure 2. It is seen that α increases monotonically with f. This type of curve is found for all the mines.

Figure 3 shows α versus f plots for a large number of mines. It is seen that the mines fall into three categories, representative of the seams in which they lie, namely: the Pittsburgh seam, the Pocahontas No. 3 seam, and the Herrin No. 6 seam, which are in order of increasing attenuation rate α.

DETERMINATION OF THE CONDUCTIVITIES

By separating the real and imaginary parts of Equation (7) we obtain the following expressions for α and β:

$$\alpha = \left\{(½)\left[(p^2 + q^2)^{½} + p\right]\right\}^{½} \tag{11}$$

$$\beta = \left\{(½)\left[(p^2 + q^2)^{½} - p\right]\right\}^{½} \tag{12}$$

where:

$$p = \frac{2(\sigma_c - 2\pi f\epsilon_c)}{h}\left(\frac{\pi\mu_o f}{\sigma_r}\right)^{½} - 4\pi^2 f^2 \mu_o \epsilon_c \tag{13}$$

$$q = \frac{2(\sigma_c + 2\pi f\epsilon_c)}{h}\left(\frac{\pi\mu_o f}{\sigma_r}\right)^{½} + 2\pi f\mu_o\sigma_c\ . \tag{14}$$

For an assumed value $K_c = 6$ for the dielectric constant of coal, we can determine the values of σ_c and σ_r that give the least square fit between the theoretical and experimental α versus f curves. The solid line in Figure 2 corresponds to $\sigma_c = 3.0 \times 10^{-5}$ Mho/m and $\sigma_r = 8.5 \times 10^{-2}$ Mho/m. The RMS error in α is 0.0018, which is about 5% of the mean α over the frequency range covered. Table I shows values of the σ's determined in this way for the various mines.

FIGURE 1
PLOT OF $H\sqrt{r}$ VERSUS r AT f = 477 kHz
ROBINSON RUN COAL MINE

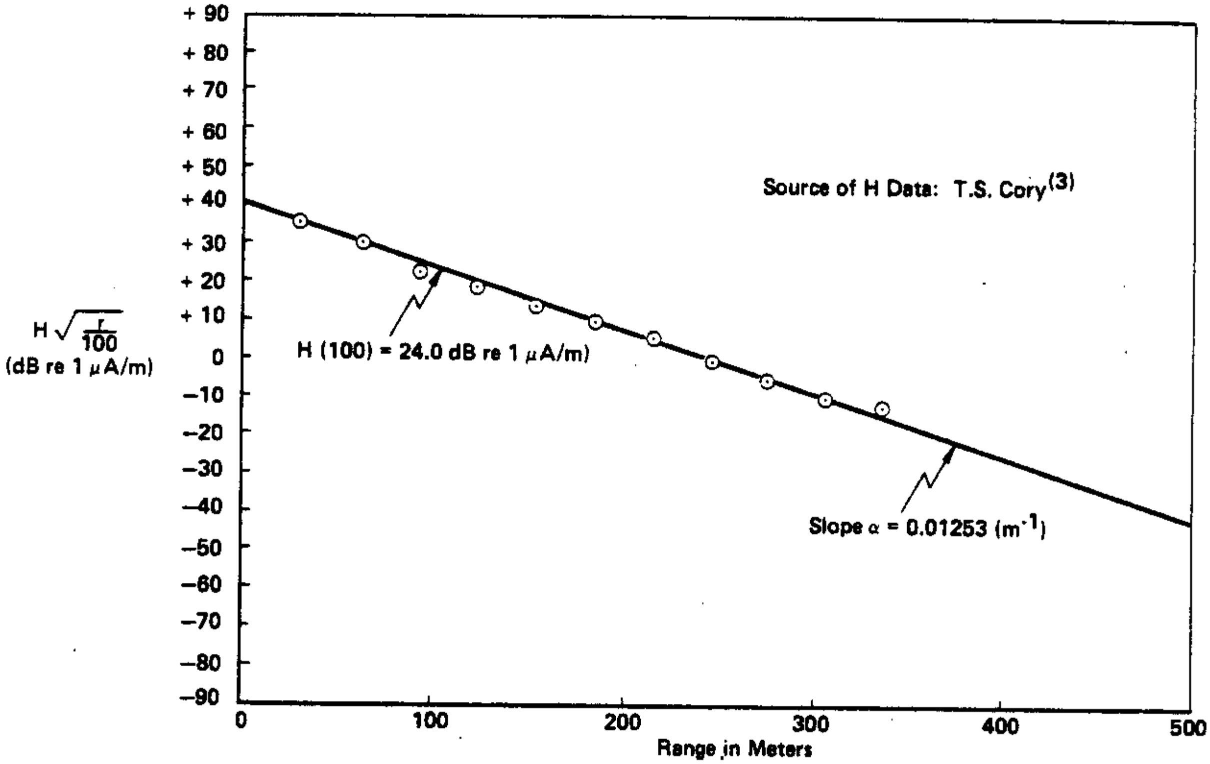


FIGURE 2
PLOT OF α VERSUS f BEHAVIOR
ROBINSON RUN COAL MINE

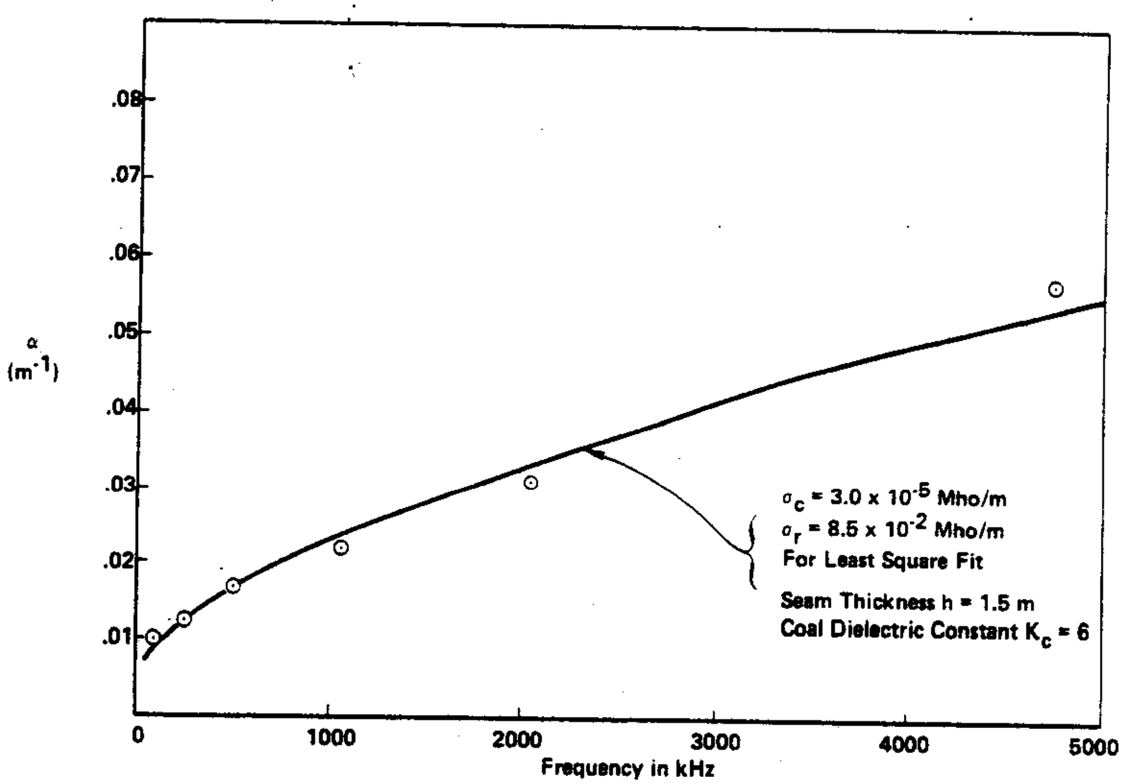
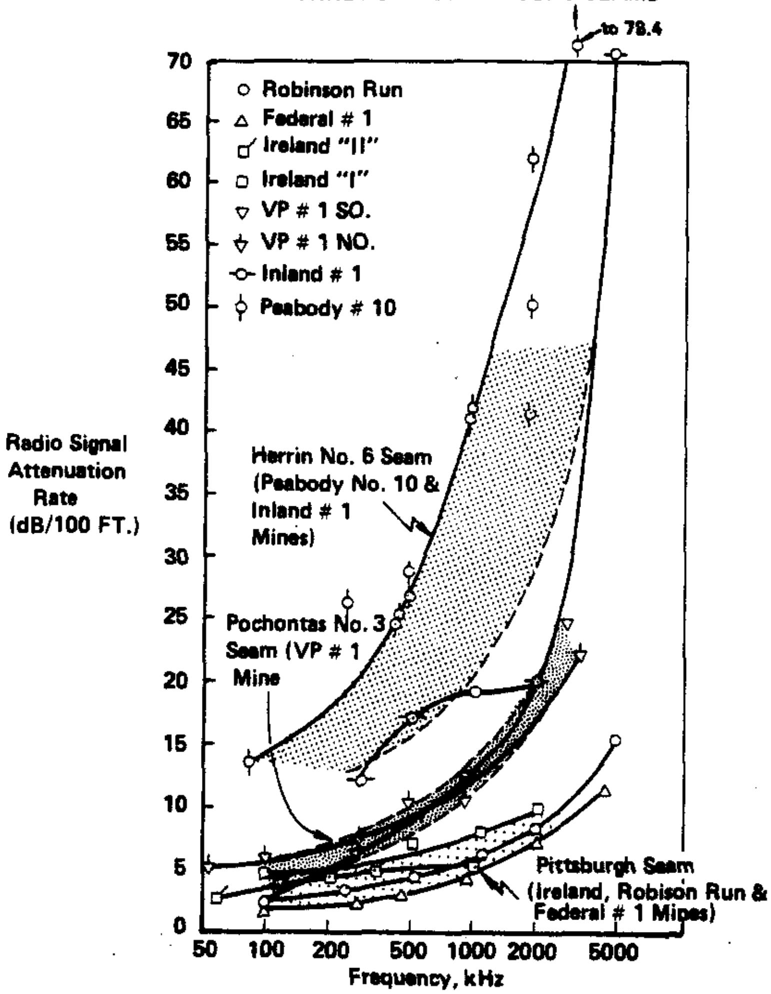


FIGURE 3
COMPOSITE PLOT OF SIGNAL ATTENUATION RATES IN dB/100 FT. FOR SIX MINES IN THREE DIFFERENT COAL SEAMS



COMPARISON OF CALCULATED AND EXPERIMENTAL VALUES OF THE MAGNETIC FIELD

From the values of σ_c and σ_r, we can determine α and β from (11) and (12) and then calculate $|H|$ versus r from (10) for each frequency. The results are shown in Figure 4 for the Robinson Run mine. The experimental curves are given in Figure 5. It is seen that the pattern of the intersecting experimental curves is well accounted for by the theory, although the theoretical values are in general somewhat too high.

The theoretical and experimental values have also been compared on a statistical basis to determine the goodness of fit between the simple three-layer theoretical model predicted results and the measured data. The ratio Δ = H (Theoretical)/H(Experimental) expressed in dB was analyzed statistically as a result of trends shown by plots of Δ versus frequency, at the standard range of 100 meters, for data taken from each of the mines. The Δ plots showed a small and relatively uniform disagreement, mainly on the high side, between about 100 and 1000 kHz, and progressively increasing disagreement, again on the high side, below 100 kHz and above 1000 kHz. The data at the higher frequencies also demonstrated considerable scatter relative to the predicted results.

TABLE I

CONDUCTIVITIES DERIVED FROM THE α VERSUS f PLOTS

Coal Mine	h (m)	K_c	σ_{coal} (Mho/m)	σ_{rock} (Mho/m)	Coal Seam
Robinson Run	1.5	6	0.3×10^{-4}	0.085	Pittsburgh
Federal No. 1	2	6	0.26×10^{-4}	0.084	Pittsburgh
Ireland "II"	2	6	1.0×10^{-4}	0.054	Pittsburgh
Ireland "I"	2	6	2.0×10^{-4}	1.09	Pittsburgh
			1.4×10^{-4}	0.3	Pittsburgh
Pocahontas No. 1					
3 South Area Entry A	1.37	6	3×10^{-5}	0.01	Pocahontas No. 3
3 South Area Entry B	1.37	6	3×10^{-5}	0.0077	Pocahontas No. 3
2 North No. 1 (Plow Area)	1.19	6	6×10^{-5}	0.017	Pocahontas No. 3
Inland No. 1	3	6	1.0×10^{-3}	0.22	Herrin No. 6
Peabody No. 10					
1 Main South 1st West 2nd North	2	6	4×10^{-3}	0.3	Herrin No. 6
1 South 5-1/2 East/ 1 South Jct.	2	6	2.5×10^{-3}	0.3	Herrin No. 6

The statistical analysis of Δ was restricted to data for the frequencies between 100 kHz and 1000 kHz at the reference distance of 100 meters. For frequencies outside the 100 to 1000 kHz range, the Δ plots indicated that the applicability of the simple three-layer model was breaking down. One hundred meters was chosen as the reference distance because it allowed most of the data from six mines in both low and high loss coal seams to be included, while avoiding near field effects in most cases. The ratio Δ in dB between theory and data in the 100 to 1000 kHz band was analyzed by:

- Computing the Sample Mean $\overline{\Delta} = \frac{\Sigma\Delta}{n}$ for each seam and the variance of Δ for the total sample population as a function of frequency (there were too few samples within each seam to compute a standard deviation on a seam basis).

- Computing the Sample Grand Mean for all mines in all three seams, and 95% Confidence Intervals for both the population and Sample Grand Mean as a function of frequency. These results are plotted in Figure 6.

- Testing the hypothesis that the theoretical model fits the data at the 95% confidence level for the frequencies between 100 kHz and 1000 kHz.

FIGURE 4

THEORETICAL CURVES OF H_ϕ VERSUS r WITH FREQUENCY AS A PARAMETER BASED ON σ_c AND σ_r DERIVED FROM DATA ROBINSON RUN MINE

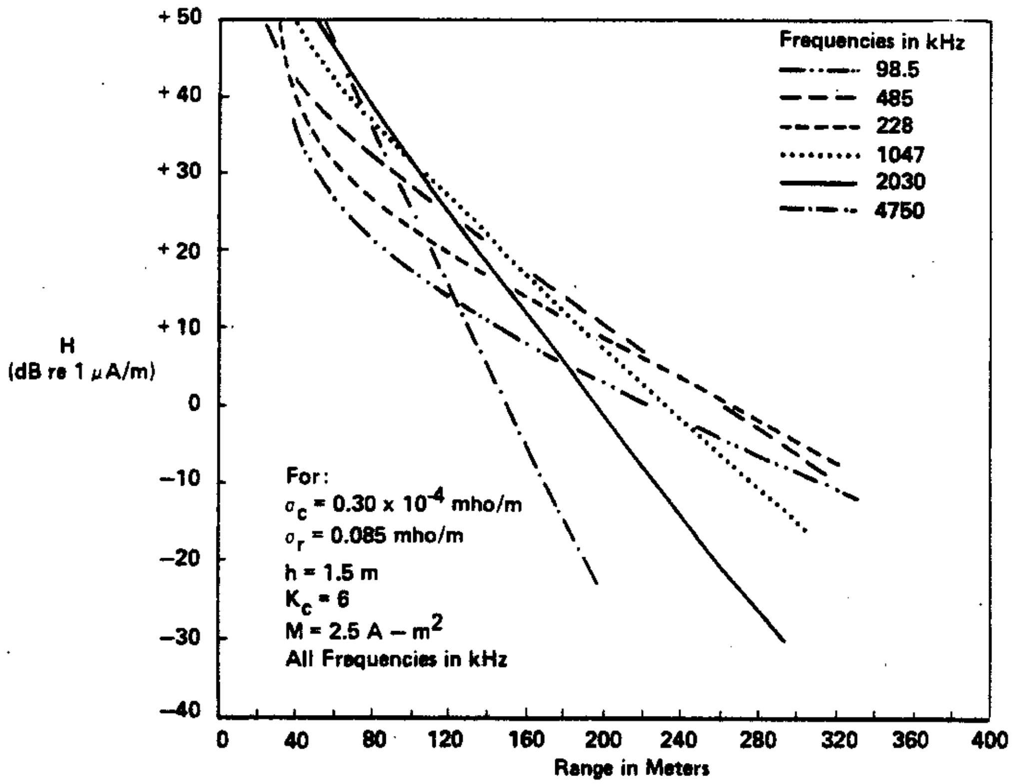
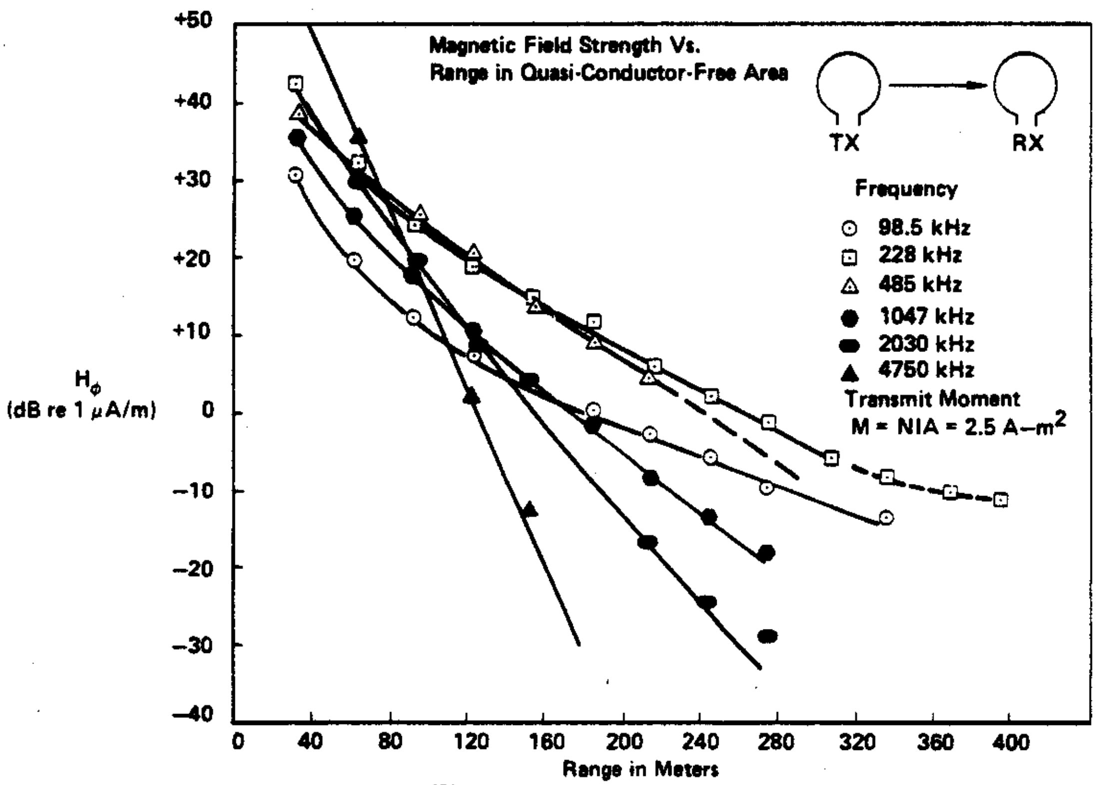


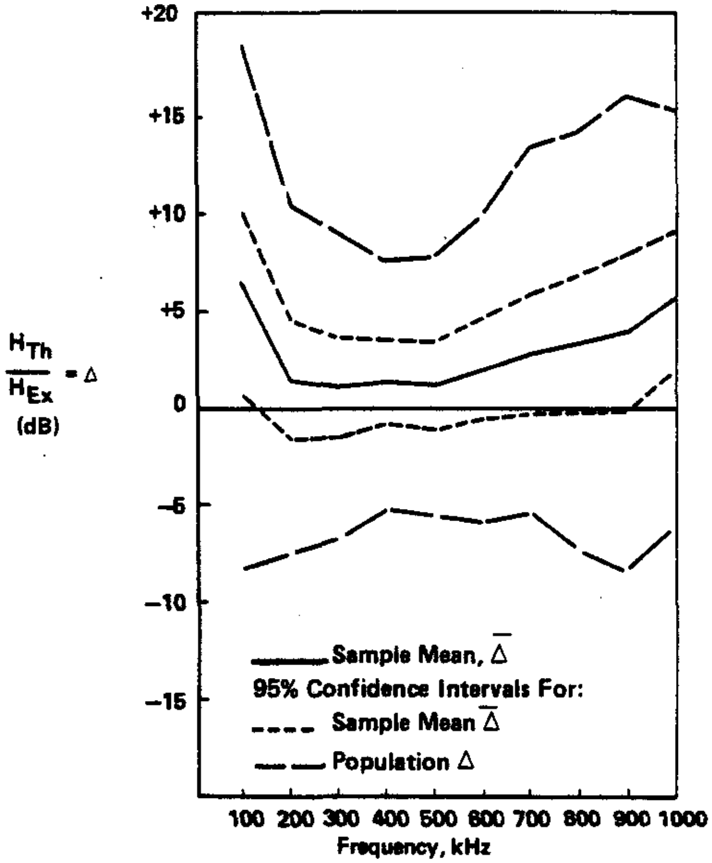
FIGURE 5

EXPERIMENTAL H VERSUS r DATA ROBINSON RUN MINE



Source: T.S. Cory[3].

FIGURE 6
STATISTICAL SUMMARY OF
H (THEORY)/H(EXPER) RATIOS IN dB



From this analysis, the following observations and conclusions were made. The differences between the model and the experimental data were similar for all coal seams. The shapes of the curves for each seam average followed the same pattern and did not differ from one another by more than 1 or 2 dB, with the exception of the Herring #6 seam at frequencies below 400 kHz. (At these frequencies, data for only one mine in the Herring #6 seam was available.) This homogeneity implies that pooling all the data to compute a Grand Sample Mean for all mines is a valid technique, and that the results from any analysis can be applied back to all the mines uniformly.

The plot of the sample $\bar{\Delta}$ and its 95% Confidence Intervals in Figure 6 is a visual hypothesis test (t-test) that the model fits the experimental data, against the alternative hypothesis that the model does not fit the data. The analysis showed that between the frequencies of 200 kHz to 900 kHz, there is *no significant* difference between the model and the actual data. In this band of frequencies the average ratio, Δ, ranges from 1.1 dB to 3.9 dB. The range from 200 kHz to 600 kHz appears to be the best range for the model; both the variance and average Δ between the model and actual data being smallest, and positive, within this frequency range.

CONCLUSIONS

Based on the physical and statistical analyses applied to the data available to date, it can be concluded that:

- MF band radio wave attenuation rates experienced in coal mine conductor-free areas are highly dependent on the coal seam in which a mine is located; and that this attenuation rate versus frequency can be determined in a simple way from measurements of H vs r.

- The simple three-layer model fits the experimental data in the 200 kHz to 900 kHz frequency band at the 100 meter reference distance, with the best agreement occurring between 200 and 600 kHz. This is the band that also promises to provide the most favorable performance for portable radio communications in coal mines.[1,4]

- The Sample Grand Mean, $\bar{\Delta}$, of the ratio H(T)/H(E) expressed in dB may be used to represent the Means for individual coal seams.

- Practical MF system performance estimates may be made in the 200 to 900 kHz band by applying the simple three-layer model to seams in which the attenuation rates have been measured, and using the appropriate $\bar{\Delta}$ to correct the predicted field values.

A more comprehensive theoretical development, analysis of data, and presentation of results can be found in reference 5. Data to date have come primarily from high-coal seams. Data from four additional mines in low-coal seams will be analyzed in the near future to assess the applicability of the model in thinner coal seams, and as a more rigorous test of the theory.

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2. P.R. Bannister, "Approximate Results for the Mutual Electromagnetic Coupling of Loops over a Homogeneous Ground," Naval Underwater System Center Report #NL-3029, New London Laboratory, 23 November 1970, NTIS No. AD717351.

3. T.S. Cory, "Propagation of EM Signals in Underground Mines," Collins Radio Group, Rockwell International Corporation, Final Report, Bureau of Mines Contract H0366028, April 18, 1977.

4. Lagace, R.L. and Emslie, A.G., "Antenna Technology for Medium Frequency Portable Radio Communication s in Coal Mines," Proceedings of U.S. Bureau of Mines Guided Wave EM Workshop, Session III, March 1978.

5. Lagace, R.L., and Emslie, A.G., "Modelling and Data Analysis of In-Mine Electromagnetic Wave Propagation," Arthur D. Little, Inc., Interim Report, Task Order No. 4, Bureau of Mines Contract No. H0346045, to be published, Spring 1978.

V. A METHOD FOR NONINTRUSIVE, IN-SITU MEASUREMENT OF COAL AND ROCK CONDUCTIVITIES IN A COAL MINE TUNNEL - Working Memorandum, June 1978.

A METHOD FOR NONINTRUSIVE, IN-SITU MEASUREMENT OF COAL AND ROCK CONDUCTIVITIES IN A COAL MINE TUNNEL

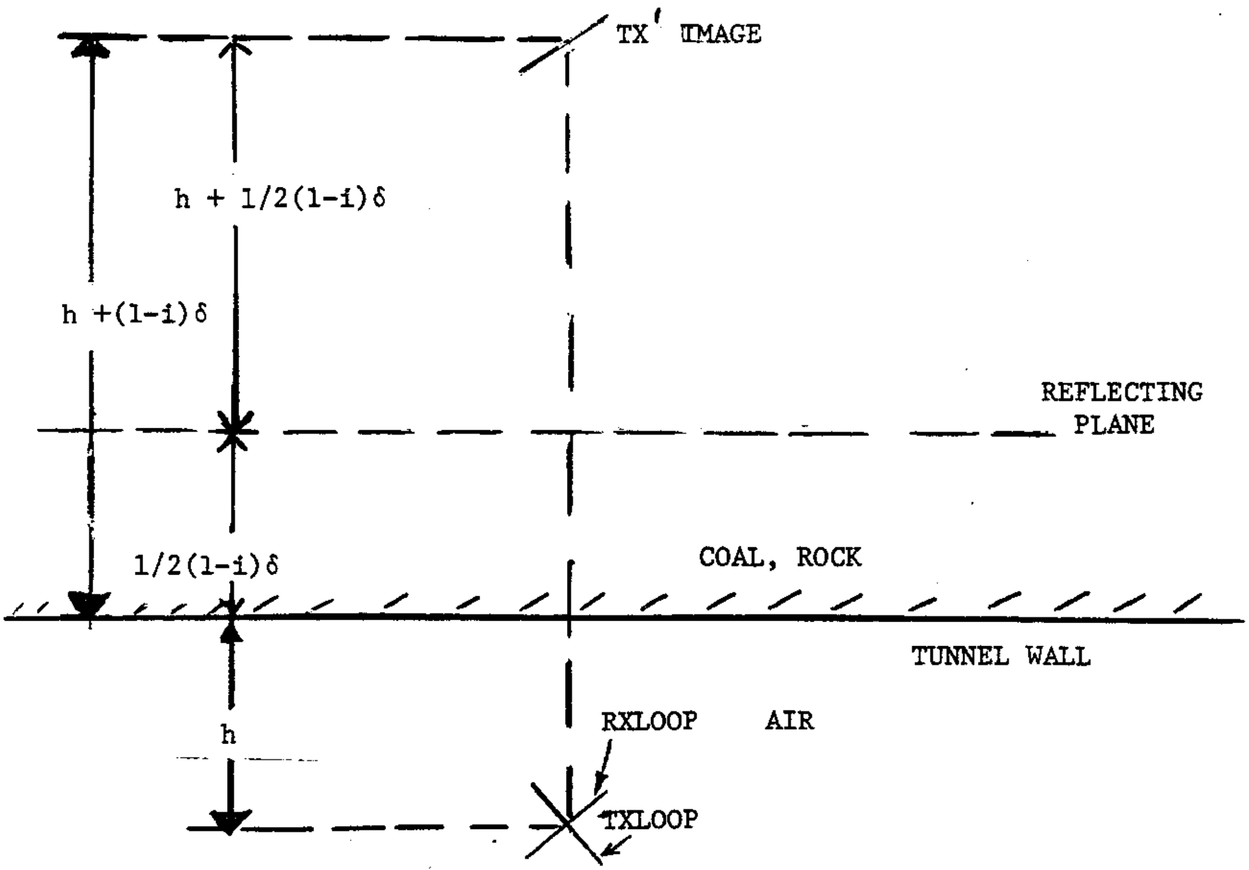
While at the EM Guided Wave Workshop in Boulder, Colorado, a method for in-situ measurement of coal and rock conductivities was conceived. A brief description of it is presented here to encourage comment and discussion.

The method is based on the idea that a crossed pair of noninteracting transmitting and receiving loop antennas will become coupled to each other when placed near a wall of a coal mine tunnel. The arrangement is shown in Figure 1 where the transmitting loop TX, with its center located a distance h from the tunnel wall, produces an image TX' at a (complex) distance $h + (1-i)\delta$ beyond the tunnel wall (according to the image theory of Peter Bannister). The image TX' couples to the RX loop and gives a signal that depends on the skin depth δ, which is related to the conductivity σ of the wall material (coal or rock) by the formula

$$\delta = \frac{1}{(\pi\mu f\sigma)^{1/2}} \tag{1}$$

where f is the frequency, μ is the magnetic permeability of the rock (usually equal to the permeability $\mu_o = 4\pi \times 10^{-7}$ H/m of free space) and σ is the rock or coal conductivity. Eq. (1) is valid when f is chosen so that $\sigma/2\pi f$ is much less than the permittivity ε of the rock or coal.

If the loop dimensions are small compared with δ, the magnetic field component, $H_\perp$, perpendicular to the plane of the receiving loop RX caused by the magnetic moment M of the image TX' (which is equal to the magnetic moment of TX) is given by



NOTE: The Image TX′ of the TX loop couples to the RX LOOP, and produces a signal which depends on the skin-depth δ of the rock or coal.

Figure 1

Crossed TX and RX Loops Near a Tunnel Wall

$$H_{\perp} = \frac{M}{8\pi[2h + (1-i)\delta]^3} \tag{2}$$

This expression is the vector sum of the free space static field components produced by the image loop which replaces the coal or rock medium in this method of analysis.

The magnitude of this field is given by

$$|H_{\perp}| = \frac{M}{8\pi\left[(2h + \delta)^2 + \delta^2\right]^{3/2}} \tag{3}$$

As an example, let $M = 0.1$ A m^2, $h = 0.2$ m, $\delta = 2$ m. Then $|H_{\perp}| = 1.3 \times 10^{-4}$ A/m. Since a field of 0.1 μA/m is easily detected by small receiving loops (supported by MF in-mine measurements of T. Cory) the signal-to-noise ratio should present no problem.

It is possible, if the phase of the RX signal, relative to the TX current is measured as well as the amplitude, that the dielectric constant of the rock or coal can be determined in addition to the conductivity. This probably requires some amplification of the simple image theory used above.

For sampling the tunnel side wall conductivity, this method is still plagued by the conflicting goals of wanting to sample deep within the coal pillar from outside it, while not sampling the nearby roof and floor material. Low interference from the roof and floor is achieved when the skin depth, δ, in the coal is small compared to the seam thickness. But then the method unfortunately samples only the near-in coal material which may be non-representative if it has dried out somewhat and lost moisture after the mining has advanced significantly beyond this location. Sampling in the immediate face area may help to avoid this dried-out wall problem. When the skin depth is large, leading to deep penetration, the effects of the roof and floor are introduced, and this "local" in-situ measurement starts to resemble more and more the propagation measurement technique that uses widely separated, independent transmit and receive loops.

For sampling the roof and floor conductivity, the mine tunnel geometry may permit the method to be less influenced by the presence of coal than the sidewall measurements are influenced by the presence of the roof and floor materials. The dried out condition will still be present however, and in addition, the closeness of the roof to the floor may require both floor and roof images to be accounted for.

Even though the above method and other available techniques may be of some merit for measuring the local in-situ values of coal and rock conductivity, the uncertainties and difficulties associated with them lead us to still conclude that a propagation measurement that spans a representative transmission path probably provides the most practical and useful "average" measures of coal and rock conductivity for MF portable radio applications in coal mines. However, we do agree that if meaningful, local, direct in-situ conductivity measurements can be easily and economically made with an available, small hand-held instrument, this too would be a useful but not necessary way for checking the findings to date. We do not believe that a special development effort to create such an instrument is warranted at this time.

VI. MODELLING AND DATA ANALYSIS OF IN-MINE ELECTROMAGNETIC WAVE PROPAGATION FROM 50 to 5000 kHz - Interim Report, December 1979.

MODELING AND DATA ANALYSIS OF
IN-MINE ELECTROMAGNETIC WAVE PROPAGATION
FROM 50 - 5000 kHz

Robert L. Lagace -- Task Leader
Alfred G. Emslie, Michael A. Grossman

INTERIM REPORT
On
Task Order No. 4
Contact No. H0346045

December 1979

C-78453

Arthur D. Little, Inc.
Cambridge, Massachusetts

I. SUMMARY

A. OBJECTIVE

The objective of this work was to formulate simple theoretical models characterizing medium frequency (MF) radio wave propagation in underground room and pillar coal mines for the purpose of predicting maximum communication ranges between portable radios carried by key miners. This objective has been achieved and confirmed experimentally for conductor-free areas of coal mines. In areas where a conductor such as a power cable is present, applicable data must yet be taken before the propagation model for this case can be confirmed.

This interim memorandum compares some theoretical results with experimental measurements made by T. Cory in a large number of mines located in various coal seams, and summarizes the findings and their implications for portable radio communications between roving miners.

B. PROPAGATION IN CONDUCTOR-FREE AREAS

A three-layer propagation model with a transmission line formulation for the propagation constant was developed that is both practical and sufficiently accurate for the application and frequency band of interest. General analyses of radio wave propagation within multi-layer stratified media can be found in the work of Wait and Gabillard. For the low, medium, and high frequencies of present interest (50 to 5000 kHz), the mode of propagation takes the form of a parallel plane (0,0) TEM transmission-line type mode with the electric field vertical and the magnetic field horizontal within a planar coal seam bounded above and below by higher conductivity rock as shown in Figure 1. Higher modes at these frequencies are well beyond cutoff since the wavelength is much larger than the thickness of the coal seam. Coupling to this TEM mode is accomplished with loops, the antennas most favorable for this frequency band and application.

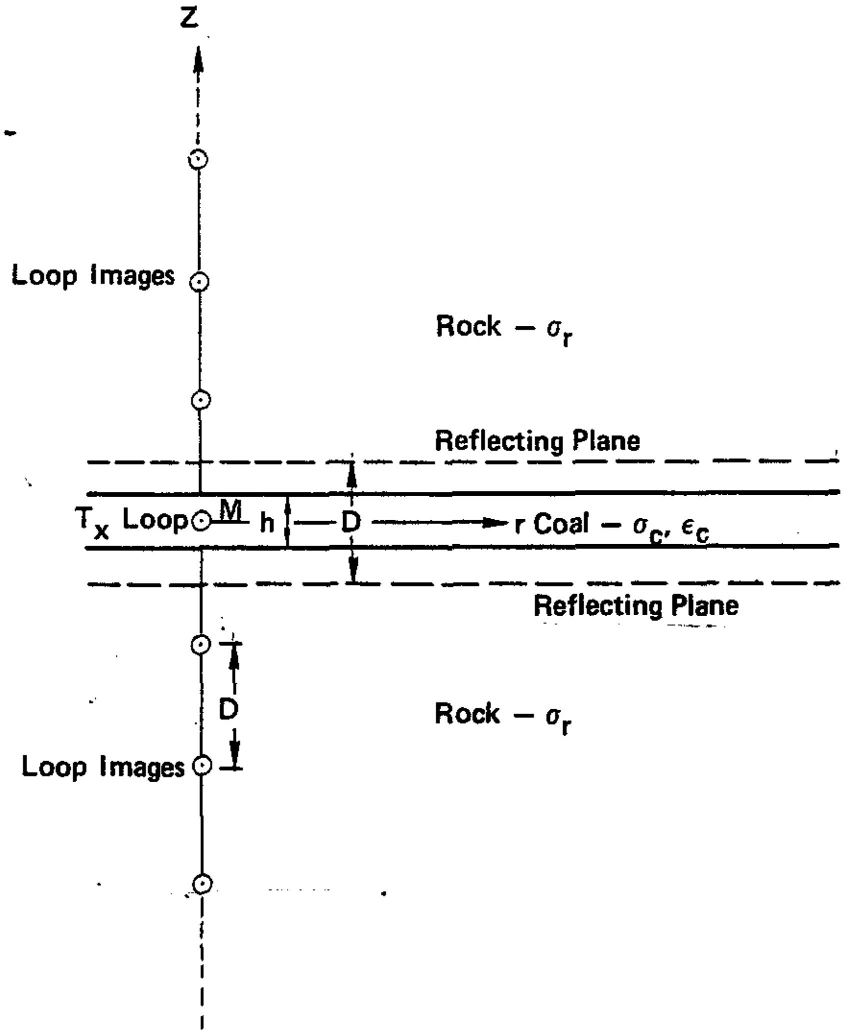


FIGURE 1 THEORETICAL MODEL FOR A LOOP ANTENNA TRANSMITTING IN A COAL SEAM WAVEGUIDE

Comparison of theory and experiment for conductor-free areas allows one to determine the electrical conductivity both of the coal seam and of the bounding rock. The comparison also establishes the validity of the theoretical formulas for the coupling of the transmit loop to the propagating mode and for the mode attenuation rate as a function of frequency. These simple formulas allow predictions to be made of radio communication range under various conditions of operating frequency, transmit magnetic moment, mine radio noise, seam thickness, and coal and rock conductivities.

The results show that significant variations in attenuation rate occur between mines located in different coal seams. Of the seams examined, the Pittsburgh seam measured in northern West Virginia has the most favorable attenuation rate, the Herrin No. 6 seam in Illinois is the worst with an attenuation rate an order of magnitude higher than that of the Pittsburgh, while the other five seams measured in the Appalachian coal fields have moderate to high rates that fall between those of the Pittsburgh and the Herrin No. 6.

Maximum radio communication range behavior versus frequency is shown to exhibit a broad peak centered between 300 and 700 kHz, a band well within the 200 to 1000 kHz frequency band over which the model is in extremely good agreement with the data. Within the optimum frequency band of 300 to 700 kHz, maximum ranges are found to be highly dependent on attenuation rate and thus on the electrical conductivities of the coal seam and its surrounding rock. Consequently, maximum communication ranges for portable, intrinisically safe radios can be expected to vary from low values of about 75 to 100 meters in a high-loss seam such as the Herrin No. 6, to high values of about 300 to 400 meters in a low-loss seam such as the Pittsburgh.

C. PROPAGATION IN THE PRESENCE OF A CONDUCTING CABLE

The above remarks apply to conductor-free areas in coal mines. When a conductor, such as a power cable, is present in a coal mine tunnel, a different type of propagation mode exists which is essentially a coaxial TEM transmission line mode with the cable acting as the center conductor and the coal and rock as the outer conductor. The electric and magnetic fields are approximately transverse to the cable and fall off exponentially with distance in the transverse plane. A properly oriented transmitting loop antenna, located not too far from the cable, can couple to this cable mode. The wave so generated travels along the cable with low attenuation, and can be picked up by a similarly oriented receiving loop which is also located not too far from the cable, thereby greatly extending portable radio communication range along the cable. A simple theory for this type of transmission is given, and is compared with some measurements made by T. Cory in coal mine areas containing conductors. There are discrepancies between theory and experiment, especially with regard to antenna orientation. More experimental data taken under carefully controlled conditions are needed to help resolve these discrepancies.

II. PROPAGATION IN CONDUCTOR-FREE AREAS

A. REDUCTION OF THE EXPERIMENTAL DATA

The asymptotic form of the theoretical equation for the magnitude of the azimuthal component of the magnetic field H_ϕ in the plane of the transmitting loop is given by

$$H_\phi \approx C \frac{e^{-\alpha r}}{\sqrt{r}} \qquad (1)$$

where C is the coupling factor, and α is the attenuation constant. This simple asymptotic form of the field propagation equation gives a good approximation to the magnetic field for ranges greater than $1/\alpha$.

The theoretical equation (1) predicts that if measurements of the magnetic field at various ranges from the transmitting loop are plotted in the form $H\sqrt{r}$ (in dB re $1\mu A/m^{1/2}$) versus r, a straight line should be obtained. The data at 485 kHz for a quasi-conductor-free area in the Stinson No. 3 coal mine, shown in Figure 2, conform fairly well to the prediction. The straight line drawn through the experimental points gives the values $\alpha_{exp} = 0.0381\ m^{-1}$ and $C_{exp} = 57.0$ dB re $1\mu A/m^{1/2}$, derived from the slope and vertical intercept of the line respectively.

It is to be noted that the first and last experimental points are above the straight line. This effect occurs repeatedly in the data from different mines at various frequencies. The explanation is that the first point is usually at a range where the asympototic form of the Hankel function is not a good approximation, and the last point is at a range where the noise level adds significantly to the received signal. For example, in the case of Figure 2, the first data point is taken at 20 m, which is within the distance defined by $1/\alpha_{exp} = 26$m.

In some mines, several points were found to lie above the straight line at ranges greater than about 100 meters. In these cases we concluded that the transmit antenna was also coupling to a low attenuation rate cable-guided mode supported by a cable located in an adjacent parallel tunnel.

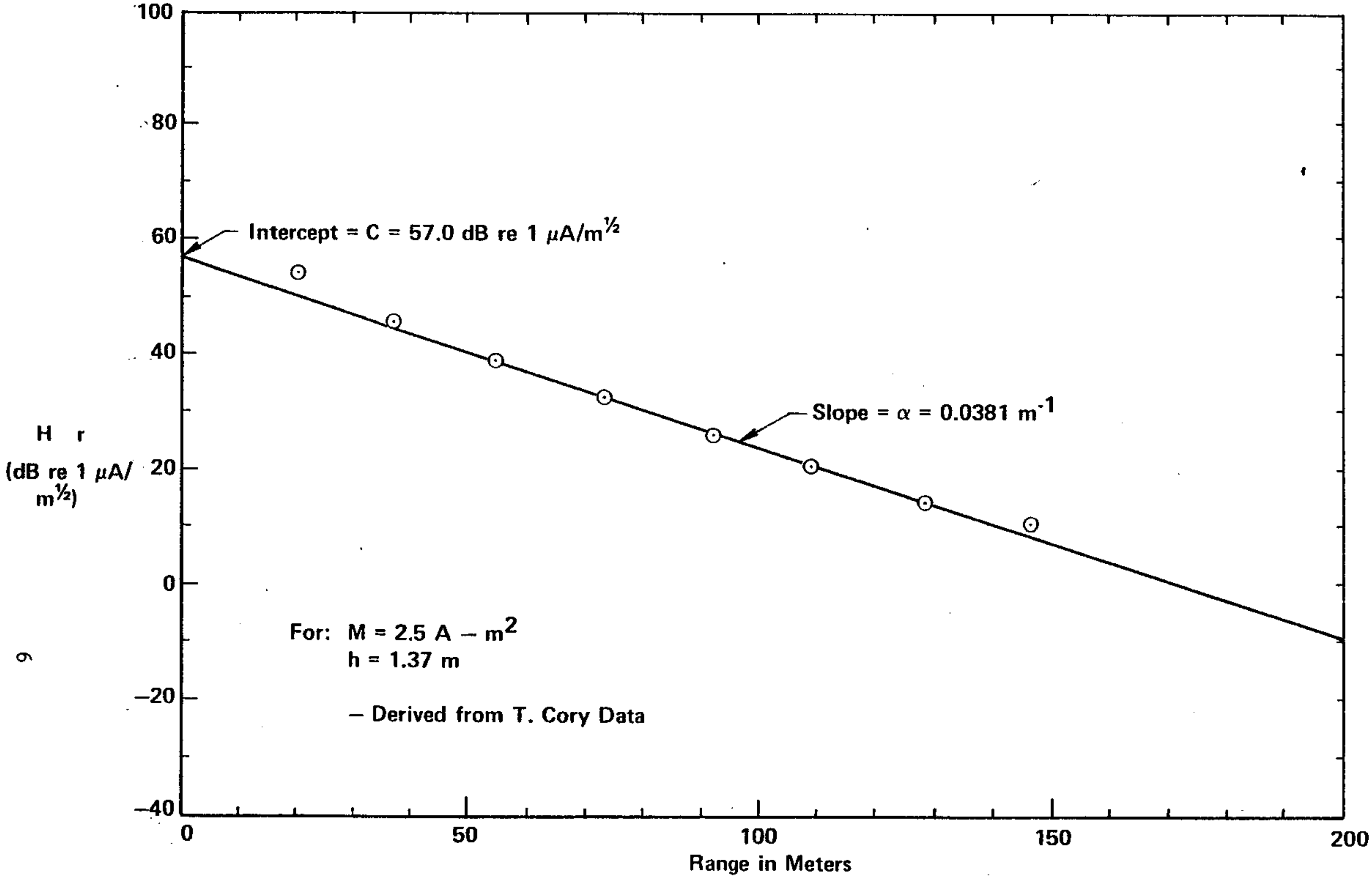


FIGURE 2 DETERMINATION OF ATTENUATION RATE α AND COUPLING FACTOR C FROM STRAIGHT LINE FIT TO $H\sqrt{r}$ DATA PLOTTED VERSUS r FOR STINSON NO. 3 MINE AT 485 kHz

The two derived experimental parameters α_{exp} and C_{exp}, namely, the attenuation constant and the coupling factor, completely specify the field strength data taken along a traverse of a coal mine tunnel at a given frequency. The set of values of α_{exp} and C_{exp} for all the frequencies investigated represents a complete description of all the data taken in a particular tunnel. The conductor-free area data taken in all mines were reduced in this manner.

B. ATTENUATION RATE VERSUS FREQUENCY

Experimentally derived attenuation rates α_{exp} plotted as a function of frequency are shown in Figure 3 for eleven coal mines located in seven seams in the Appalachian and Illinois coal fields. Examination of Figure 3 reveals that the attenuation rates increase with increasing frequency as expected from theory, and that the mines sampled fall roughly into three classes with respect to attenuation rate--low, very high, and moderate-to-high. The mines sampled in the Pittsburgh seam in northern West Virginia exhibit the lowest attenuation rates recorded. On the other hand, mines sampled in the Herrin No. 6 seam in southern Illinois exhibit prohibitively high attenuation rates from a radio communication standpoint. The attenuation rates of the mines sampled in the remaining five seams in Pennsylvania, West Virginia, Virginia, and Kentucky fall into a rather broad moderate-to-high category characterized by values which approach those of the Pittsburgh seam at low frequencies and those of the Herrin No. 6 seam at high frequencies. Unfortunately, it appears that the low Pittsburgh seam rates, which result in the longest communication ranges, may be the exception rather than the rule. The reason for this is not yet clear.

C. DETERMINATION OF THE CONDUCTIVITIES

Each α_{exp} versus f curve contains enough information for the determination of the conductivities σ_c and σ_r by means of the transmission line formula. This is best accomplished by means of a least square fit of the real part, α_{theor}, of the right-hand side of the transmission line formula to the experimental values α_{exp} for the set of frequencies used, with σ_c and σ_r treated as adjustable parameters. In this procedure a constant average value $\varepsilon_c/\varepsilon_o = 6$ is assumed for the

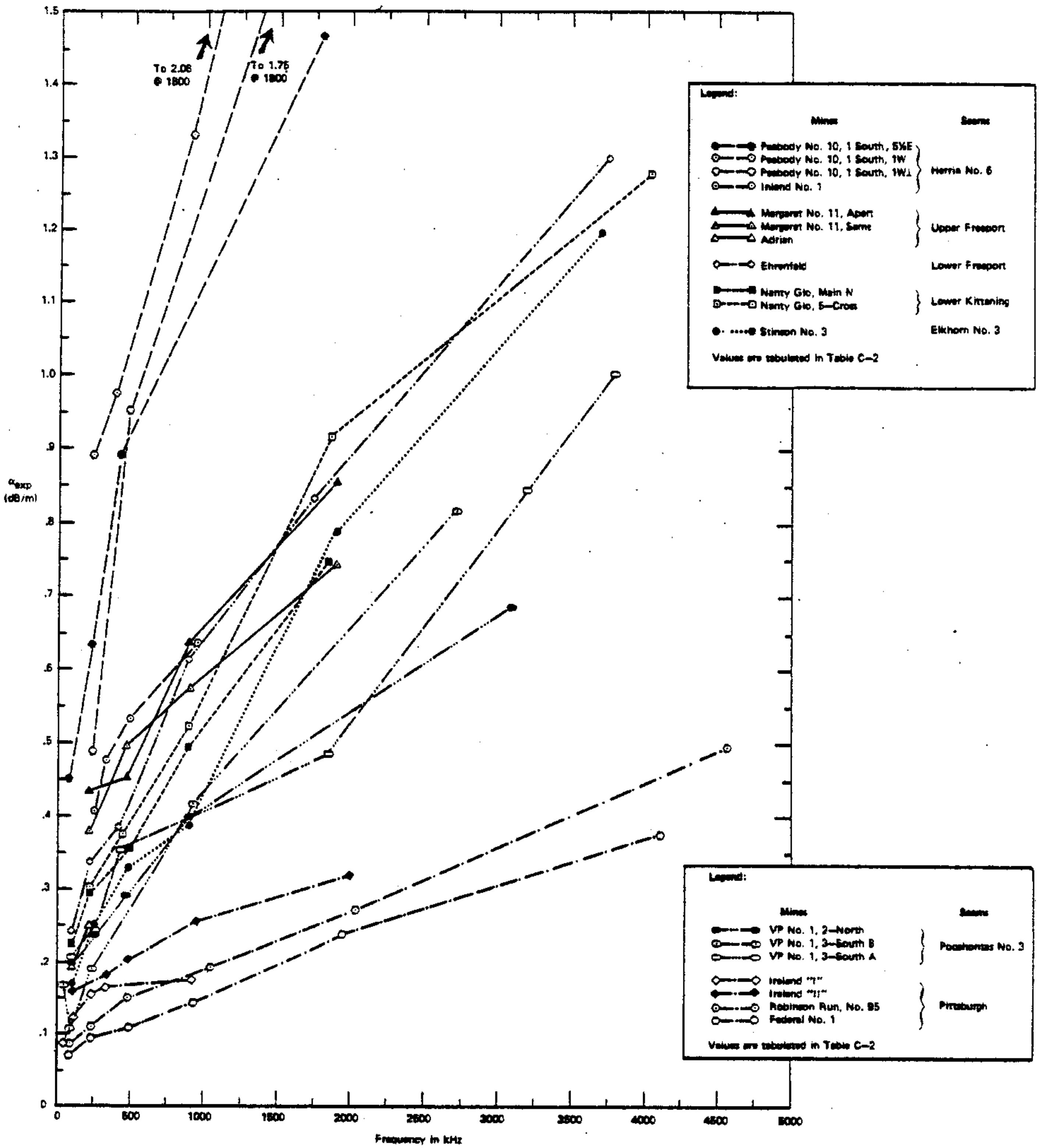


FIGURE 3 EXPERIMENTAL ATTENUATION RATES α_{exp} VERSUS FREQUENCY FOR ELEVEN COAL MINES IN SEVEN COAL SEAMS

dielectric constant of the coal, since α_{theor} is found to be very insensitive to $\varepsilon_c/\varepsilon_o$. The thickness h is taken to be the actual measured value of coal-seam thickness.

Figure 4 shows a comparison of the least square fit curve α_{theor} with the experimental values α_{exp} for the Stinson No. 3 mine. The optimum fit occurs for $\sigma_c = 3.0 \times 10^{-5}$ Mho/m. The root mean square difference between α_{theor} and α_{exp} is $(\Delta\alpha)_{rms} = 0.0013\ m^{-1}$ which is about 2% of the value of α_{theor} at 890 kHz. This close fit gives further justification for the use of the simple transmission-line equation and for the three-layer model on which the equation is based. The good fit also means that experimental determination of α at a number of frequencies can be viewed as an excellent nonintrusive method for obtaining the conductivities of both the coal and the rock. Figure 5 shows a plot of σ_c versus σ_r where each test location in each mine is characterized by its pair of σ_c, σ_r values for all mines sampled. Figure 5 shows that there is a rough correlation between σ_c and σ_r and that σ_r/σ_c is about 100 on the average. The tendency of the two conductivities to vary together may be caused by a correlation in the water contents of the coal and adjacent rock layers. Decreases in mode attenuation rates occur as the coal and rock conductivity values move downward and to the right respectively in Figure 5. Based on the trends and clusterings shown in Figure 5, the following (σ_c, σ_r) conductivity pairs were chosen to represent low, moderate-to-high, and very high attenuation rate propagation conditions respectively; (2.5×10^{-5}, 8×10^{-2}), (5×10^{-5}, 8×10^{-3}), and (2×10^{-3}, 1) in Mho/m

D. COMPARISON OF THE THEORETICAL AND EXPERIMENTAL COUPLING FACTORS

A comparison of the theoretical coupling factor, C theor with experimental coupling factor C exp provides an absolute test of the theory of the coal-seam mode. Figure 6 shows such a comparison for the Stinson No. 3 mine. It is seen that the agreement is quite good over the whole frequency range of 98 kHz to 3710 kHz.

The agreement between the experimental and theoretical values for the coupling factor was tested for all mines in seven frequency bands ranging from 83 kHz to 4570 kHz. The range of frequencies and number of runs in each of the seven bands is shown in Table I. The coupling factors for all mines were studied simultaneously, the only stratification being

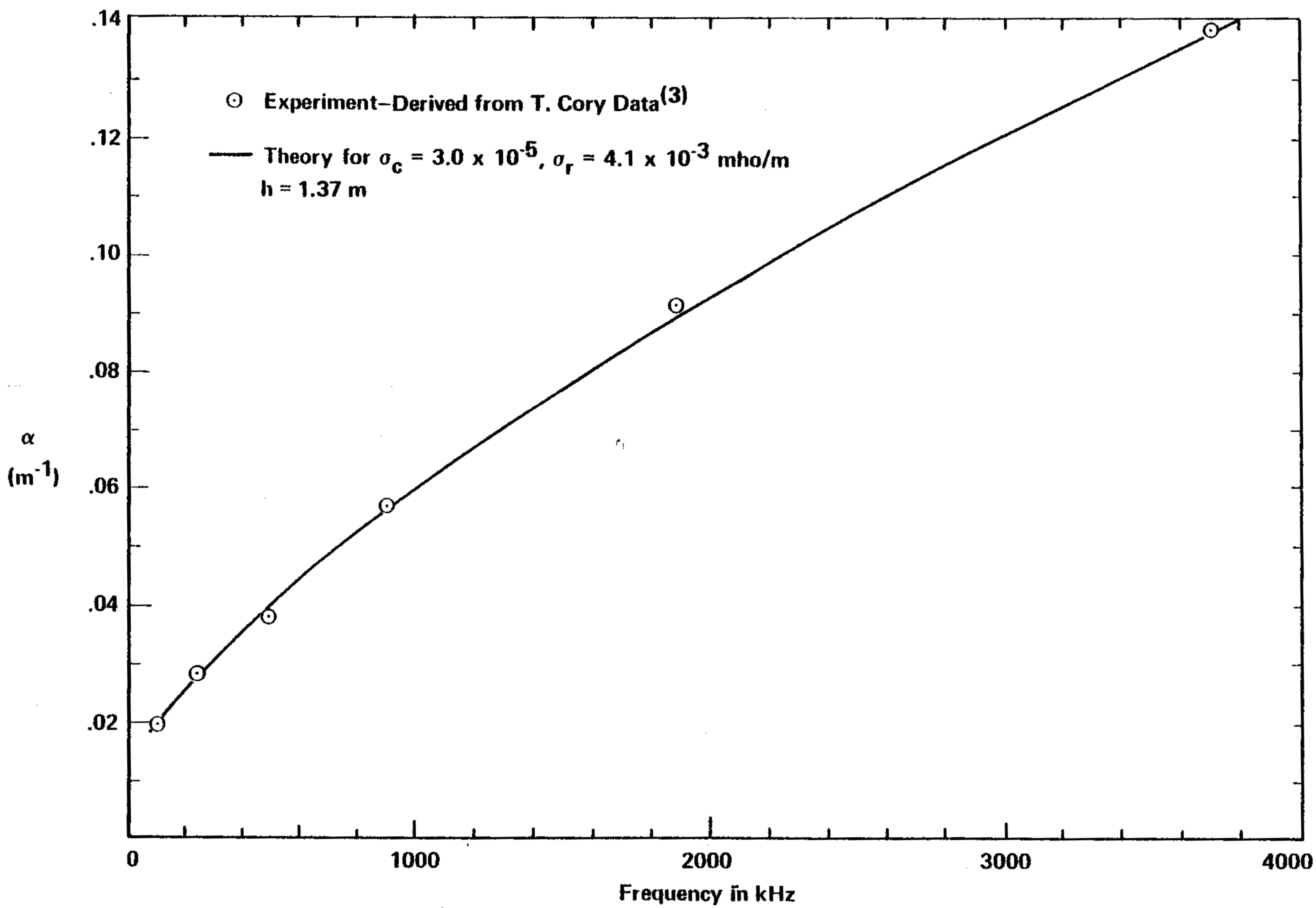


FIGURE 4 LEAST SQUARE FIT α VERSUS f THEORETICAL CURVE TO α DATA FOR STINSON NO. 3 MINE

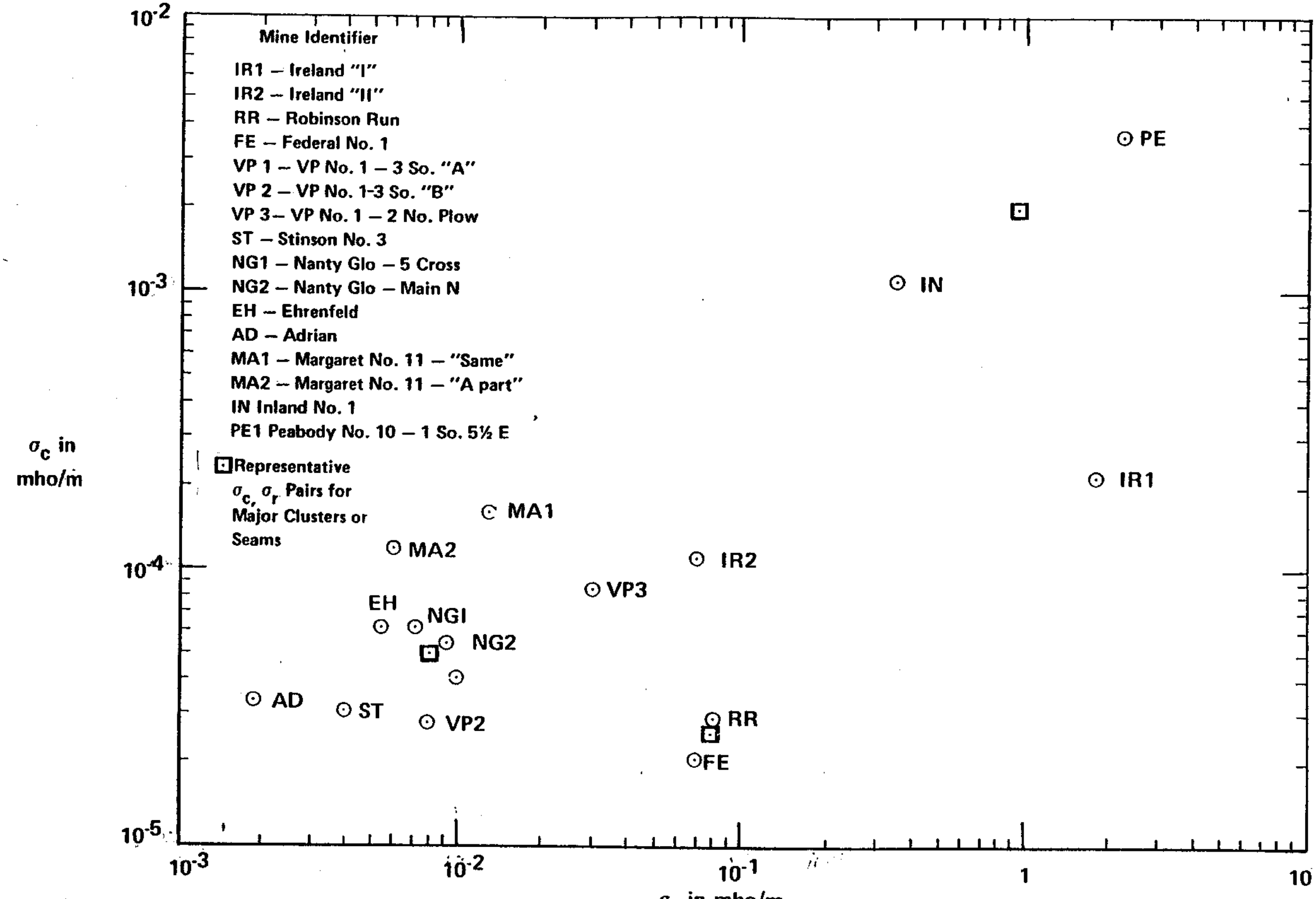


FIGURE 5 COMPOSITE PLOT OF DERIVED CONDUCTIVITY PAIRS (σ_c, σ_r) FOR TEST LOCATIONS IN EACH COAL MINE

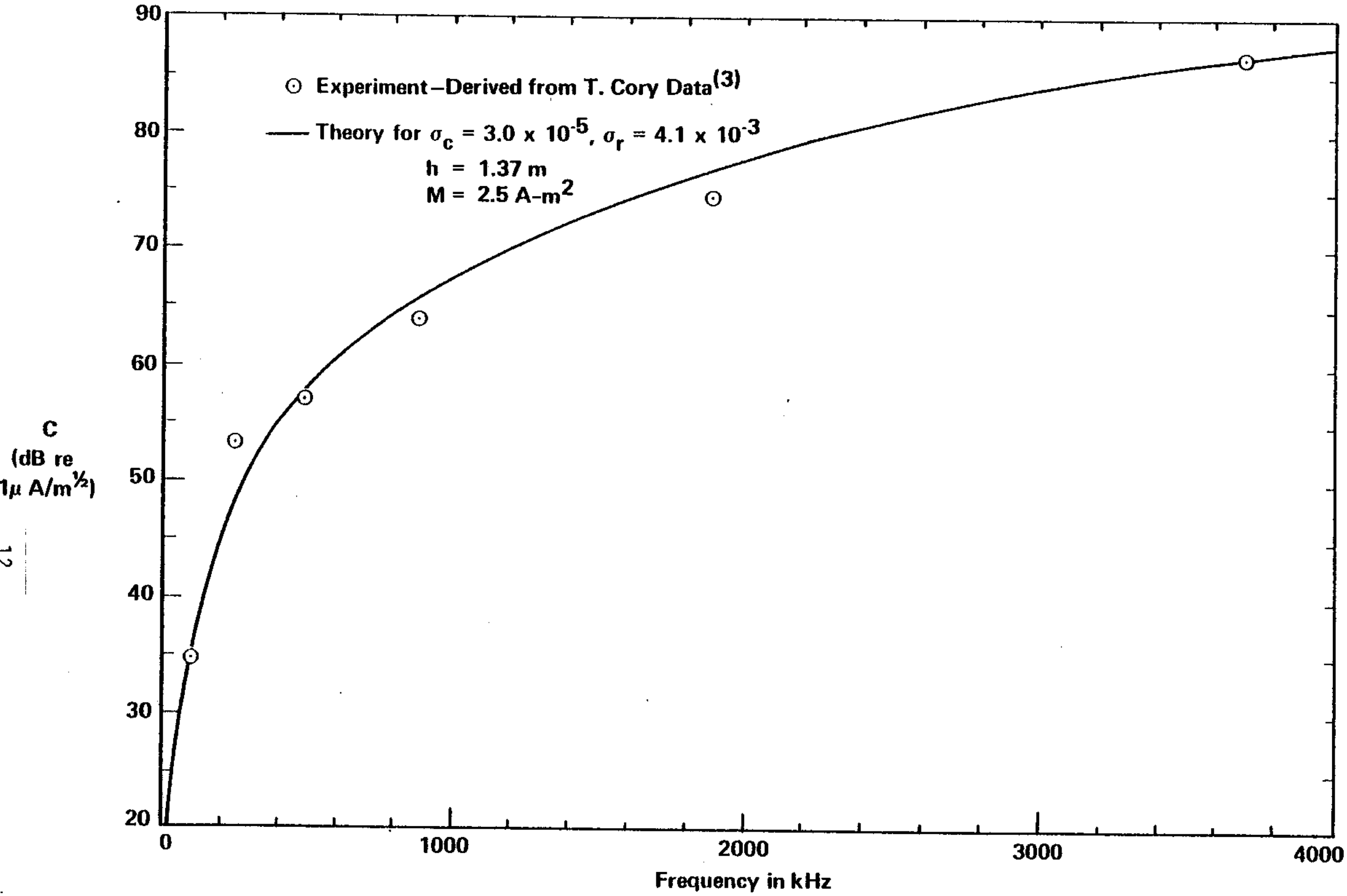


FIGURE 6 COUPLING FACTOR, C, THEORETICAL CURVE AND EXPERIMENTAL DATA VERSUS f FOR STINSON NO. 3 MINE

the seven frequency bands. Therefore, the results of the analysis within each band are applicable to all mines examined.

TABLE I

FREQUENCY RANGES USED FOR EXPERIMENTAL MEASUREMENTS

Band No.	Frequency Range (kHz)	No. of Runs
1	83 - 115	12
2	218 - 252	17
3	335 - 350	4
4	420 - 495	14
5	880 - 1047	15
6	1750 - 2030	13
7	2720 - 4570	12

The difference, $\Delta C = C_{theor} - C_{exp}$, between theoretical and experimental values for the coupling factor expressed in dB was calculated for all available measurements. These differences were then tested statistically using a one-sample t-test for each of the seven frequency bands to assess the goodness of fit of the model to the data. In bands 2 through 5 there is a mean difference of less than +1 dB between the three-layer model and the experimental data, and the variance of the mean is less than 1.3 dB within these bands.

The one-sample t-test used to statistically test the hypothesis that the model fits the data within each frequency band showed that this hypothesis <u>cannot</u> be rejected at the .05 level for bands 2 through 5. (This is equivalent to a 95% confidence interval for the mean $\overline{\Delta C}$ containing the origin, i.e., the mean difference can be zero.) Based on this series of tests, the less than +1 dB mean difference between theoretical and experimental coupling factors and the very small variance of the mean difference, we conclude that the three-layer model fits the data extremely well between the frequency ranges of 218 kHz and 1047 kHz. Outside this range, the model either does not fit the data, or the large variability in the data may be hiding a significant mean difference; i.e., the large positive and negative errors may be fortuitously canceling each other out in band 7.

E. EFFECT OF SEAM THICKNESS ON THE ATTENUATION RATE AND THE COUPLING FACTOR

The attenuation coefficient α and the coupling factor C depend on the seam height h as well as on the conductivities of the coal and rock. Figures 7 and 8 show α versus f and C versus f curves, respectively, calculated from theoretical equations for three values of h, for constant values $\sigma_C = 5 \times 10^{-5}$ Mho/m and $\sigma_r = 8 \times 10^{-3}$ Mho/m of the conductivities. These conductivities are representative of several moderately high loss mines, as seen by the clustering of points around this pair of values in Figure 5.

It is seen in Figure 7 that α, at any given frequency, depends strongly on h. At 2000 kHz, for example, α is about twice as large for a low-coal mine with h = 1 m as for a high-coal mine with h = 3 m. This, by itself, means that the range of communication would be much greater for the high-coal seam.

Figure 8 shows, on the other hand, that C, although greater for a low-coal than for a high-coal mine, changes quite slowly with h. The gain in coupling factor for the low-coal mine, however, by no means offsets the larger loss in signal strength caused by the increase in α . Thus MF radio communication will be more favorable in high-coal than in low-coal seam waveguides having the same electrical properties.

F. MAXIMUM COMMUNICATION RANGE AND OPTIMUM FREQUENCY

The parameter of greatest predictive interest is the maximum theoretical communication range r_m, at a given frequency, determined by the signal propagation loss and the noise level at the receiver. We consider the following two cases:

(1) ~~limitation by set noise, given by the formula~~

$$N = 8 - 20\text{Log}\left(\frac{f}{10}\right) \qquad (16)$$

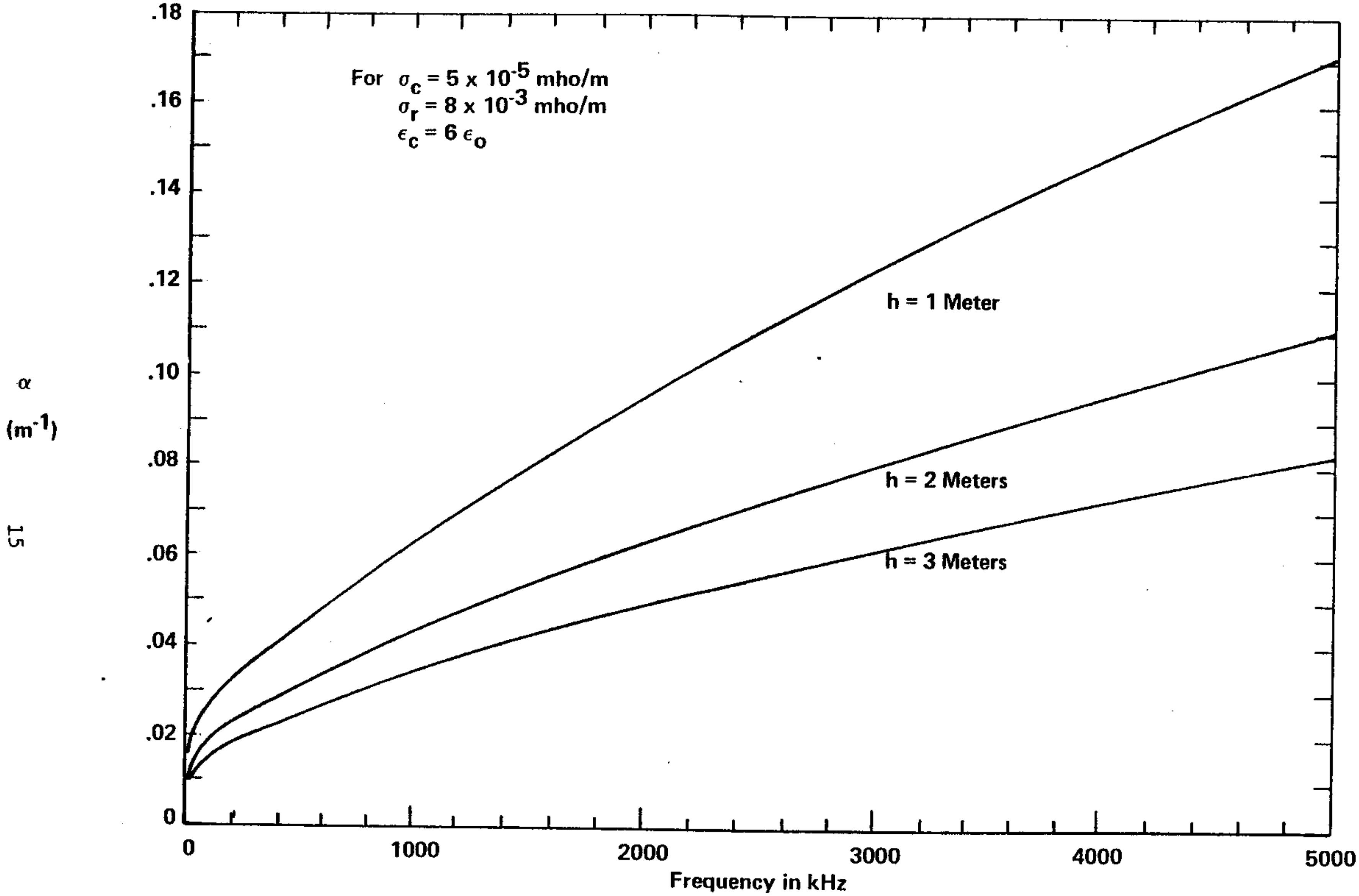


FIGURE 7 THEORETICAL ATTENUATION RATE, α, VERSUS FREQUENCY CURVES WITH SEAM THICKNESS, h, AS A PARAMETER

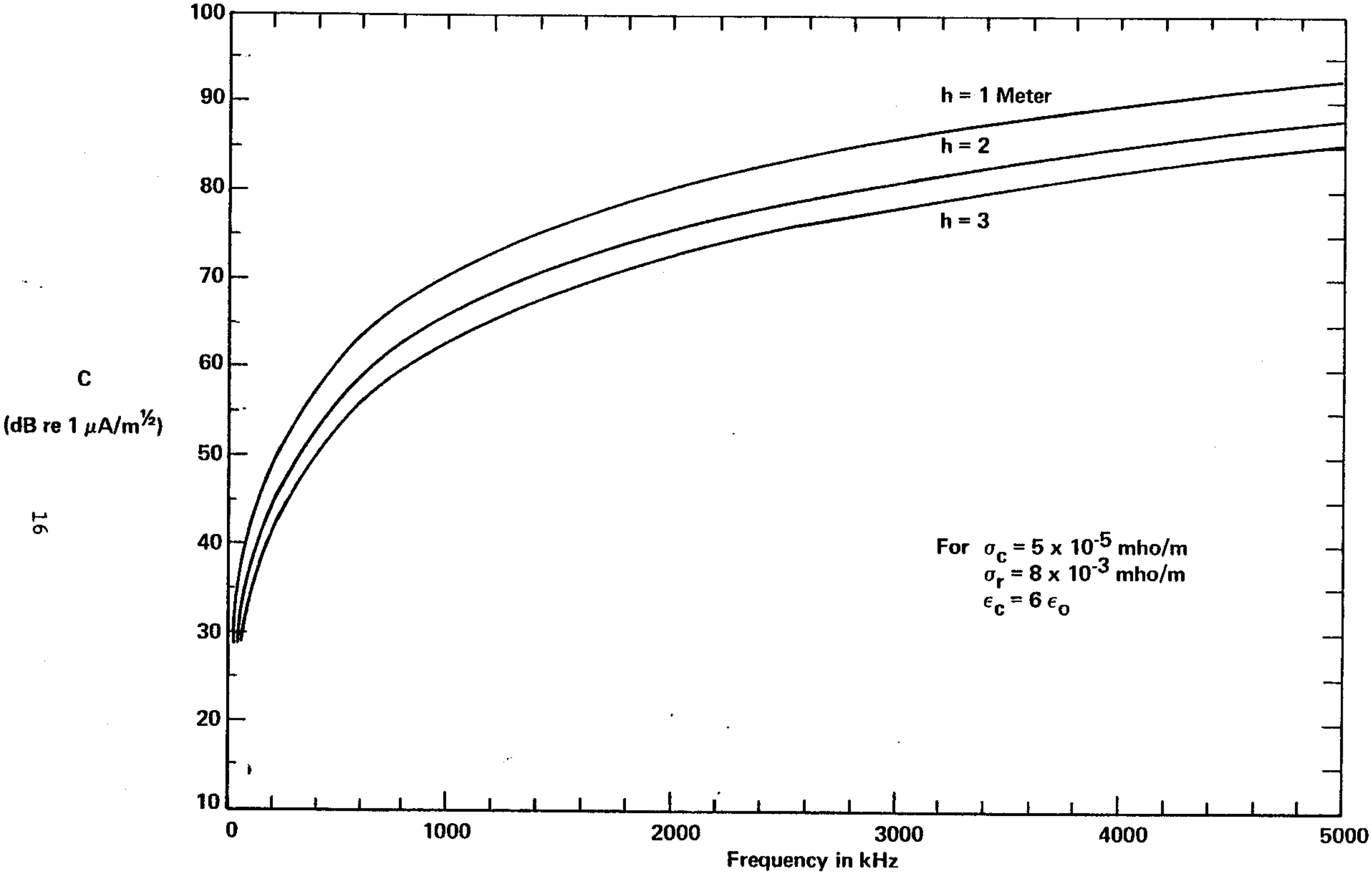


FIGURE 8 THEORETICAL COUPLING FACTOR, C, VERSUS FREQUENCY CURVES WITH SEAM THICKNESS, h, AS A PARAMETER

for the equivalent magnetic field rms noise level N in dB re 1 μA/m, for a receiver having a noise figure of 6 dB, bandwidth of 12 kHz, and loop antenna turns area of 1 m^2. f is the frequency in kHz.

(2) limitation by average mine noise, given by the formula

$$N = 34 - 20\text{Log}(\frac{f}{10}), \text{ for } 10 \text{ kHz} \leq f \leq 1000 \text{ kHz}$$
$$N = -6 - 15\text{Log}(\frac{f}{1000}), \text{ for } 1000 \text{ kHz} \leq f \leq 10{,}000 \text{ kHz} \quad (17)$$

with N representing the "average" rms mine noise level in dB re 1 μA/m. This representation of mine noise level is based on data taken in mines by the National Bureau of Standards and consolidated by Arthur D. Little, Inc.

In each case we define a maximum range as that range where the signal-to-noise ratio decreases to 10 dB. Thus

$$H(r_{max}) = 10 + N \text{ in dB re } 1\ \mu A/m \quad (19)$$

For an FM system, a 10 dB average rms carrier-to-noise ratio gives a Circuit Merit Figure 3 radio service performance level (occasional message repetition required).

Figures 9 and 10 show values of r_{max} versus f for seam heights of 2 m (high coal) and 1 m (low coal), respectively, when performance is limited by receiver noise. The values were calculated for three representative pairs of coal and rock conductivities. These pairs represent the Pittsburgh Seam ($\sigma = 2.5 \times 10^{-5}$, $\sigma_r = 8 \times 10^{-2}$ Mho/m), and the Herrin No. 6 Seam ($\sigma = 2 \times 10^{-3}$, $\sigma_r = 1.0$ Mho/m), which are low- and high-loss extremes, respectively, and a seam of intermediate loss characteristics ($\sigma = 5 \times 10^{-5}$, $\sigma_r = 8 \times 10^{-3}$ Mho/m) like the Pocahontas No. 3 and lower Kittaning seams.

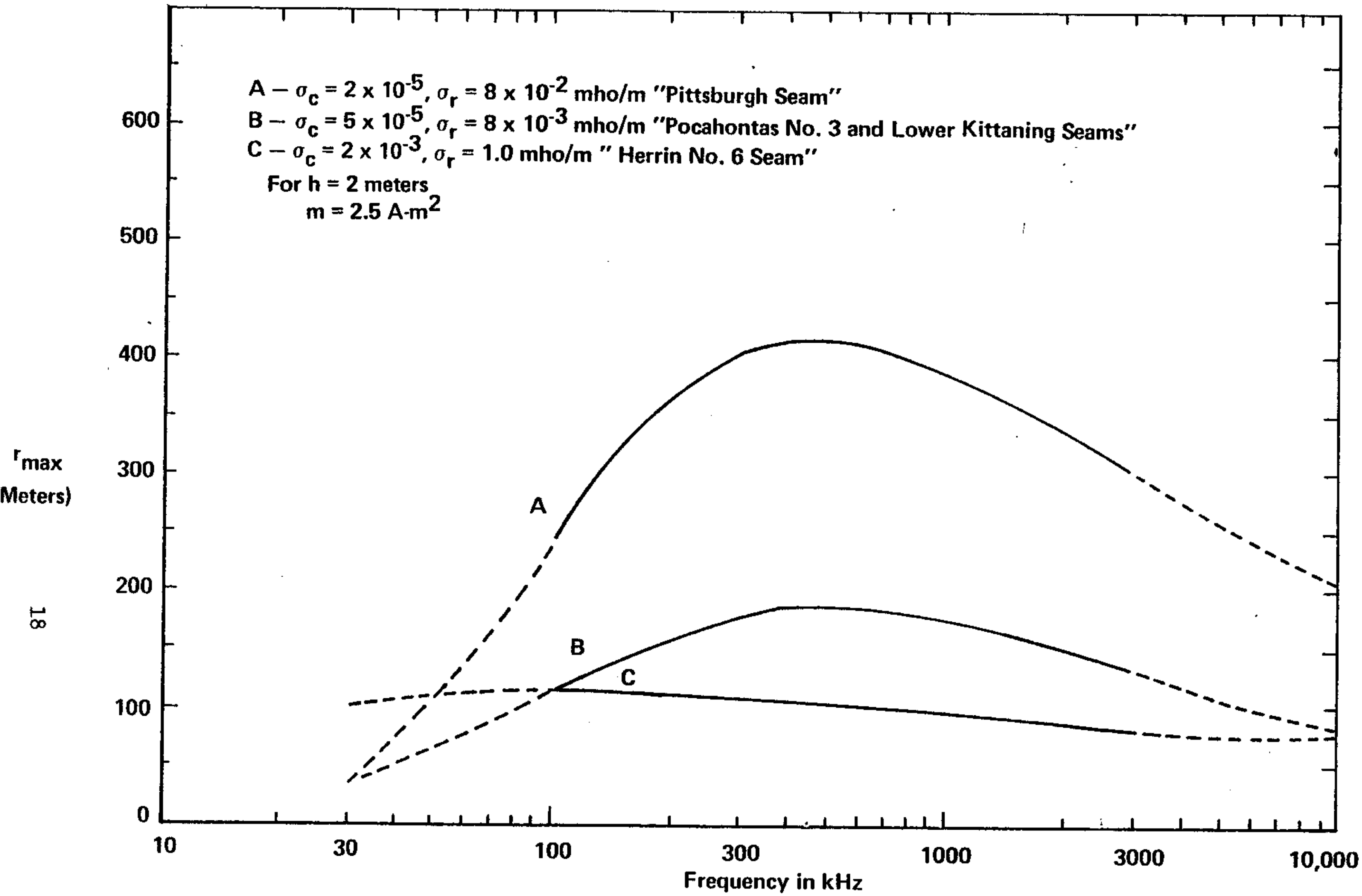


FIGURE 9 THEORETICAL MAXIMUM RANGE ESTIMATES (r_{max}) VERSUS FREQUENCY UNDER RECEIVER NOISE CONDITIONS IN <u>HIGH</u> COAL FOR THREE REPRESENTATIVE SEAMS

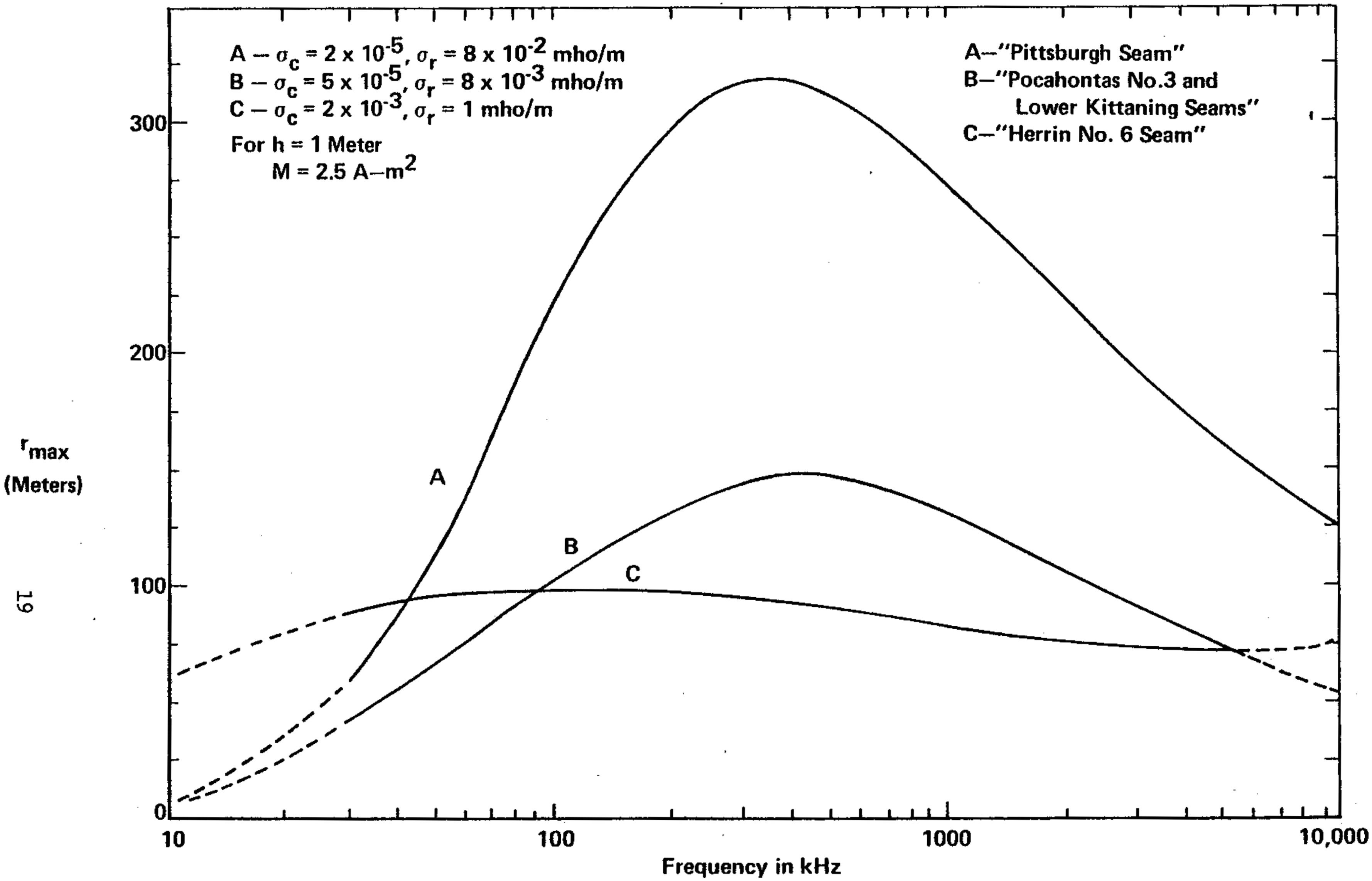


FIGURE 10 THEORETICAL MAXIMUM RANGE ESTIMATES (r_{max}) VERSUS FREQUENCY UNDER RECEIVER NOISE CONDITIONS IN LOW COAL FOR THREE REPRESENTATIVE SEAMS

It is seen that in all six cases r_{max} rises fairly rapidly with frequency to a maximum and then declines more slowly. The figure indicates that a frequency range of 400 to 500 kHz is optimum for the three types of seam taken together. Figures 11 and 12 show values of r_{max} when performance is limited by mine noise in high and low coal respectively. The maximum range is reduced and the optimum frequency range is increased slightly to 600 to 700 kHz.

The values of predicted maximum communications range shown in Figures 9 to 12 are also in good agreement with those derived by T. Cory for specific mines, based on measured values of signal magnetic field strength and independent estimates of receiver noise and mine noise conditions. Figures 9 through 12 taken together, suggest that the optimum frequency for all types of seams, for both kinds of noise, and for both seam heights, is about 500 kHz. It is indeed fortuitous that this frequency lies near the center of the frequency band of 200 - 1000 kHz for which the theory is in best agreement with experiment.

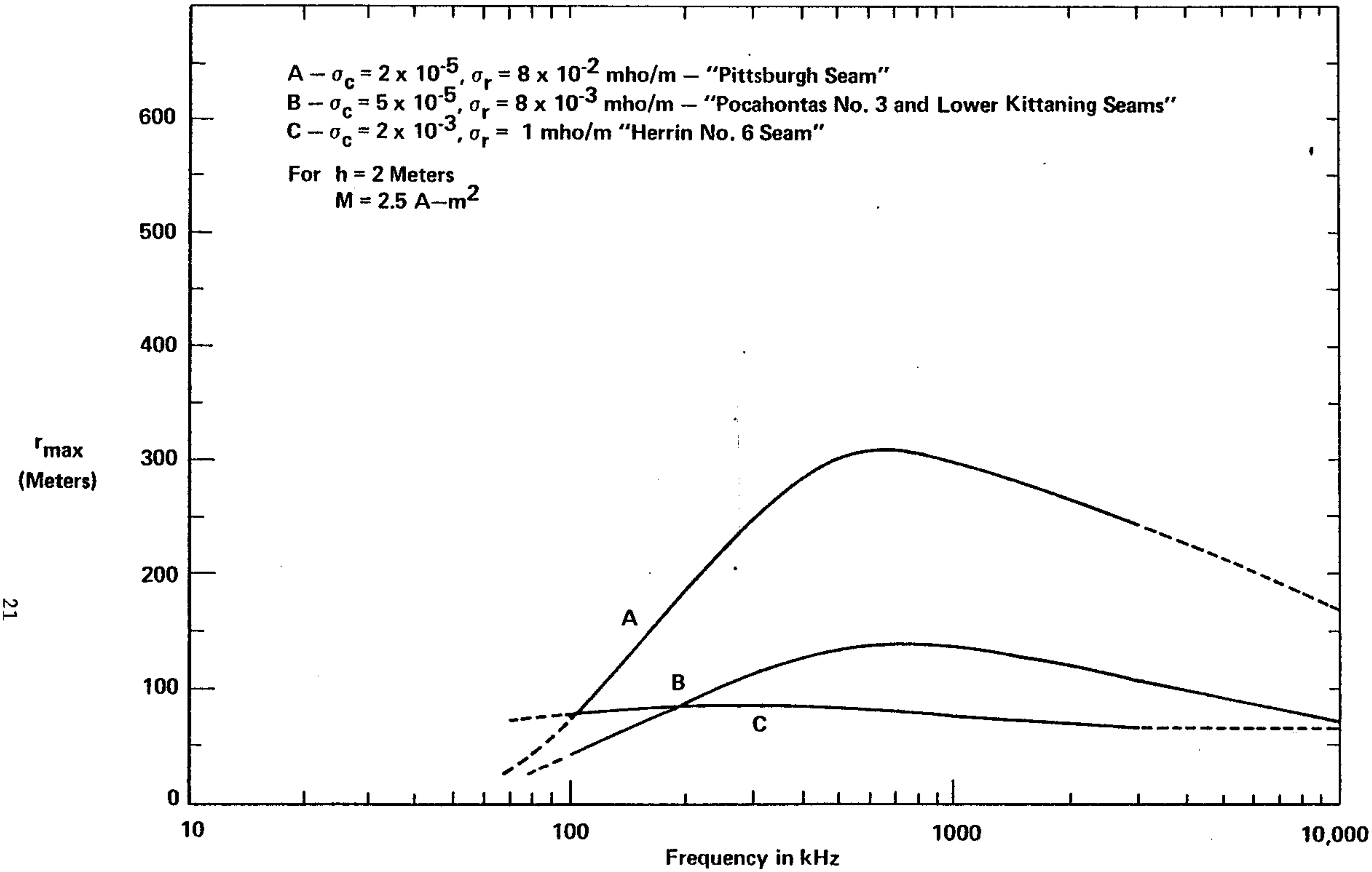


FIGURE 11 THEORETICAL MAXIMUM RANGE ESTIMATES (r_{max}) VERSUS FREQUENCY UNDER "AVERAGE" MINE NOISE CONDITIONS IN HIGH COAL FOR THREE REPRESENTATIVE SEAMS

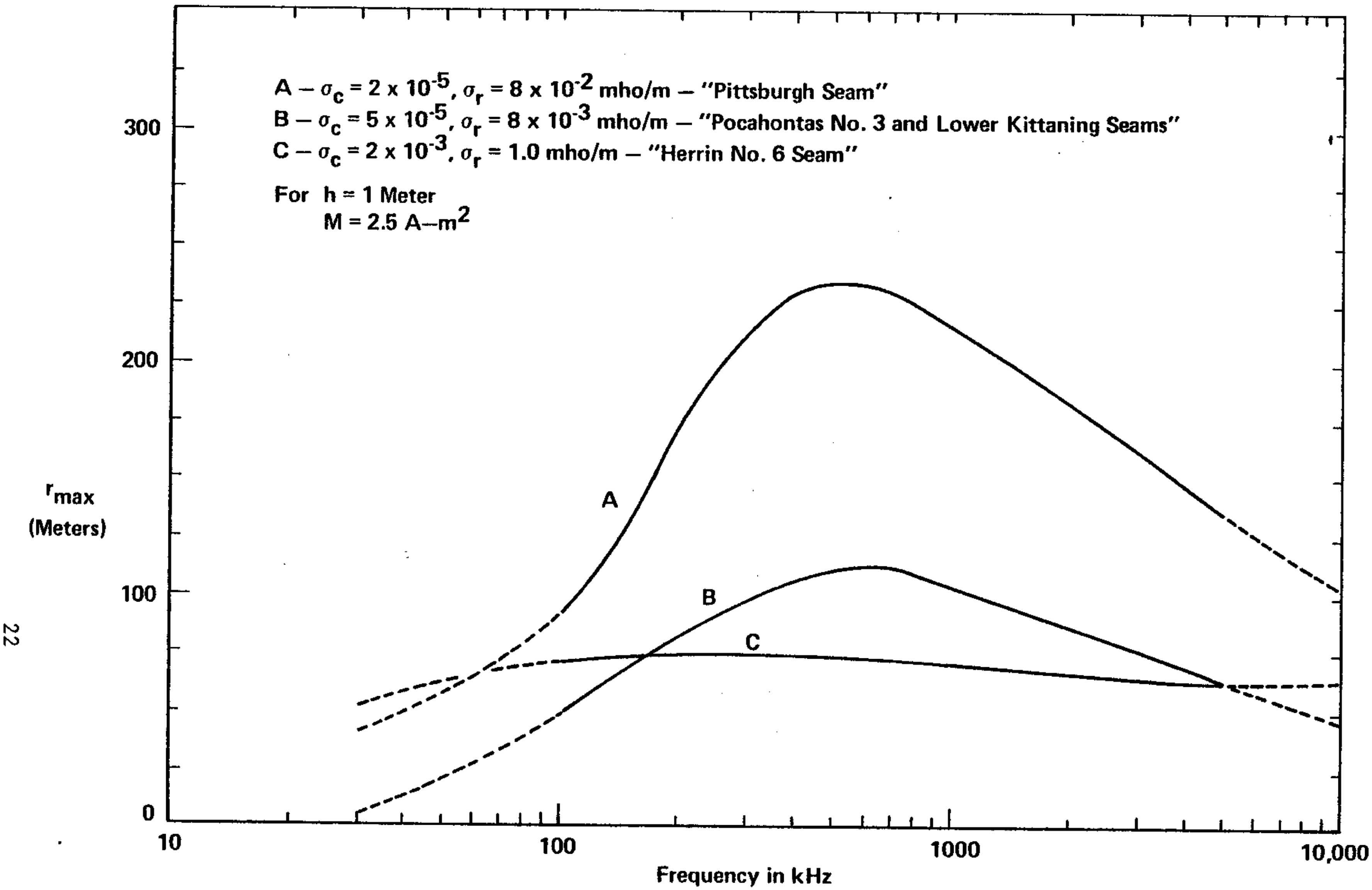


FIGURE 12 THEORETICAL MAXIMUM RANGE ESTIMATES (r_{max}) VERSUS FREQUENCY UNDER "AVERAGE" MINE NOISE CONDITIONS IN LOW COAL FOR THREE REPRESENTATIVE SEAMS

CAMBRIDGE,
MASSACHUSETTS

SAN FRANCISCO
WASHINGTON
ATHENS
BRUSSELS
LONDON
PARIS
RIO DE JANEIRO
TORONTO
WIESBADEN