Communications Research Centre

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IN POTASH TUNNELS AND ITS IMPACT ON RADIO SYSTEMS

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Department of Communications   Ministère des Communications

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Sherman Chow
Communications Research Centre
Department of Communications
Government of Canada

ABSTRACT

This report shows that radio waves at about 900 MHz can propagate in the tunnels of a potash mine with low loss and low multipath distortion. These results were first derived using a theoretical model and were later confirmed by measurements. The attenuation of radio waves per unit distance in a potash tunnel within this frequency band is less than the attenuation in a coaxial cable. This result is important because many commercial systems such as cellular radio, radio LANs and personal communication systems operate in this frequency band and can be adapted to work in a potash mine, replacing the more expensive leaky feeder systems used in other types of underground mines.

EXECUTIVE SUMMARY

Canada is the major supplier to the world of potash, a principal component of many commercial fertilizers. The industry consists of seven mines in Saskatchewan and two in New Brunswick with a total annual revenue of approximately 1.4 billion dollars. The estimated national reserve of potash is over 1000 years. Most of the production is exported thereby providing an important source of revenue to the local and national economies. For all practical purposes, potash mining can be considered to be a unique Canadian enterprise as the scale of domestic operations dwarfs those of the few foreign producers.

Potash mines consist of an interconnected network of straight tunnels at a depth of about 3000 feet. The total length of tunnel system varies from 20 to 40 kms. Currently, there are no means of wireless communications except for some walkie-talkies that might be issued to miners working in the same section of the tunnel. The lack of adequate mine-wide communication underground is recognized as an impediment to improving efficiency and productivity.

This report describes the results obtained in a program to characterize the radio propagation conditions encountered in potash mines. This program is jointly supported by the Communications Research Center of the Department of Communications, Noranda Technology Center and Central Canada Potash Mines (CCP). The mines consider communication systems which would provide voice, data and video to be crucial to their on-going efforts to improve efficiency through automation of the mining process. These services will also enhance worker safety underground. Emphasis was placed on quantifying radio propagation parameters which impact performance of communication systems that would be used to provide these services.

The key result of this work is the identification of a band of frequencies which can support radio communications in potash mines. Radio waves in frequency bands between 800 and 950 Mhz can travel a long distance with low loss and freedom from distortion. This phenomenon is attributed to the dielectric constant of the ore body and applies only to potash.

A radio system called "Distributed Antenna System" (DAS) has been designed based on the results obtained under this program. Tests at CCP have confirmed that the potash mining process can be monitored by video provided that the radio frequency used is confined to the forementioned band. In addition, it has been shown that a standard cellular radio system, whose frequency assignment is in this band, can be deployed to provide mine-wide communications to workers in vehicle and on foot. The DAS system opens up the possibility of monitoring hazardous mining operations by video from a distant point. Reliable voice communication permits workers to be quickly dispatched to problem areas to repair damaged equipment or rescue injured workers.

1.0 INTRODUCTION

This report describes the results of a research program aimed at designing a new radio communication system for potash mines to improve operational efficiency and to enhance worker safety. A potash mine consists of a network of interconnected straight tunnels. The nodes of the communication system in the tunnel structure can be fixed, portable or mobile. The information carried by the radio network can be voice, data or video.

Since it is not necessary to obtain a licence for an underground radio system, the system designer is free to choose whatever frequencies will give the best performance. One prime consideration in the choice of frequencies will certainly be the level of attenuation suffered by a radio wave as it propagates down the tunnel. Other propagation characteristics such as group delay distortion produced by multipath propagation are also important to the performance of radio systems which require a wide bandwidth, such as high speed digital data and video.

During August of 1991, a measurement program was initiated to determine the radio propagation characteristics, including attenuation and group delay distortion, at several different frequencies using the facilities of the Central Canada Potash Mine located in Colonsay, Saskatchewan, Canada . The project was jointly sponsored by the Department of Communications, the Noranda Technology Center and the Central Canada Potash Corporation. This report highlights the important experimental results obtained in the first phase of the program and discusses the implications of these results for designing a radio system for potash mines. More complete results can be found in [1].

2.0 WAVEGUIDE MODEL

The tunnels in a potash mine form a network of long straight segments with nearly constant cross section. It is useful to model each straight section as a wave guide with rough surfaces. This concept has already been applied to coal mines where the attenuation of radio waves is expressed in terms of electrical characteristics such as polarization and frequency as well as characteristics of the tunnel such as cross sectional dimensions, roughness of the walls, dielectric constant of the material and tilt of the tunnel floor [2]. The results obtained using this model for coal mines conformed well with experimental data. Of particular importance in [2] is confirmation that a range of frequencies exists for which the losses are a minimum and is therefore the best choice for radio systems.

Similar techniques to those used in [2] have been applied to estimate propagation losses in potash mine tunnels which are approximately 25 feet wide and 11 feet high. The dielectric constant of potash used in the calculation is 5.03. [3] It is assumed that the total loss comprises three components: losses due to refraction, losses due to the roughness of the walls and losses due to "antenna tilt".

The refraction loss is the normal loss associated with lossy waveguides where a part of the energy of waves incident on the wall is refracted into the wall and absorbed. This component would be present even if the walls were perfectly smooth. Refraction loss calculated using the model for the 25 ft by 11 ft tunnel for both vertical and horizontal polarization is shown in Figure 1. It can be seen that, considering refraction alone, the loss is greater for vertical polarization than for horizontal polarization. This is due to the shape of the tunnel which is about three times wider than its height. The model predicts that the refraction loss for both polarizations increases rapidly for frequencies below about 500

MHz. On the other hand, the refraction loss shows little additional improvement above 800 MHz.

The roughness of the walls affects the attenuation because it diffuses or disperses the transmitted wave as the wave propagates down the tunnel. The roughness loss is dependent upon the average variation of the surface relative to a smooth wall and it increases as the radio wavelength is increased. The roughness is estimated to be 0.5 feet for the tunnels used in the measurement.

"Antenna tilt" is defined as the error caused by misalignment of the transmitter/receiver antennas in the horizontal plane. Such tilt will occur, for example, if the receiving antenna is mounted on a vehicle travelling down a rough roadway in the mine. In this case, the receiving antenna will change in orientation. It is difficult to estimate the actual angle of tilt under the experimental conditions but a tilt of one degree is assumed for the purpose of calculation. The tilt loss is assumed to increase linearly with the radio frequency, and in this paper values from [2] are used.

In Figure 2, the three individual factors making up the loss are calculated and plotted as a function of frequency. The total loss was obtained by summing the three components.

Intersymbol interference refers to a type of distortion which causes some of the energy to be stretched in time or frequency. Delay distortions, for example, may delay some of the energy from one symbol until it falls into the adjacent symbol, changing the value of both. Intersymbol interference can impose a lower limit on the error rate that is achievable because increasing the transmitter power will not be reflected in a corresponding reduction in error rate. The exact effect of such pulse stretching on system performance is dependent upon the type of modulation used, but it is generally accepted that pulse stretching of 10% of a symbol duration should have a minimal negative effect on system performance. The causes of intersymbol interference in this case are identified as coming from two sources, dispersion and multipath propagation.

Dispersion in this paper is defined as pulse stretching due to the characteristics of the tunnel alone. The waveguide model can be used to calculate a "bandwidth" which in turn implies a limit on the bandwidth of the radio signals which can be propagated through the tunnel. Appendix A discusses the dispersion affect in detail and shows that dispersion is less for the higher frequencies than the lower frequencies if the distance between the transmitter and receiver is held constant, and dispersion is greater for a longer path than a short path if the frequency is held constant.

Multipath propagation can be caused by reflections from machinery and vehicles between the transmitter and receiver. It can also be caused by a side tunnel intersecting the main tunnel between transmitter and receiver. These irregularities represent abrupt changes of characteristic impedance of the waveguide thereby causing reflections to occur, which in turn will stretch the received pulse length. It is difficult to predict the extent of the pulse stretching that will be encountered as it is dependent upon the size of the irregularity as well as its location.

3.0 DESCRIPTION OF THE EXPERIMENT

3.1 ATTENUATION MEASUREMENTS

The measurements were made at three frequencies: 150 MHz, 500 MHz and 900 MHz. The reason for selecting these frequencies is that standard commercial equipment is readily available at these frequencies. The antennas used for all measurements were 5 element Yagis, cut to the specific frequencies. During the measurement process it became apparent that the losses at 150 MHz were substantially higher than at the two higher frequencies, and would not be suitable for practical systems. For this reason, propagation at 150 MHz was not examined in the same level of detail as for the higher frequencies.

The transmitting antenna was mounted on a pole about 9.5 ft from the floor of the tunnel and about 1.5 ft below the roof. The receiving antenna was mounted on a jeep at a height of about 5 ft from the floor. A receiver and a portable computer were also carried in the jeep to measure and record the signal strength as the jeep travelled down the tunnel. The distance was obtained from a mechanism fixed to the rear wheel hub of the jeep which recorded the distance travelled and automatically caused a measurement to be made and stored every two centimetres. The experiment was repeated for vertical and horizontal polarizations.

3.2 MULTIPATH AND DISPERSION MEASUREMENTS

The transmitting antenna was fixed on a vertical pole at a height of about 9.5 ft above ground and 1.5 ft below the roof. The transmitter emitted a train of 10 nanosecond pulses at the selected frequency. The pulse repetition period was 260 nanoseconds. The receiver and antenna, carried in a jeep, were driven to various points in the tunnel. The experiment was carried out at 150, 500 and 900 MHz. using both vertical and horizontal polarizations. The amplitude and the shapes of the received pulses were measured and stored in a computer for analysis off-line.

4.0 HIGHLIGHTS OF THE EXPERIMENTAL RESULTS

4.1 ATTENUATION RESULTS

Horizontally polarized waves suffered significantly less attenuation than vertically polarized waves at a given frequency. This was predicated by the model (see Figure 1) and confirmed by the experimental results shown in Table I.

Table I: Losses in Potash Tunnel (db/100 ft)

Frequency	500 MHz	900 MHz
Losses (vertical polarization)	5.6	2.37
Losses (horizontal polarization)	2.59	1.49

The experimentally determined losses are also shown in figure 2. The calculated loss is less than that derived from the measured data at 900 MHz and greater than that which was derived at 500 Mhz. The differences can easily be attributed to the estimated values of roughness and tilt used in the calculation. However, the calculated values should be sufficiently accurate for use in designing radio systems in potash mines.

Figure 3 is a recording made during the experiment showing attenuation as a function of distance, for a frequency of 900 MHz and horizontal polarization. The average loss as a function of distance was calculated by a fitting a straight line through the experimental data. Losses at short ranges are much higher than the average (indicated by the points of the measured data falling below the "average" line). This is attributed to the difference in height of the two antennas causing a large "tilt" loss when the range between the transmitter and receiver is short. The large reduction in signal strength near the 400 meter range occurred when the jeep turned into a side tunnel at an acute angle to the original path.

Some insight into the level of attenuation suffered within a potash tunnel was obtained when two commercial "walkie-talkies" operating at 800 MHz were used successfully over a range of 5750 ft. The output power was nominally two watts. The antenna of one of the walkie-talkies was replaced by a fixed Yagi while the other used the antenna supplied with the unit.

4.2 MULTIPATH AND DISPERSION RESULTS

No multipath propagation was observed when the tunnel was clear of obstructions. Strong and distinct paths were detected when there were vehicles or machinery between the transmitter and the receiver, especially when the transmitter and the receiver were both close to the obstruction. Figure 5 shows the results from one measurement at 900 Mhz where there was a conveyer 45 ft from the transmitter. Three distinct peaks can be seen with a total delay spread of about 30 nanoseconds when the receiver was also close to the obstruction. As the receiver was moved away from the transmitter and obstruction, the distinct paths previously observed were blended together by the dispersion effects. In general, measurements confirmed that dispersion as measured by rise time was greater for 500 MHz than for 900 Mhz, and was greater for longer path than shorter path when the frequency was fixed.

In all cases measured, the time spread due to a combination of the dispersion and multipath was less than 30 nanoseconds. When the tunnel was clear of obstructions, the delay spread, due only to the rise time of the pulse, was significantly less. This implies that most of the delay spread can be attributed to obstructions rather than dispersion and would tend to confirm the prediction based on the model of Appendix A. Further confirmation of the model may be seen if Figure 3, obtained from experiments in a potash mine is compared with Figure 4, showing the results obtained in a copper mine. The recording of signal strength variations in Figure 4 shows two components, one which varies slowly with distance and is attributable to the tilt loss caused by undulation of the mine floor similar to that seen in Figure 3, and a component which fluctuates over distances that are on the order of a half wavelength. The fast fluctuations, typical of multipath fading, are missing in the potash results. The absence of multipath propagation in a potash tunnel is predicted in Appendix A where the ray model is discussed.

5.0 CONCLUSIONS

The results obtained in this experiment indicate that a potash mine represents a benign environment for the propagation of radio waves compared to hardrock mines. Radio waves in the neighbourhood of 900 MHz range suffer little attenuation or multipath distortion. The loss for potash tunnels is measured to be about 1.5 db per 100 feet as compared to a loss for hardrock mines of about 15 db per 100 feet. For this reason, for potash and coal mines, wireless communication systems may offer a less expensive alternative to leaky feeders commonly used in hardrock mines [3]. Delay distortion in the 800-900 Mhz range is principally due to reflections caused by machinery and irregularities in the tunnel between the transmitter and receiver. Total delay distortion observed was always less than 30 nanoseconds. The experimental results indicate that a digital system using a symbol duration of 0.3 microseconds or more, would not be adversely affected by intersymbol interference.

Since most potash mines.have tunnels with similar size and shape, it is likely that the propagation results obtained can be applied to all potash mines. Many common commercial radio systems such as cellular, spread spectrum radio LANs and cordless phones system such as CT2 and CT3 operate in the 800 to 900 MHz frequency range and can be easily adapted for use in this environment [4]. The use of standard technology will greatly reduce cost and simplify maintenance problems of underground systems.

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REFERENCES

[1] Investigation into Distributed Antenna Network for Potash Mine - Interim Report, Central Canada Potash, Noranda Technology Center, October 12,1991.

[2] Alfred E. Emsile, Robert L. Lagace and Peter F. Strong, Theory of the Propagation of UHF Radio Waves in Coal Mine Tunnels, IEEE Transaction on Antennas and Propagation Vol. AP-23, No.2, March 1975,pp 192-205.

[3] Private communications, Dr. G. Herget, Department of Energy Mines and Resources, Government of Canada.

[4] D. R. Martin, Leaky Feeder Communication in Tunnels, Wireless World, July 1982.

[5] David J. Goodman,Trends in Cellular and Cordless Communications, IEEE Communications Magazine, June 1991, pp31-40.

APPENDIX A

In appendix C of [2], it was shown that the propagation phenomena can be explained using a ray method which assumes that the propagation in the tunnel is achieved by two rays, one bouncing from wall to wall and a second ray by bouncing from ceiling to floor. Attenuation of the rays will occur unless the phase shift after two reflections is 360 degrees. This is expressed by the relationship for the two grazing angles:

$$\sin g = L/2W \qquad \text{(A1)}$$

$$\sin k = L/2H \qquad \text{(A2)}$$

where g is the grazing angle the ray makes with the walls and k is the grazing angle at the ceiling and floor. L is the wavelength, W is the width of the tunnel and H the height. Rays which do not satisfy equations A1 and A2 represent higher mode of propagation and will suffer much higher loss as it propagates in the potash tunnel. The walls of the hardrock mines have different dielectric constant from the potash mines, allowing the higher modes to propagate. For this reason, destructive interference due to multipath is more pronounced in a hardrock mine than a potash mine.

The side-to-side rays travel a distance P over tunnel length of M, (see figure A1), where P is expressed as :

$$P = M/\cos g \qquad \text{(A3)}$$

similarly, the ceiling-to-floor ray travels a distance Q over a tunnel length tunnel M, where Q is expressed as :

$$Q= M/\cos k \qquad \text{(A4)}$$

The impulse response u(t) of the tunnel is in the form of two Dirac delta functions $\partial(t)$, T seconds apart:

$$u(t) = E\,\partial(t) + F\,\partial(t+T) \qquad \text{(A5)}$$

$$T = (P-Q)/c \qquad \text{(A6)}$$

where c is the velocity of light and T is related to the wavelength and tunnel parameters by equations A1, A2, A3 and A4. E and F are constants denoting the amplitude of the two Direc delta functions which can be calculated from Fresnel formulas given in [2]. For the parameters of tunnel used in the experiment the amplitude of the two delta functions would was found to have about equal value. The complex frequency response is obtained by applying Fourier transform of the impulse response u(t). The magnitude of the complex frequency response can be written as a periodic function of frequency if E=F is assumed:

$$|U(f)| = |\cos \pi f T/2| \qquad \text{(A7)}$$

Under this assumption, $|U(f)|$ has zeros at frequencies $f = \pm 1/T$, $f= \pm 2/T$,.... If the tunnel can be considered to be a filter, then it is possible to define the half power points of the filter as a bandwidth, which in this case occurs between $f = \pm 1/2T$. Since the value of T is a function of the wavelength L and the distance M, the bandwidth and hence the rise time will also be a function of both M and L.

Table A1 indicates the bandwidth of the half power points (1/T) for three values of tunnel length M and two frequencies.

If E is significantly different from F then |U(f)| will not have zeros at the selected frequencies but will approach some finite minimum value |E-F|. Consequently the depth of the fade will less when the impulse response values of E and F are different.

Table A1 Transmissible bandwidth (1/T) in MHz for Potash Tunnels

Tunnel distance M in ft Frequency	1000	2000	4000
900 MHz (L= 0.984 ft) 500 MHz (L= 1.71 ft)	1000 310	500 155	250 77.5

Intersymbol interference due to dispersion will not be a problem if the bandwidth of the signal is less than the value of the transmissible bandwidth.

FIG 1.

LOSSES FOR VERTICAL AND HORIZONTAL POLARIZATION

(REFRACTION LOSS ONLY)

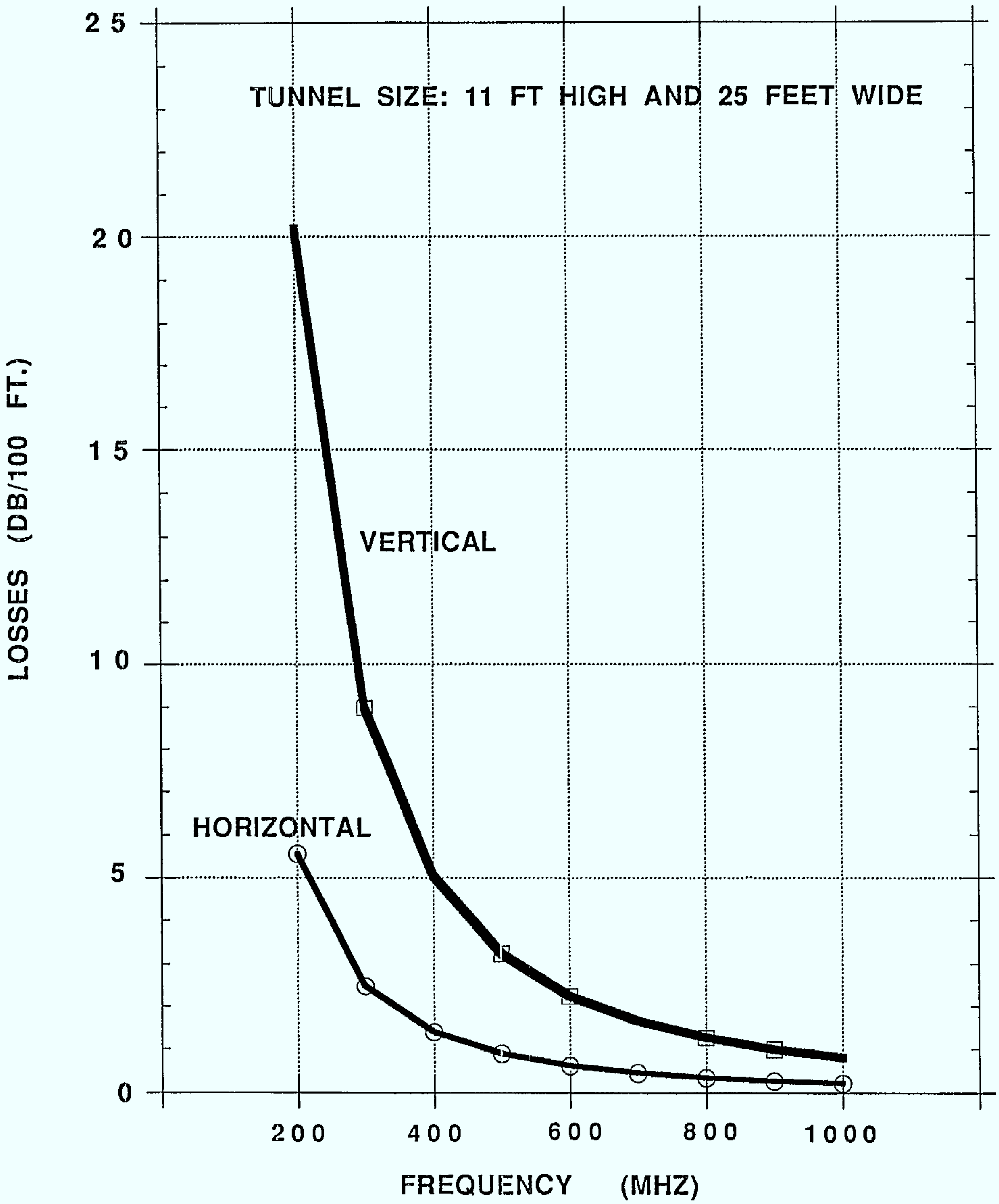
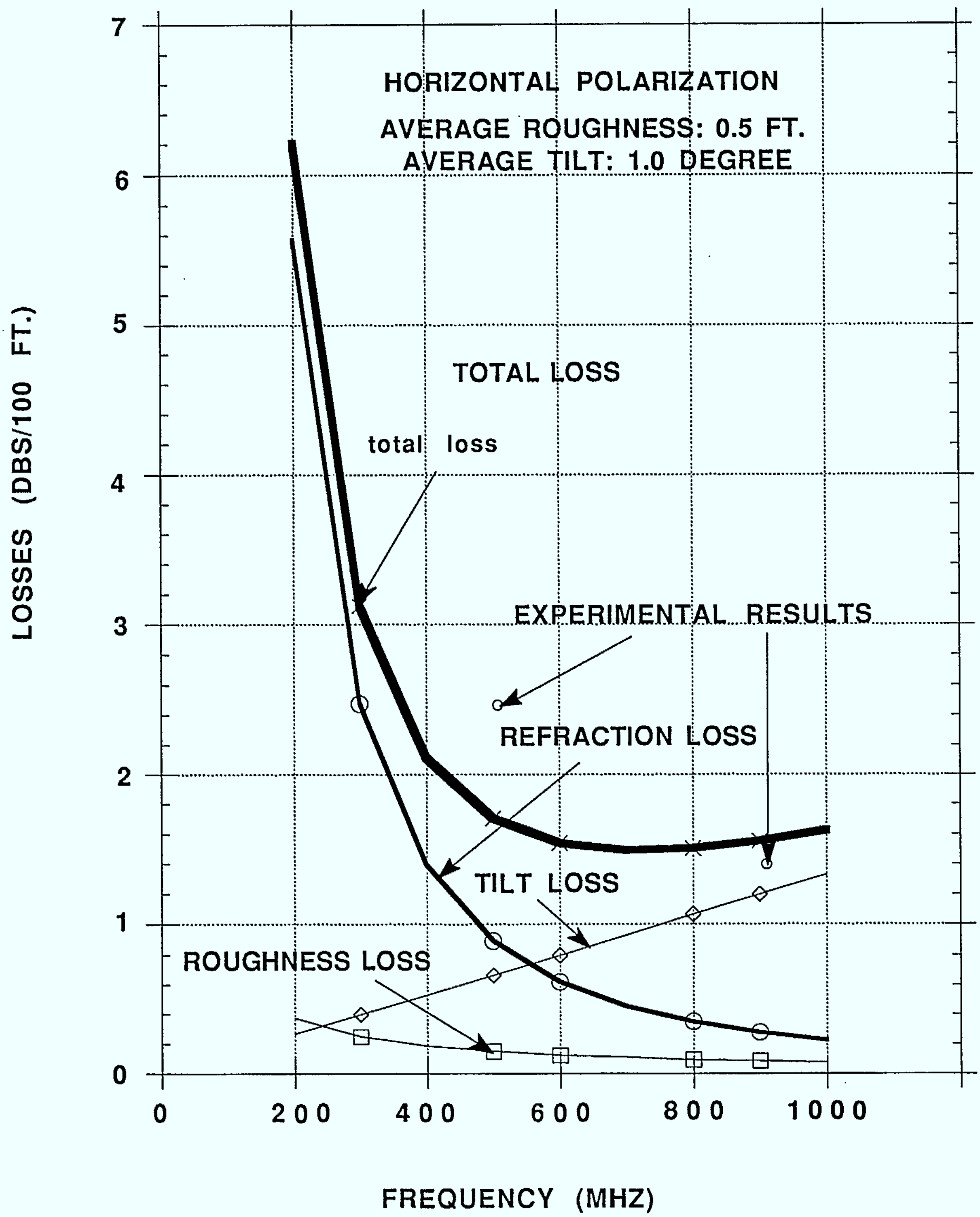


FIG. 2

LOSSES IN POTASH TUNNEL

EXPERIMENTAL AND THEORETICAL RESULTS



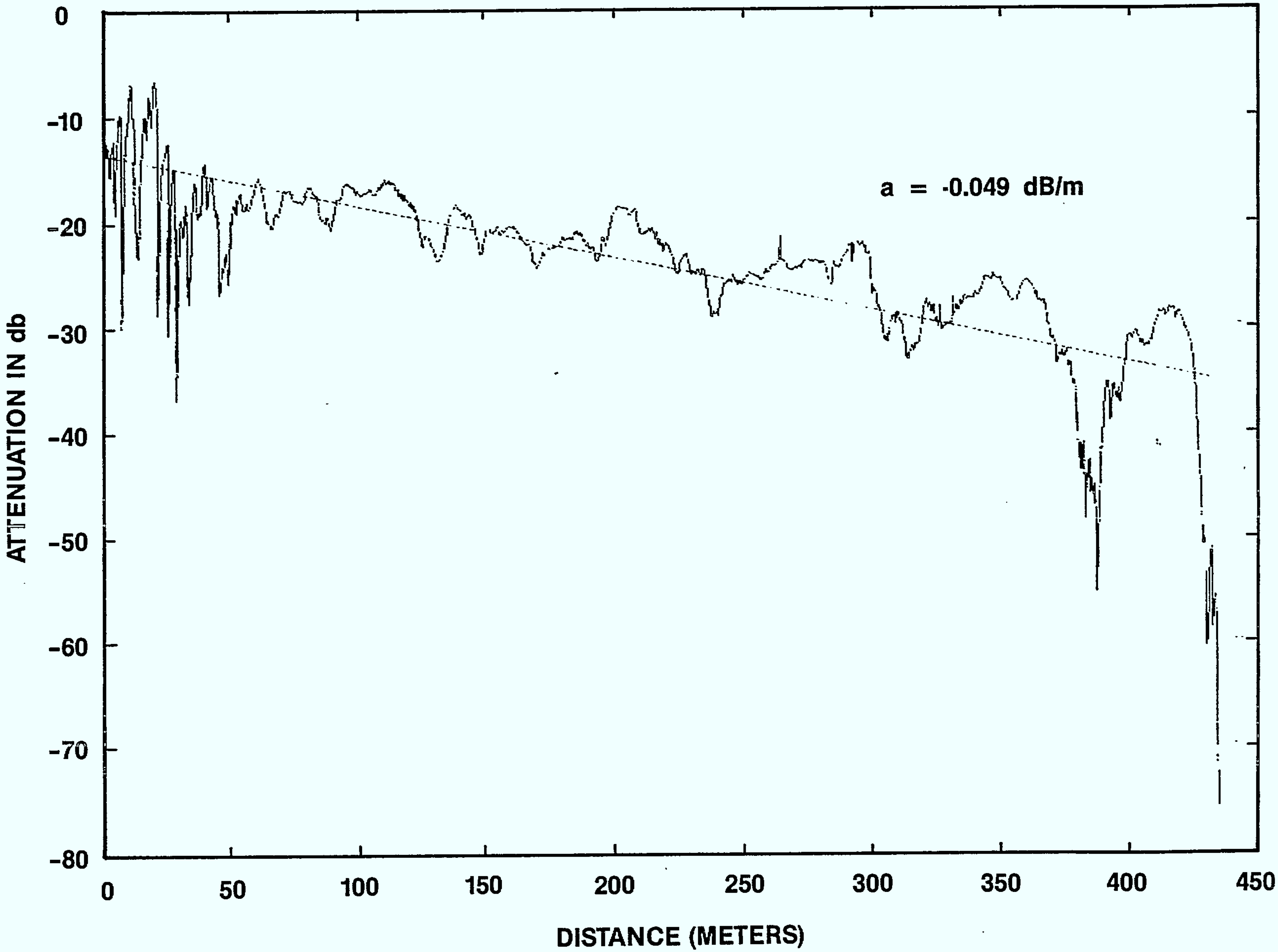


FIG 3. LOSSES AT 900 MHZ IN POTASH TUNNEL

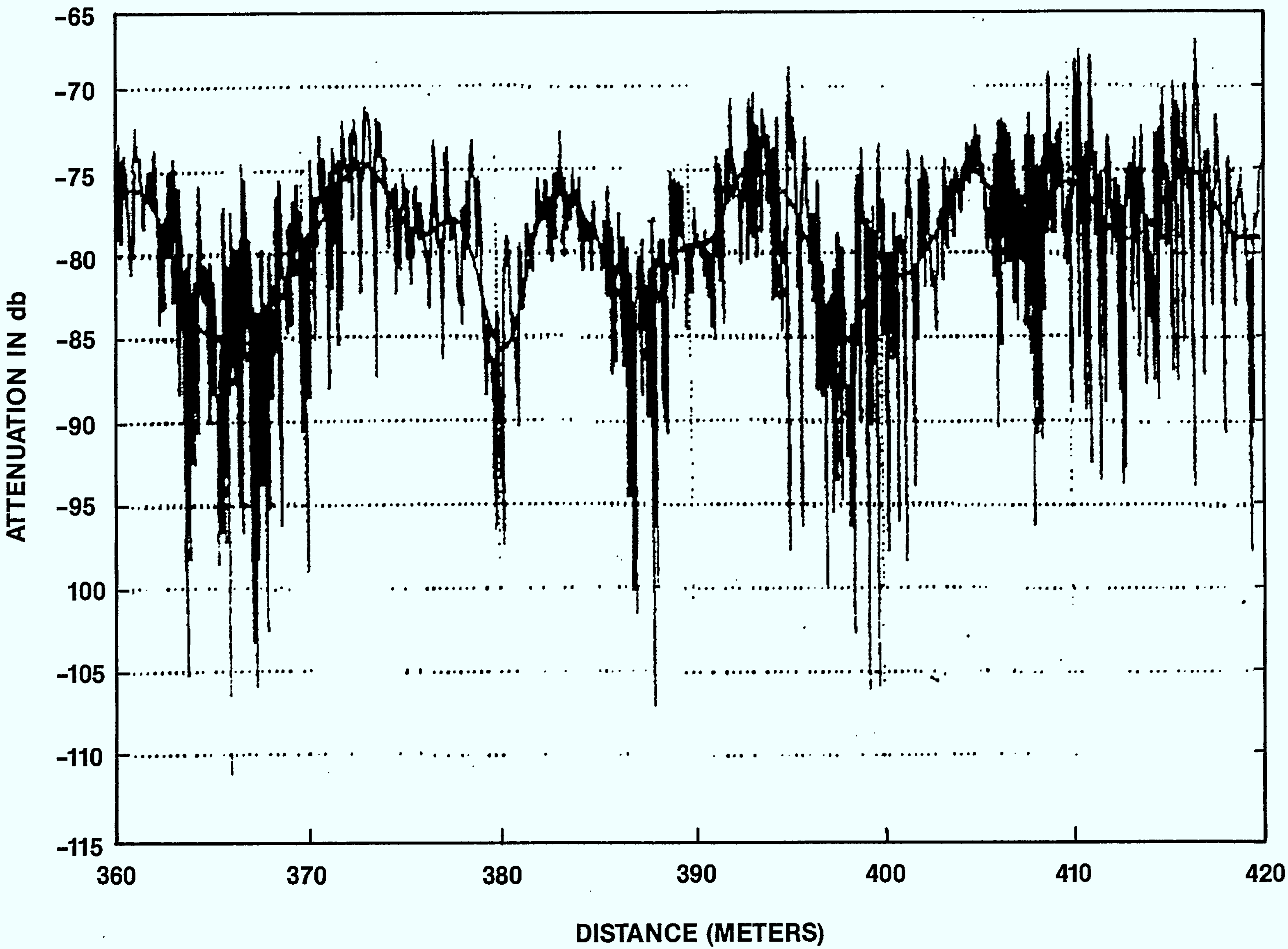


FIG. 4 LOSSES IN COPPER MINE

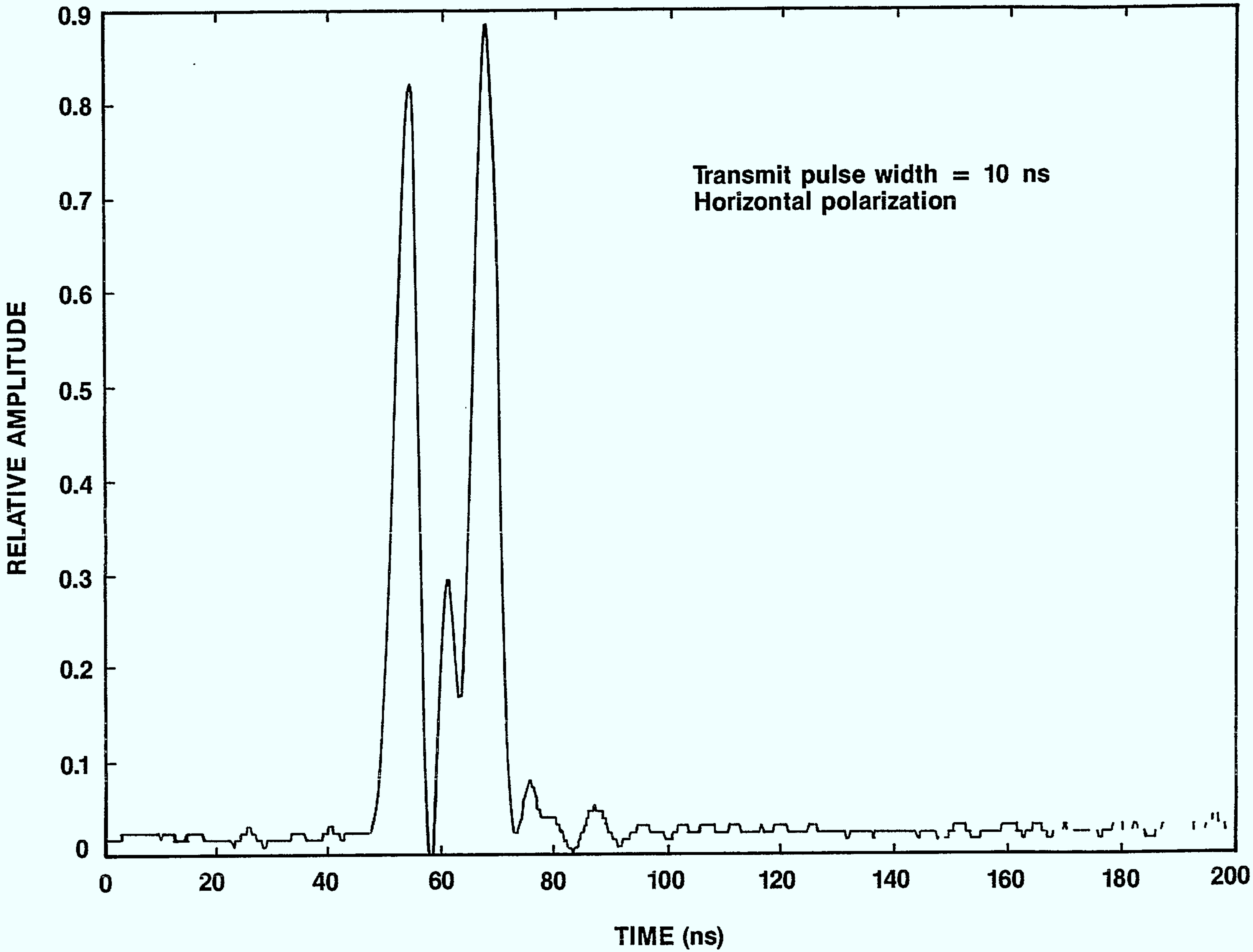


FIG. 5 IMPULSE RESPONSE IN POTASH TUNNEL

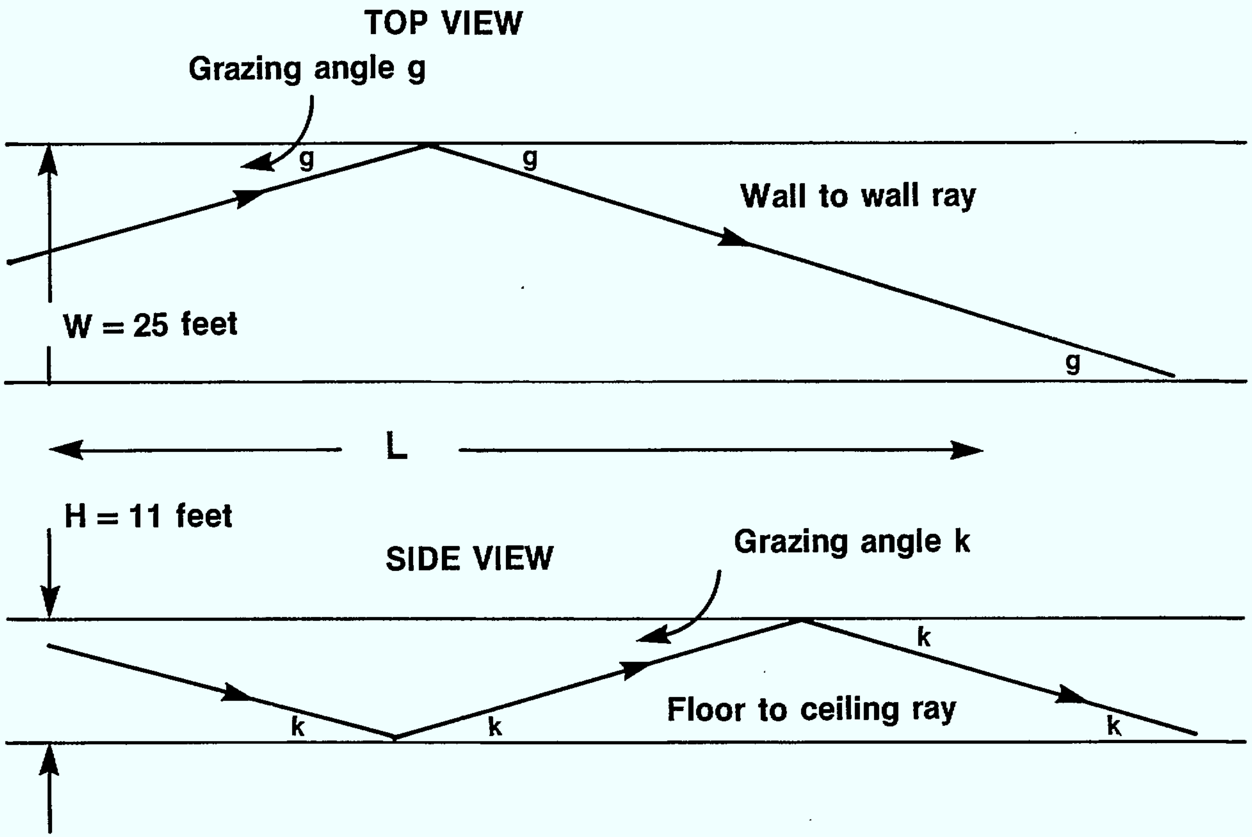


FIG. 1A RAYS IN WAVEGUIDE

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