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USNUOS Consecutive No. 316
(First Revision)

U. S. NAVAL UNDERWATER ORDNANCE STATION
NEWPORT, RHODE ISLAND

ELECTROMAGNETIC RADIATION
IN SEA WATER

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# U. S. NAVAL UNDERWATER ORDNANCE STATION
## NEWPORT, RHODE ISLAND

## ELECTROMAGNETIC RADIATION
## IN SEA WATER

Prepared by: *E. D. HILLIARD, JR.*

Aug 1960

34 p.

G. G. GOULD
Technical Director

J. H. BRANDT
Captain, USN
Commanding

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## FOREWORD TO
## FIRST REVISION

This publication supersedes USNUOS Consecutive No. 316, dated April 1960, which should be destroyed in accordance with regulations governing disposal of classified material. The overall intent and conclusions of the original report remain unchanged.

## ABSTRACT

A knowledge of the effects of sea water on electro-
magnetic waves is essential to any study of torpedo command
guidance systems using either radio or wire links. This
report presents a set of theoretical curves to illustrate
the transmission of electromagnetic waves in a sea water
medium. The curves presented are for sea water at 17°C.
They are intended as a theoretical starting point for
further discussion or investigation.

Curves considered to be most descriptive and useful,
and included in this report, are: (1) intrinsic impedance
of sea water medium versus frequency; (2) wave length of
electromagnetic radiation in sea water; (3) attenuation
versus frequency; (4) variation of transmission coefficient
with angle of incidence - for both vertical and horizontal
polarization of the incident wave; and (5) attenuation to
be expected when loss through the interface and through sea
water are accounted for.

Conclusions that may be drawn from this survey are:
(1) that there are probably no "holes" or "windows" in the
electromagnetic spectrum of sea water below 100 kilo-
megacycles which may be used for communication with or
direct surveillance of submerged vehicles; (2) that radio
control or communications systems to be developed should
employ, wherever possible, vertically polarized transmitting
antennae to maximize the signal passed through the air-sea
interface and minimize the dependence of this signal on
angle of incidence; and (3) that in the selection of a
carrier frequency for proposed underwater vehicle control
systems the minimum interface-sea water attenuation formula
derived in this report be considered.

In general, this report confirms, in respect to electro-
magnetic waves, a conclusion drawn by acousticians regarding
sound waves; namely, that sea water is a very difficult
medium to use for the transmission of signals.

## ACKNOWLEDGMENT

## INTRODUCTION

In the study of torpedo command guidance systems using either radio or wire links, a knowledge of the effects that sea water has on electromagnetic waves is essential.

This report presents a set of theoretical curves describing the transmission of electromagnetic waves in a sea water medium. While there are many references which give information on how to calculate the parameters of interest, these calculations have apparently not been carried out to the point where curves could be drawn to show how index of refraction, index of absorption, attenuation, wave length, and intrinsic impedance vary with frequencies from 100 cps to 100 kmcs. Two partial exceptions to this statement exist in references 1 and 2. The first gives curves of refraction coefficient of sea water from 10 kilocycles to 10 megacycles and a curve of attenuation versus depth for frequencies from 10 to 500 kilocycles. The second gives a theoretical curve showing variation of attenuation of electromagnetic radiation in sea water over the range from 1 megacycle to 100 kilo-megacycles.

Two other sets of curves are required for an understanding of radio transmission through the air-water interface. These are transmission coefficient versus angle of incidence for various frequencies for both horizontal and vertical polarization of the incident wave. These curves have been calculated and plotted.

The curves presented here are for sea water at 17°C. No attempt has been made to determine how far the values for other temperatures will depart from those plotted. These curves are intended to serve as a handy guide to electromagnetic radiation into and through sea water, and as a theoretical starting point for further discussion or investigation.

## UNITS AND SYMBOLS

The symbols used throughout are the same as those used in the principal reference (3. "Dielectrics and Waves" by A. Von Hippel). All quantities are expressed in the rationalized m.k.s. system. The subscript 0 designates the quantity in a vacuum, subscript 1 the quantity in air, and subscript 2 the quantity in sea water.

| | | |
|---|---|---|
| Attenuation constant | $\alpha = \dfrac{1}{x} \ln \dfrac{E_o}{E}$ | nepers |
| Complex dielectric constant | $\epsilon = \epsilon' - j\epsilon''$ | farad m |
| Complex index of refraction | $n = n(1 - jk)$ | |
| Complex permeability | $\mu = \mu' - j\mu''$ | henry/m |
| Complex propagation function | $\gamma = \alpha + j\beta$ | 1/m |
| Dielectric conductivity | $\sigma = \omega\epsilon''$ | mho/m |
| Dielectric constant (permittivity) | $\epsilon'$ | farad/m |
| Electric field strength | $E$ | volt/m |
| Electric loss factor | $\epsilon''$ | farad/m |
| Impedance (intrinsic) | $Z = E/H$ | ohm |
| Index of absorption | $k = \alpha/\beta$ | |
| Index of refraction | $n = \lambda_o/\lambda$ | |
| Magnetic field strength | $H$ | amp/m |
| Magnetic loss factor | $\mu''$ | henry/m |
| Magnetic permeability | $\mu'$ | henry/m |
| Phase constant | $\beta = 2\pi/\lambda$ | 1/m |

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Relative dielectric constant $\qquad \kappa' = \epsilon'/\epsilon_0$

Relative magnetic permeability $\qquad \kappa'_m = \mu'/\mu_0$

Wave length $\qquad\qquad\qquad\qquad \lambda \qquad\qquad$ meters

$$\omega = 2\pi f \qquad\qquad \text{rad/sec}$$

$$\epsilon_0 = \frac{1}{36\pi} \times 10^{-9} \qquad \text{farad/m}$$

$$\mu_0 = 4\pi \times 10^{-7} \qquad \text{henry/m}$$

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 376.6 \quad \text{ohms}$$

## THEORY

Fundamental to all of the following calculations are the values of the intrinsic impedance of sea water, $Z_2$, for the frequencies from 100 cycles per second to 100 kilo-megacycles per second. Reference 4 gives experimental values for the real and imaginary parts of $\kappa_2^*$, the relative dielectric constant of sea water at 17°C. This graph is reproduced as figure 1. The symbols on the curves have been modified to agree with the preceding section (Units and Symbols).

$$Z_2 = \sqrt{\frac{\mu_2^*}{\epsilon_2^*}} \qquad\qquad = \sqrt{\frac{\mu_2' - j\mu_2''}{\epsilon_2' - j\epsilon_2''}} \qquad\qquad (1)$$

Since there are assumed to be no magnetic losses in the sea water,

$$\mu_2'' = 0 \qquad \text{and} \qquad Z_2 = \sqrt{\frac{\mu_2'}{\epsilon_2' - j\epsilon_2''}} \qquad\qquad (2)$$

3

DIELECTRIC CONSTANT
OF SEAWATER AT 17° C

$K' = \dfrac{\epsilon'}{\epsilon_o}$

$K'' = \dfrac{\epsilon''}{\epsilon_o}$

$K = \dfrac{\sigma}{\omega\epsilon_o}$ FOR $\sigma = 3.61$ MHO PER METER

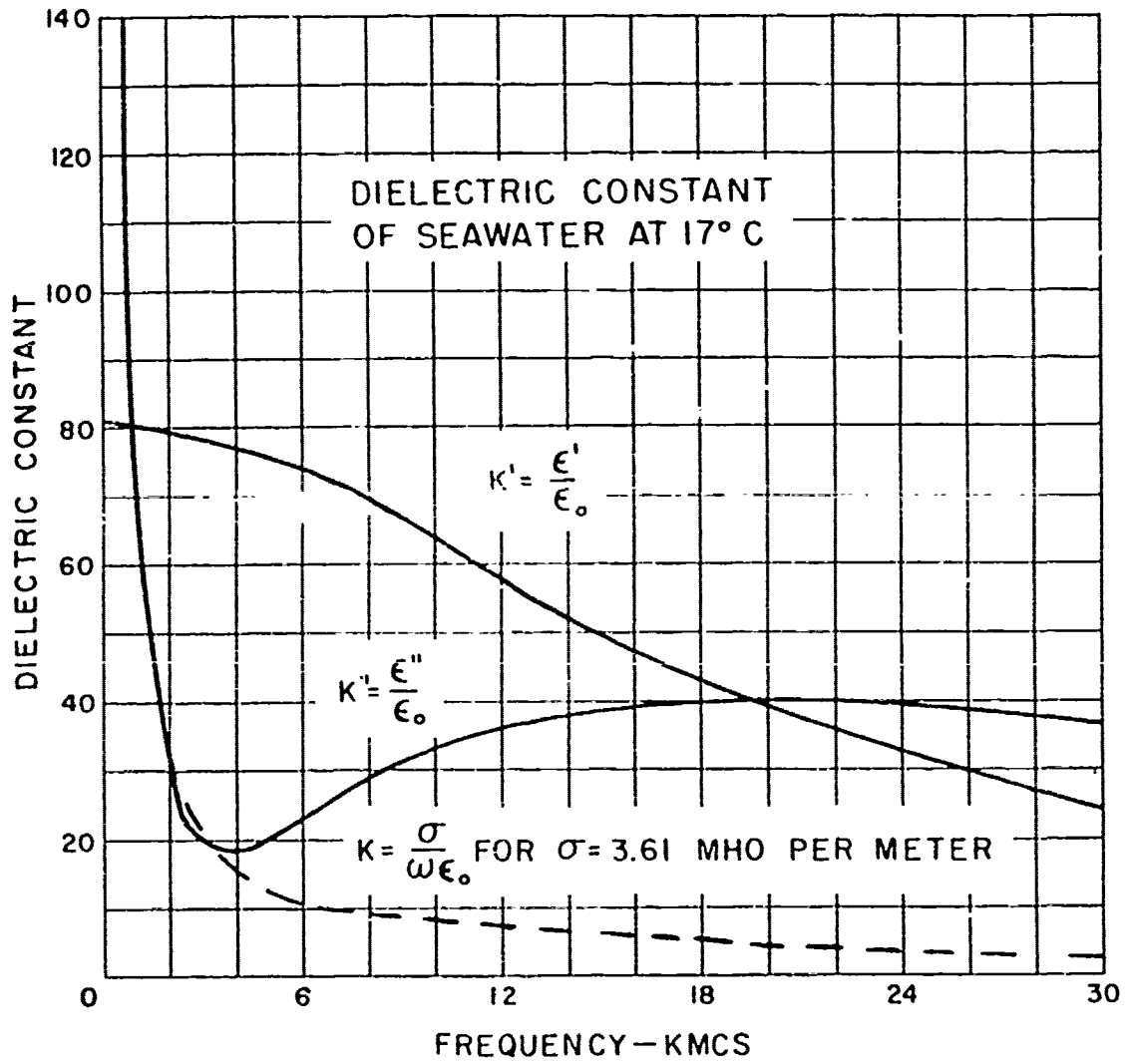DIELECTRIC CONSTANT

FREQUENCY—KMCS

FIGURE 1

Figure 1 shows that up to 2 kmc, $\epsilon_2'' = \sigma/\omega$. Therefore, from 100 cps to 2 kmc, $Z_2$ was calculated using these values of $\epsilon''$, with $\sigma = 3.61$ mho·meter and assuming that $\epsilon' = 81\epsilon_0$. Above 2 kmc to 30 kmc, the values for $K_2'$ and $K_2''$ were taken from the graph to be applied as follows:

$$Z_2 = \sqrt{\frac{K_{m2}' \, \mu_0}{K_2' \, \epsilon_0 - jK_2'' \, \epsilon_0}} \tag{3}$$

Since $K_{m2}' = 1$, $\hspace{4cm}$ (4)

$$Z_2 = \sqrt{\frac{\mu_0}{K_2' \, \epsilon_0 - j \, K_2'' \, \epsilon_0}}$$

The complex index of refraction is found in terms of the intrinsic impedances of air and sea water. Numbers in brackets [ ] refer to equation numbers in reference 3.

By [7.25], $Z = j\omega\mu^*/\gamma$ ; $\hspace{3cm}$ (5)

and by [2... ?], $\dfrac{\gamma_2}{\gamma_1} = n_{2i}^* \, (1 - jk_2)$ $\hspace{2cm}$ (6)

Then $n_{21}^* \, (1 - jk_2) = \dfrac{\gamma_2}{\gamma_1} = \dfrac{j\omega\mu_2^*/z_2}{j\omega\mu_1^*/z_1}$ $\hspace{2cm}$ (7)

Since it is assumed that

$$\mu_2^* = \mu_1^* \, , \quad n_{21}^* \, (1 - jk_2) = \frac{z_1}{z_2} \; ; \tag{8}$$

where, according to [20.3],

$$n_{21} = \beta_2 / \beta_1 \tag{9}$$

$$k_2 = \alpha_2 / \beta_2 \tag{10}$$

The computation can now proceed, using equation (8) to determine index of refraction $n_{21}$ and absorption coefficient $k_2$ from the values calculated for $Z_2$ and the value $Z_1 = Z_0$ .

Since $\beta_1 = 2\pi/\lambda_1$ , $\beta_2$ may be found from equation (9), while $\alpha_2$, the attenuation constant, may now be found from equation (10). The values of $\lambda_2$ , the wave length in sea water, may be calculated from the relationship $\beta_2 = 2\pi/\lambda_2$ ; or, more directly,

$$n_{21} = \frac{\beta_2}{\beta_1} = \frac{2\pi/\lambda_2}{2\pi/\lambda_1} = \frac{\lambda_1}{\lambda_2} \qquad (11)$$

The transmission coefficient is the ratio of field strength just below the air-sea water interface to field strength just above the interface. [15.16] in reference 3 gives the two equations necessary. For the E vector normal to the plane of incidence as shown in figure 2, and defined here as a horizontally polarized wave:

$$t_{en} = \left(\frac{E_t}{E_i}\right)_n = \frac{2z_2 \cos\phi}{z_2 \cos\phi + z_1 \cos\psi} \qquad (12)$$

For the E vector parallel to the plane of incidence as shown in figure 3, and defined here as a vertically polarized wave:

$$t_{ep} = \left(\frac{E_t}{E_i}\right)_p = \frac{2z_2 \cos\phi}{z_2 \cos\psi + z_1 \cos\phi} \qquad (13)$$

In these expressions $\phi$ is the angle of incidence, $\psi$ is the angle of refraction, and $Z_1$ and $Z_2$ are the intrinsic impedances of air and sea water respectively.

Snell's Law gives the relationship between $\phi$ and $\psi$ as:

$$\sin\phi = \frac{\gamma_2}{\gamma_1} \sin\psi \qquad (14)$$

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However, in the case of lossy dielectrics, such as sea water, the ratio $\gamma_2/\gamma_1$ is complex and equation (14) cannot be used. In reference 3, Von Hippel develops a way around this mathematical impasse based on a geometrical index of refraction N for the planes of constant phase, which "can be measured by the customary optical methods as long as medium 2 (sea water) is of sufficient transparency." This index of refraction is a function of the angle of incidence. Four equations are shown, [20.10] and [20.11] . These equations define the relationships between $\beta_1$ , $\beta_2$ , $\alpha_2$ , N, $\psi'$ the geometric angle of refraction, and two quantities, p and q, introduced to account for the shift in $\psi$ to $\psi'$ . These equations are:

$$\frac{\sin\phi}{\sin\psi'} = N = \frac{\sqrt{q^2 + \beta_1^2 \sin^2\phi}}{\beta_1} \qquad . \qquad (15)$$

$$\beta_1^2 N - p^2 = \beta_2^2 - \alpha_2^2 \qquad . \qquad (16)$$

$$pq = \alpha_2 \beta_2 \qquad . \qquad (17)$$

$$\beta_1 N p = \frac{\alpha_2 \beta_2}{\cos\psi'} \qquad . \qquad (18)$$

Since $\alpha_2 = k_2 \beta_2$ , and $\beta_2 = n_{21} \beta_1$ , equation (17) can be rewritten as:
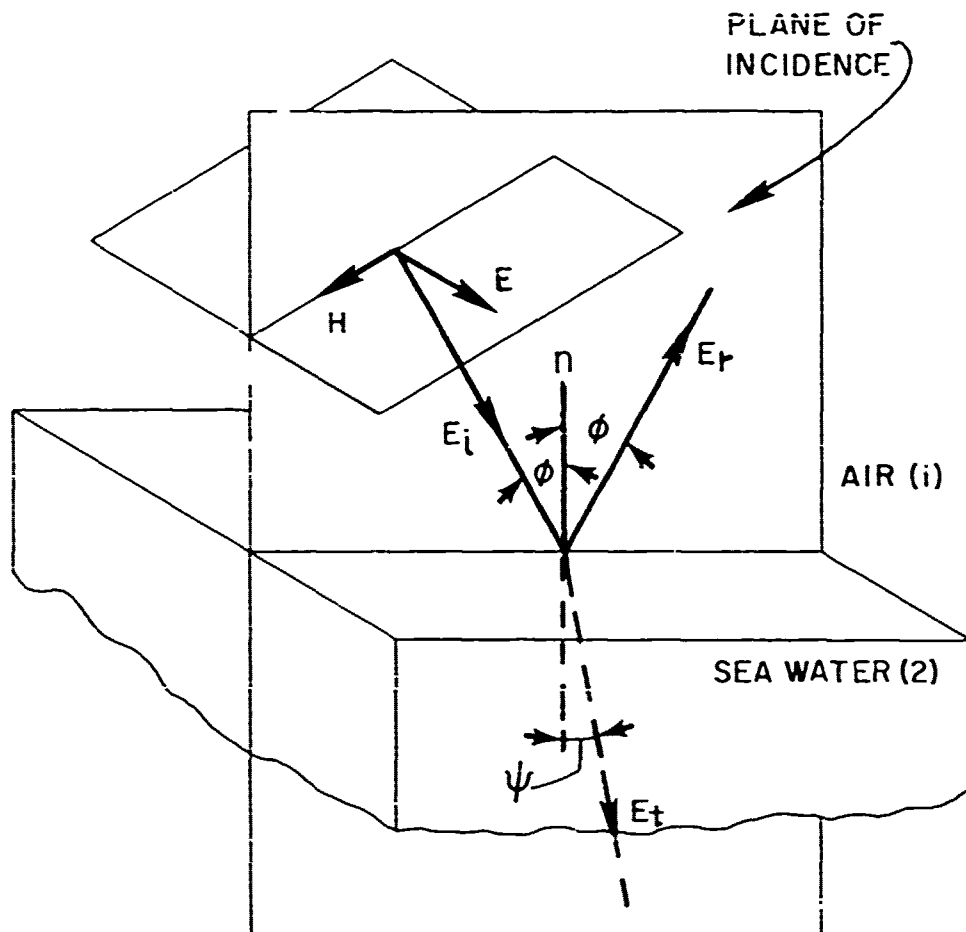
$$p = \frac{(k_2 \beta_2)(n_{21} \beta_1)}{q} \qquad . \qquad (19)$$

Combining (19) with (16) gives:

$$\beta_1^2 \left( N - \frac{n_{21}^2 k_2^2 \beta_2^2}{q^2} \right) = \beta_2^2 (1 - k_2^2) \qquad ;$$

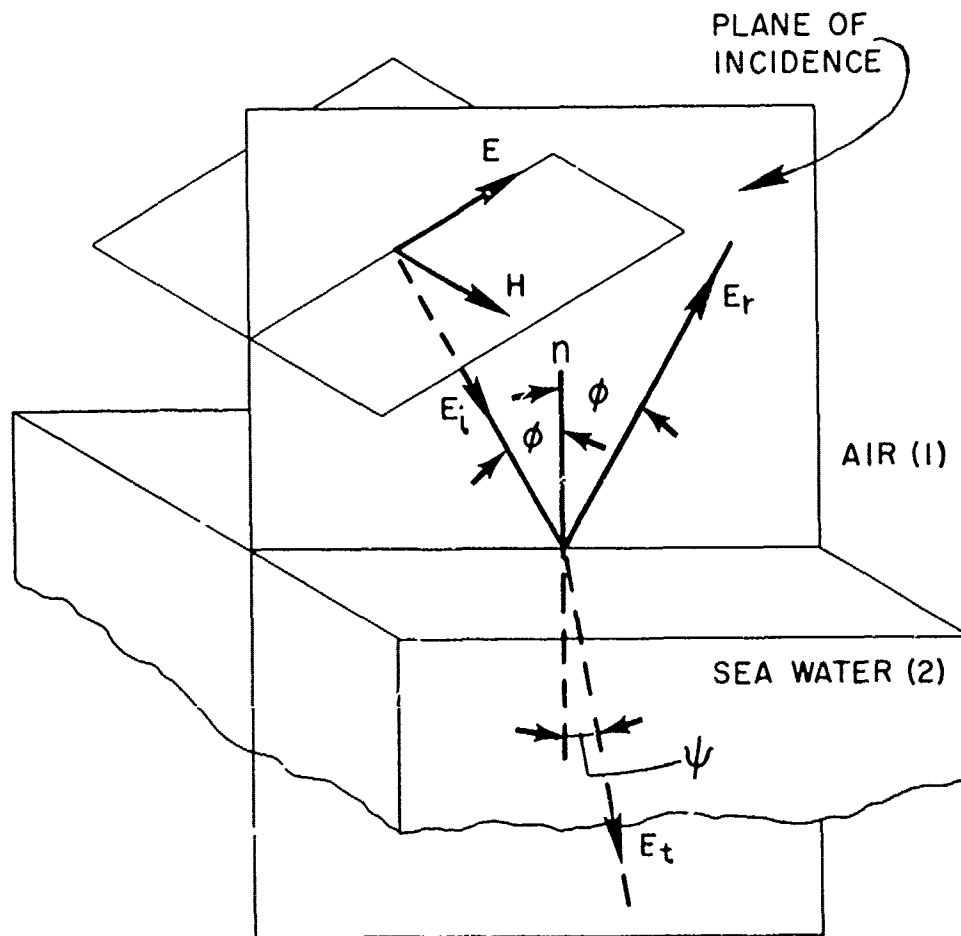$$\frac{n_{21}^2 k_2^2 \beta_2^2}{q^2} = N - n_{21}^2 (1 - k_2^2) \qquad ;$$

$$q^2 = \frac{n_{21}^2 k_2^2 \beta_2^2}{N - n_{21}^2 (1 - k_2^2)} \qquad . \qquad (20)$$

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PLANE OF
INCIDENCE

REFLECTION AND REFRACTION FOR A
HORIZONTALLY POLARIZED E M WAVE

FIGURE 2

REFLECTION AND REFRACTION FOR A
VERTICALLY POLARIZED E M WAVE

FIGURE 3

Solving (15) for $q^2$,

$$q^2 = \beta_1^2 \left( N^2 - \sin^2 \phi \right) \tag{21}$$

Equating (20) and (21),

$$N^2 - \sin^2 \phi = \frac{\beta_2^2}{\beta_1^2} \; \frac{n_{21}^2 \, k_2^2}{N - n_{2i}^2 \left( 1 - k_2^2 \right)} \quad ;$$

$$N^3 - N^2 \left[ n_{21}^2 \left( 1 - k_2^2 \right) \right] - N \left[ \sin^2 \phi \right] + \left( \sin^2 \phi \right) \left[ n_{21}^2 \left( 1 - k_2^2 \right) \right] - n_{21}^4 \, k_2^2 = 0$$

$$\tag{22}$$

This equation expresses the geometric index of refraction in terms of the calculated quantities $n_{21}$ and $k_2$ and values of $\phi$ between $0°$ and $90°$. There will be at least one positive real root for all values of $n_{21}$, $k_2$ and $\phi$ for the frequencies considered in this study.

For frequencies up to 10 Mc, $k_2 = 1$; and equation (22) reduces to $N^3 - N \left[ \sin^2 \phi \right] - n_{21}^4 = 0$. $\qquad$ (23)

The solution of equation (23) by the algebraic method given in reference 5 indicates that the coefficient of N can be neglected.

Therefore: $N = \left( n_{21} \right)^{4/3}$ $\qquad\qquad\qquad$ (24)
for frequencies up to and including 10 Mc. However, for this study, these equations were solved by a computer for all values of $n_{21}$, $k_2$, and $\sin \phi$.

Values of $\psi'$ are now obtained from a modified version of Snell's Law.

$$\sin \psi' = \frac{\sin \phi}{N} \tag{25}$$

The resulting pairs of values of $\phi$ and $\psi'$ are inserted in equations (12) and (13), with the frequency dependent values of $Z_2$, to calculate the transmission coefficients.

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CURVES

Of the many curves which may be plotted from the results
of the calculations made, the following are considered to
be the most descriptive and useful.

1.   Intrinsic impedance of the sea water medium
versus frequency is shown in curve 1 (figure 4).  While the
plot of phase angle is somewhat distorted by the log-log
scales, it is felt that this distortion is permissible in
order to keep the amplitude and phase angle together on one
graph.  The plot shows that the impedance varies directly
as the square root of frequency up to 100 Mc. with the
phase angle at 45 degrees.  The dip in the phase angle curve
corresponds with the minimum in $\kappa_2''$ at approximately 3.5 kmcs.

2.   Curve 2 (figure 5) is a plot of wave length of
electromagnetic radiation in sea water.   $\lambda_2$ varies inversely
as the square root of frequency up to 100 Mc.

3.   Curve 3 (figure 6) shows that the attenuation
varies directly as the square root of the frequency up to
100 Mc.  Of at least passing interest is the notch in the
region between 3.5 and 4 kilo-megacycles.  The depth of the
notch, measured from the local maximum at about 2 kmc, is
at most 5 nepers per meter.  (In db, this is 5 x 8.686 =
43.4 db.)  Since the level in this region is about 70 nepers
per meter (608 db per meter), the percentage decrease is a
minute 0.8 per cent.  Beyond this valley, the curve rises
sharply to the imposing height at 100 kmcs of 4000 nepers
per meter or 34,800 db per meter.

4.   Curve 4 (figure 7) shows the variation of trans-
mission coefficient with angle of incidence for vertical
polarization of the incident wave.  For the lower frequen-
cies shown, the transmission coefficient is practically
independent of angle of incidence for angles below 89.5°.
The angles of refraction were always less than 6.5° for the
values of $\phi$ chosen.  For 10 kmc and below, the angles of
refraction were always below 1°.  Curves 5 and 6 (figures 8
and 9) show transmission coefficient and the phase angle
between the incident and refracted waves, plotted on an
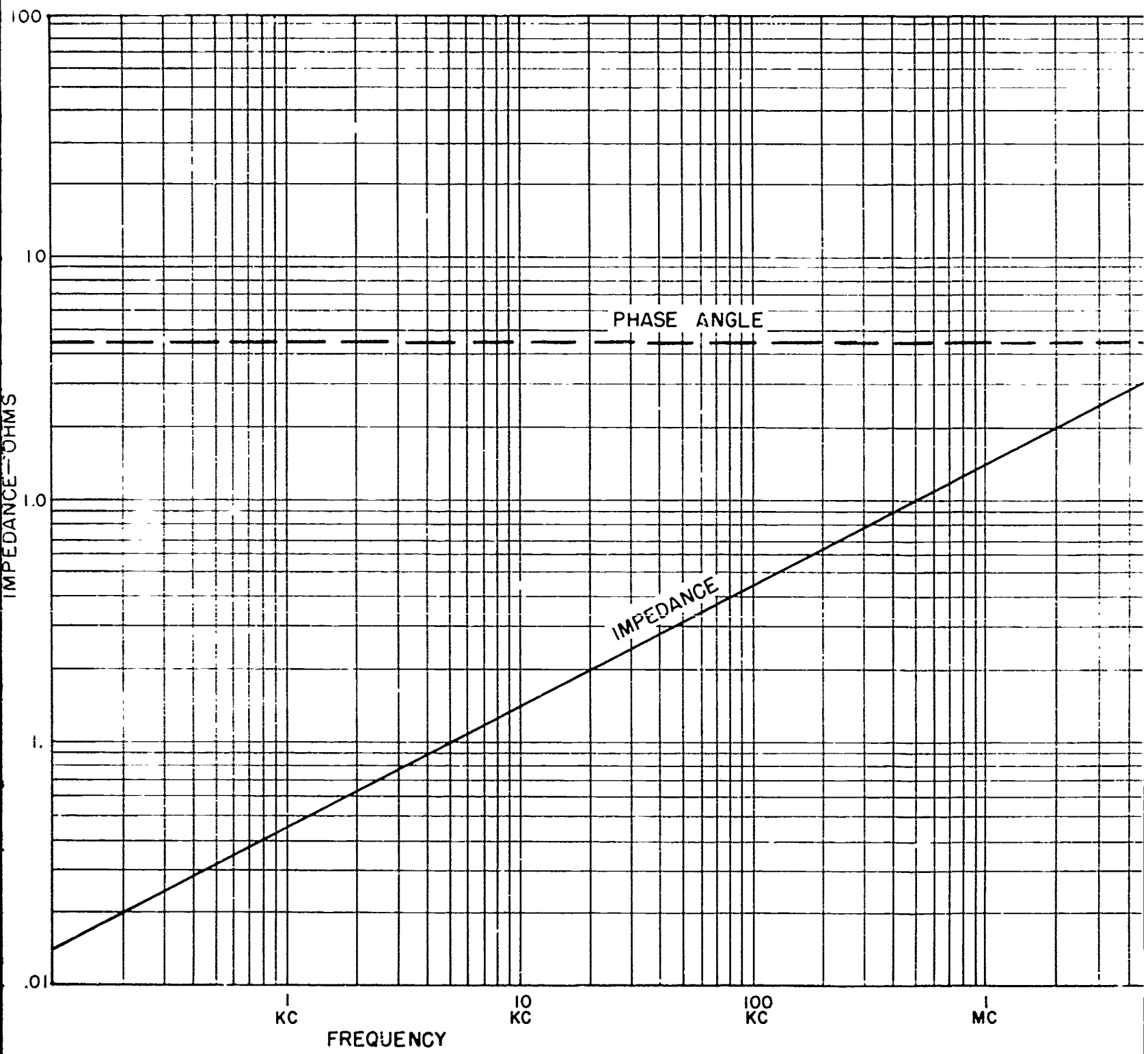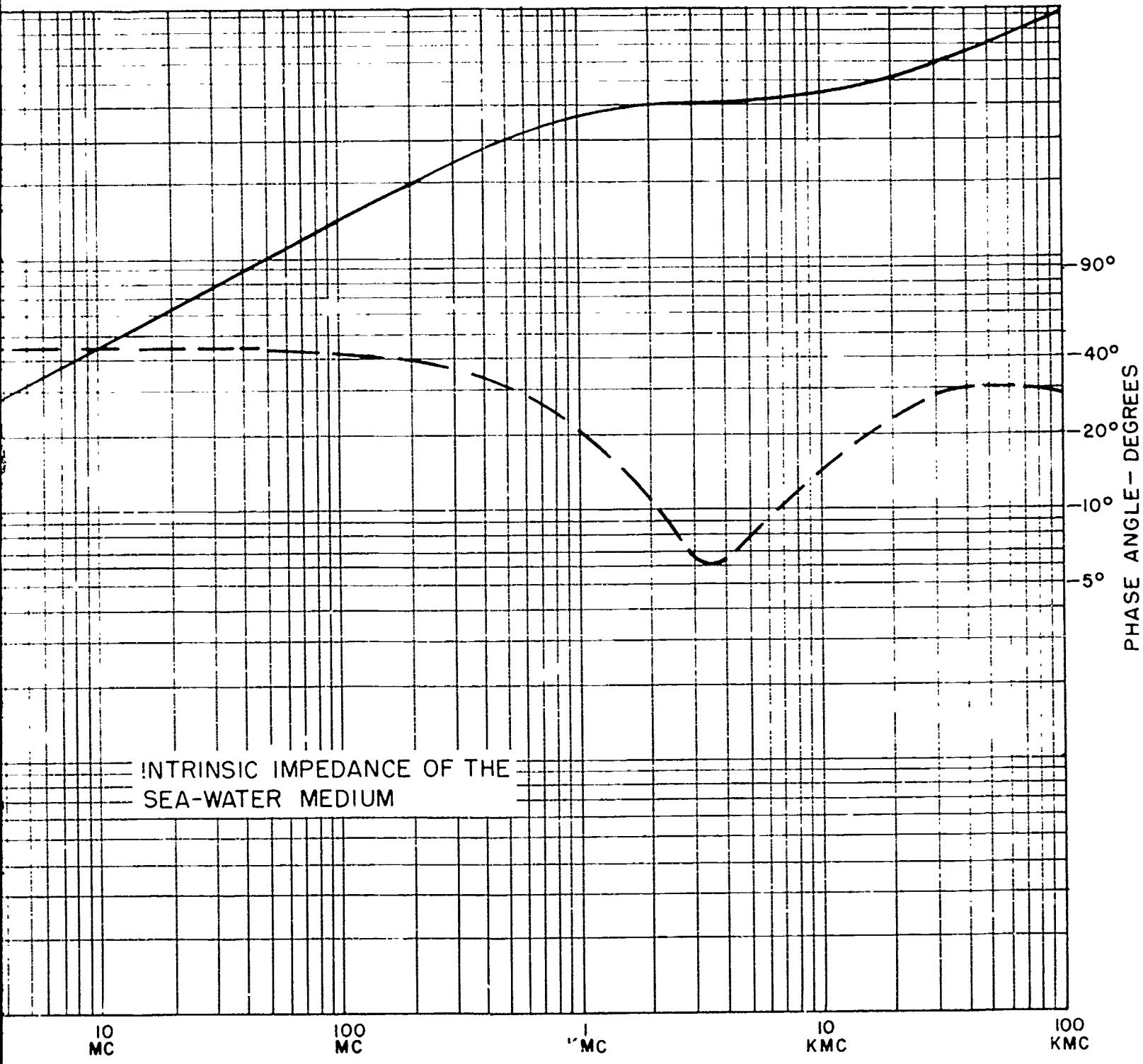expanded scale of angle of incidence between 80 and 90
degrees.

FIGURE 4

INTRINSIC IMPEDANCE OF THE
SEA-WATER MEDIUM

WAVELENGTH OF E[...]
IN S[...]
V[...]
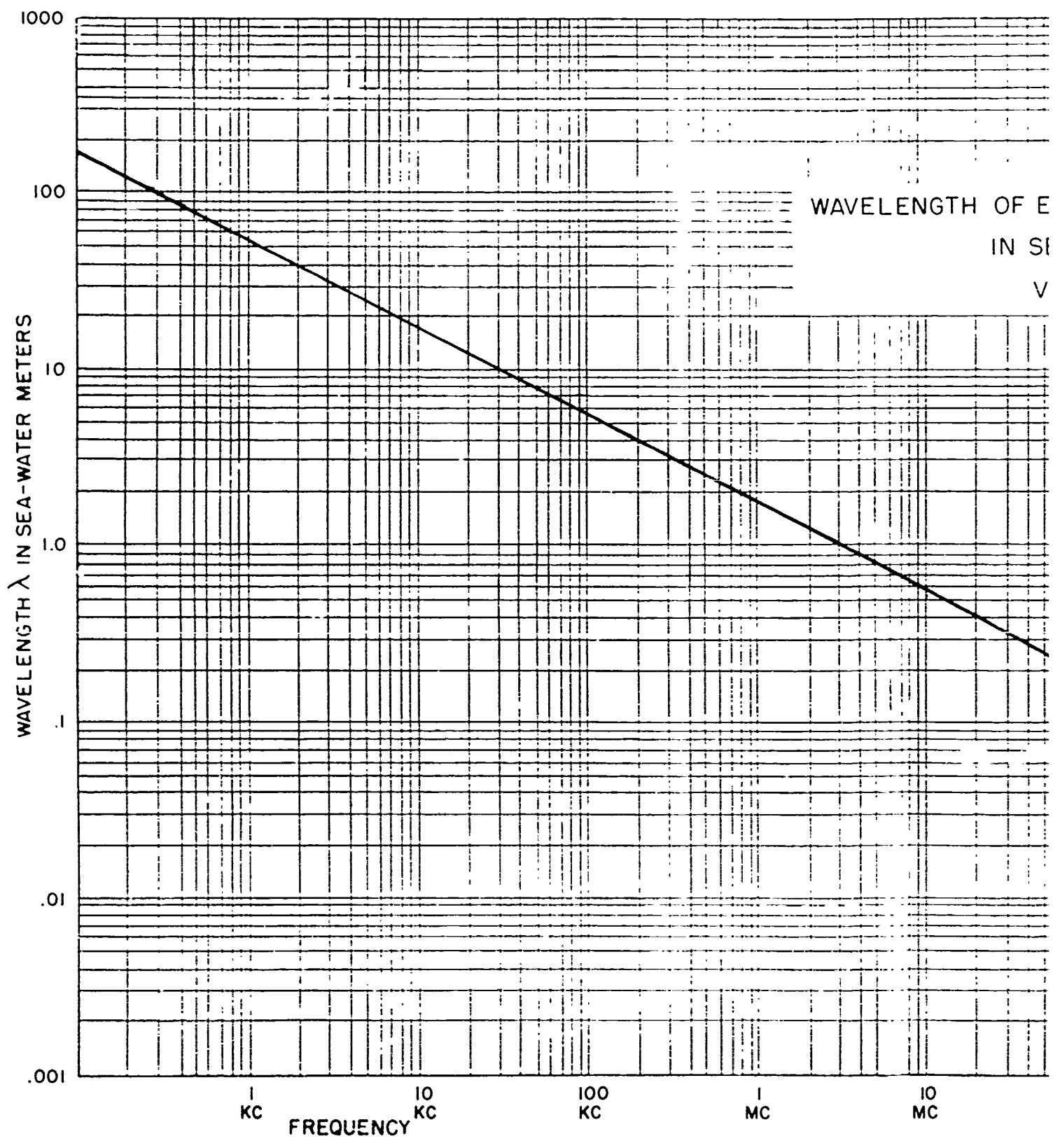
FIGURE 5

WAVELENGTH OF ELECTRO MAGNETIC RADIATION
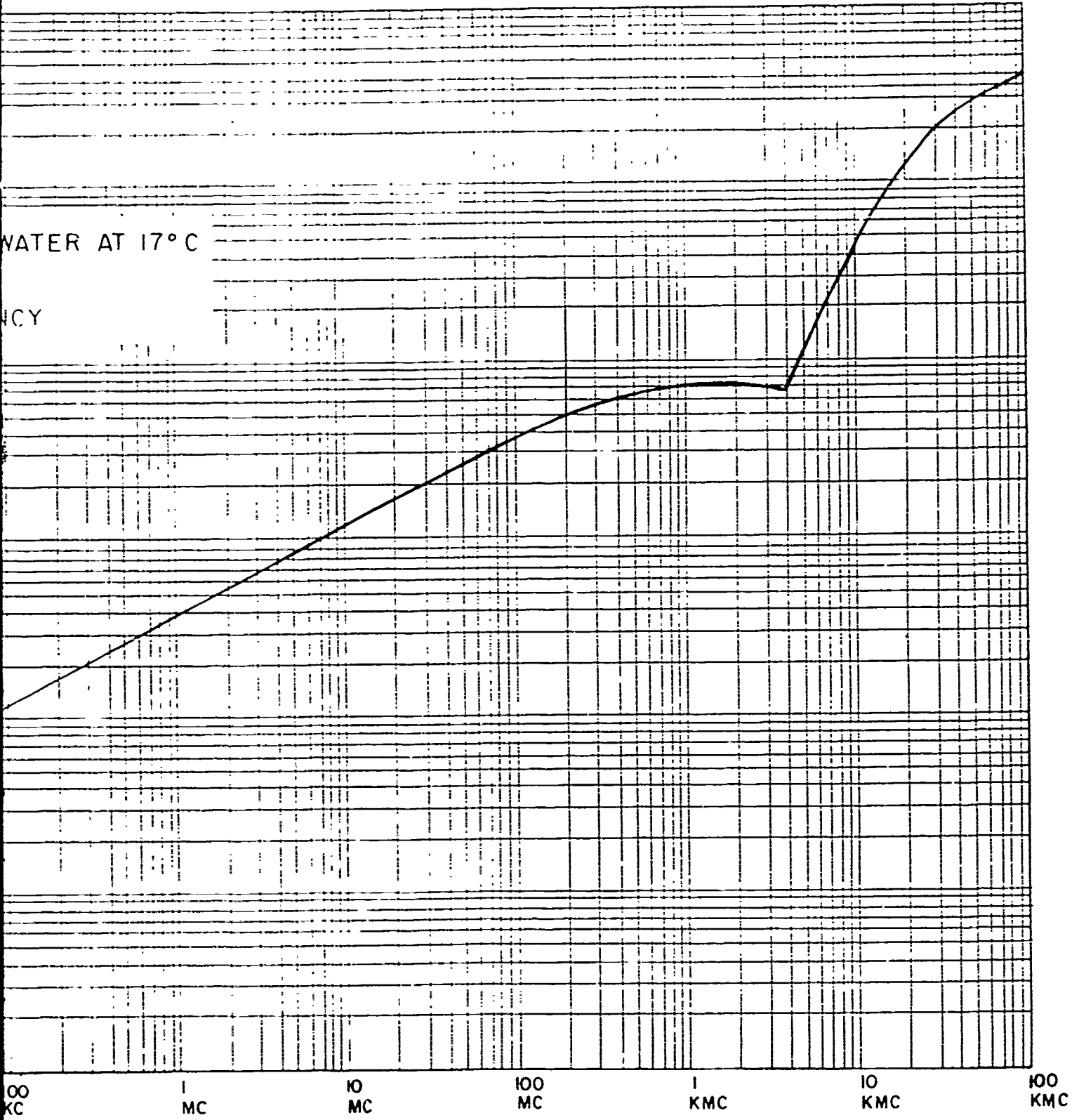IN SEAWATER AT 17°C
VS FREQUENCY

| 100 KC | 1 MC | 10 MC | 100 MC | 1 KMC | 10 KMC | 100 KMC |

ATTENUATION OF SEAWATER AT 17°C
VS
FREQUENCY

FIGURE 6

WATER AT 17°C

NCY

| | | | | | |
|---|---|---|---|---|---|
| 00 KC | 1 MC | 10 MC | 100 MC | 1 KMC | 10 KMC | 100 KMC |
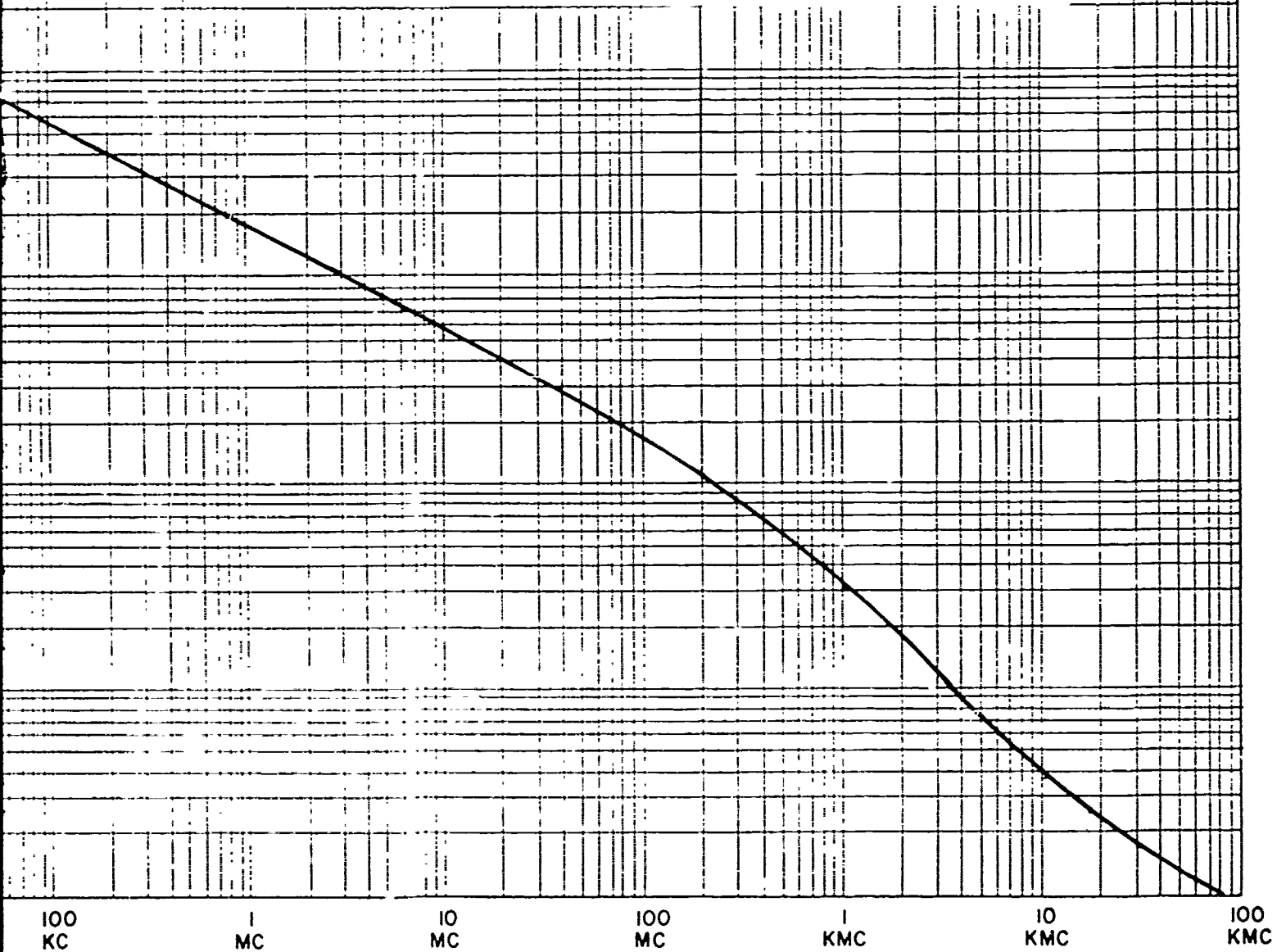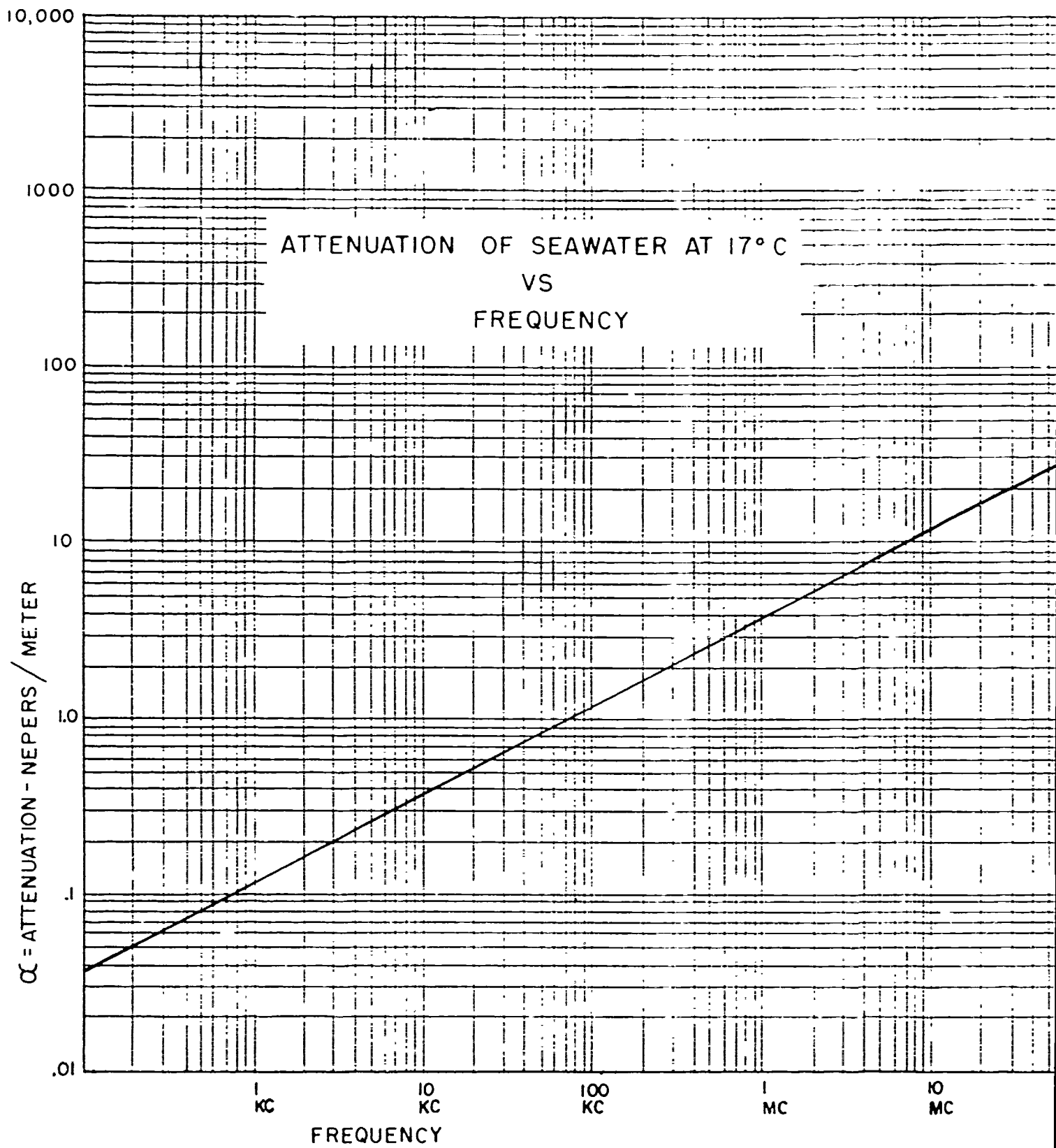
TRANSMISSION COEFFICIENT
VERTICAL POLARIZATION



FIGURE 7

VERTICAL POLARIZATION

100 KMC
10 KMC
1 KMC
100 MC
10 MC
1 MC
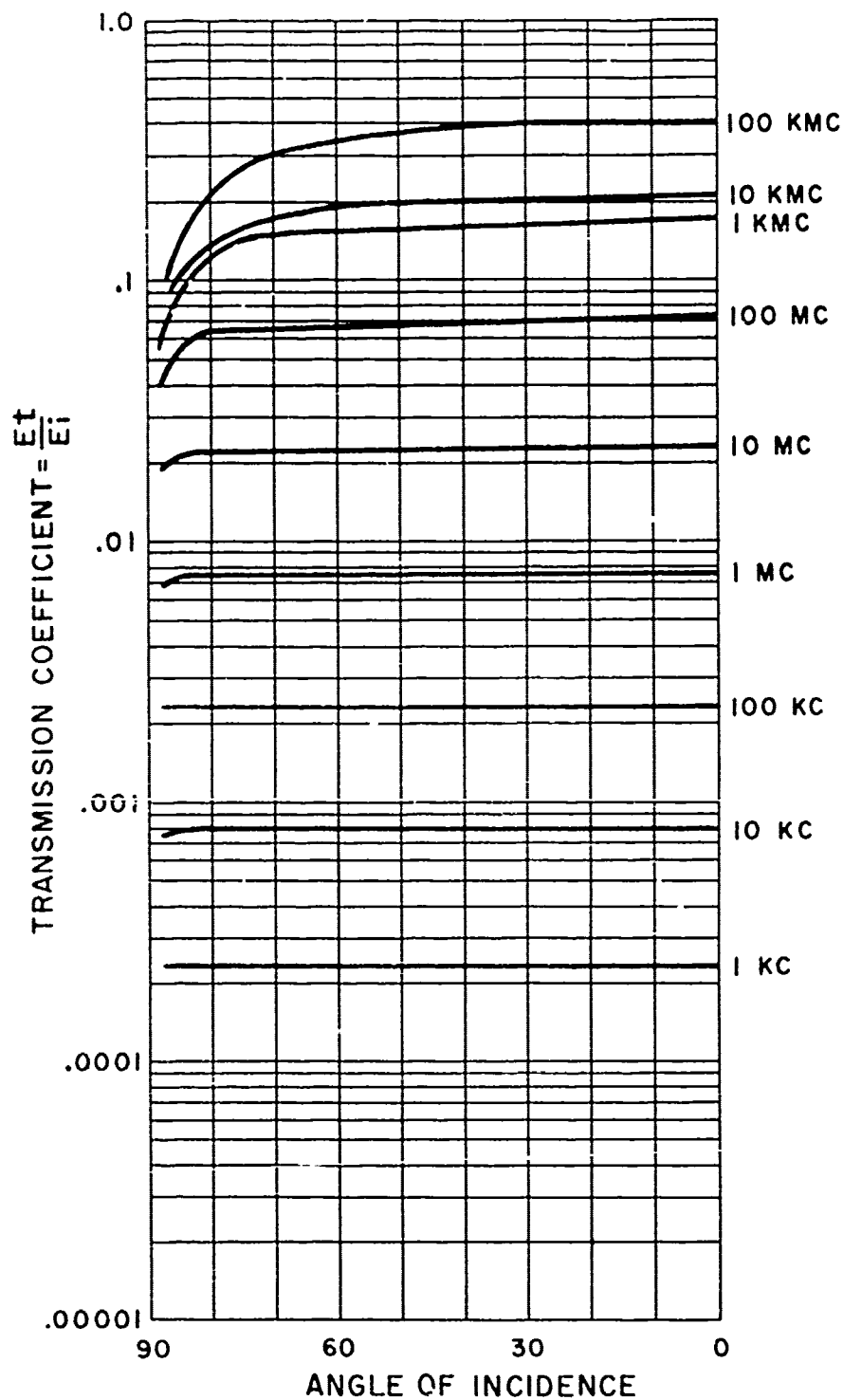100 KC
10 KC
1 KC

TRANSMISSION COEFFICIENT
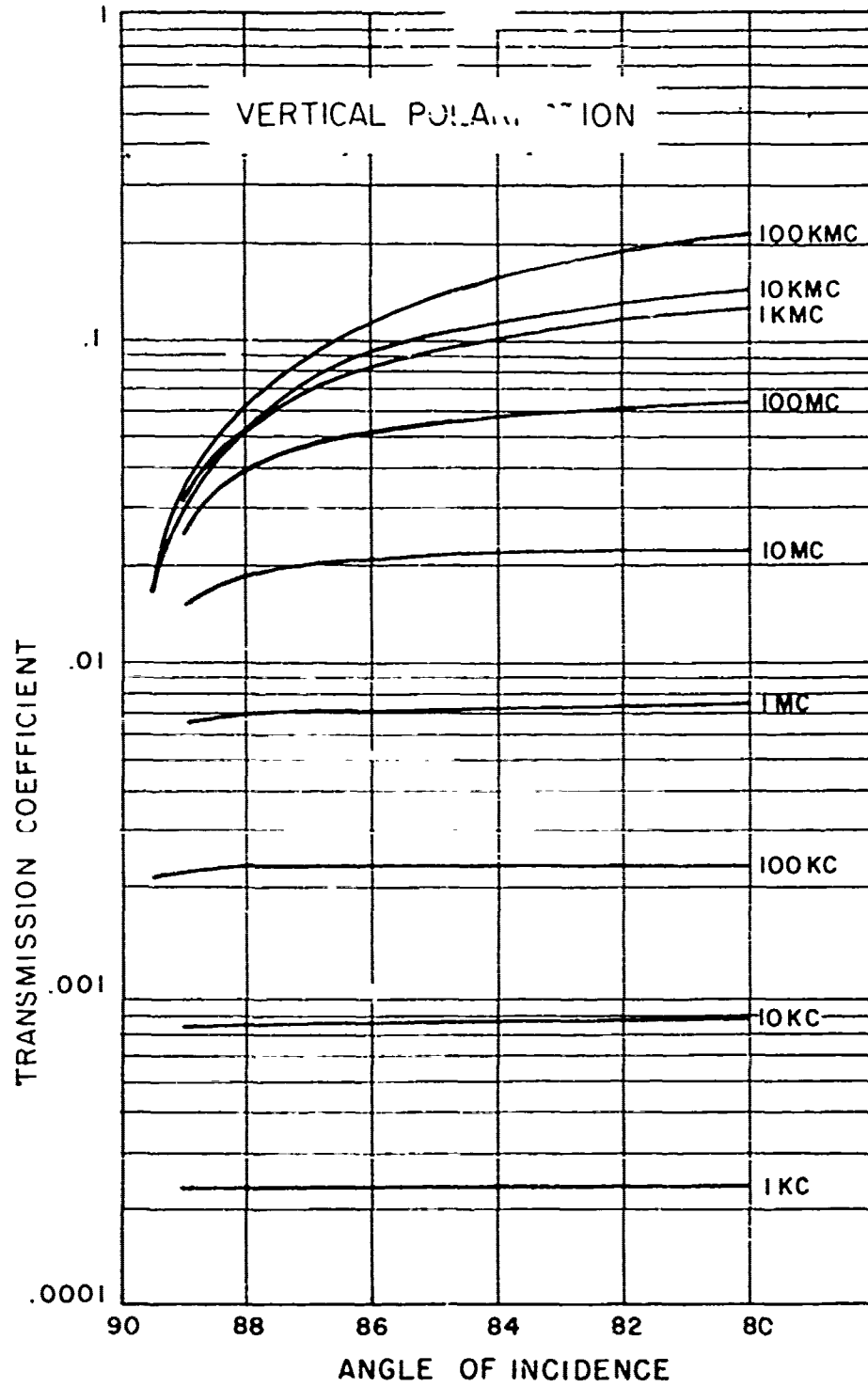
ANGLE OF INCIDENCE

FIGURE 8

PHASE ANGLE OF T.C. FOR
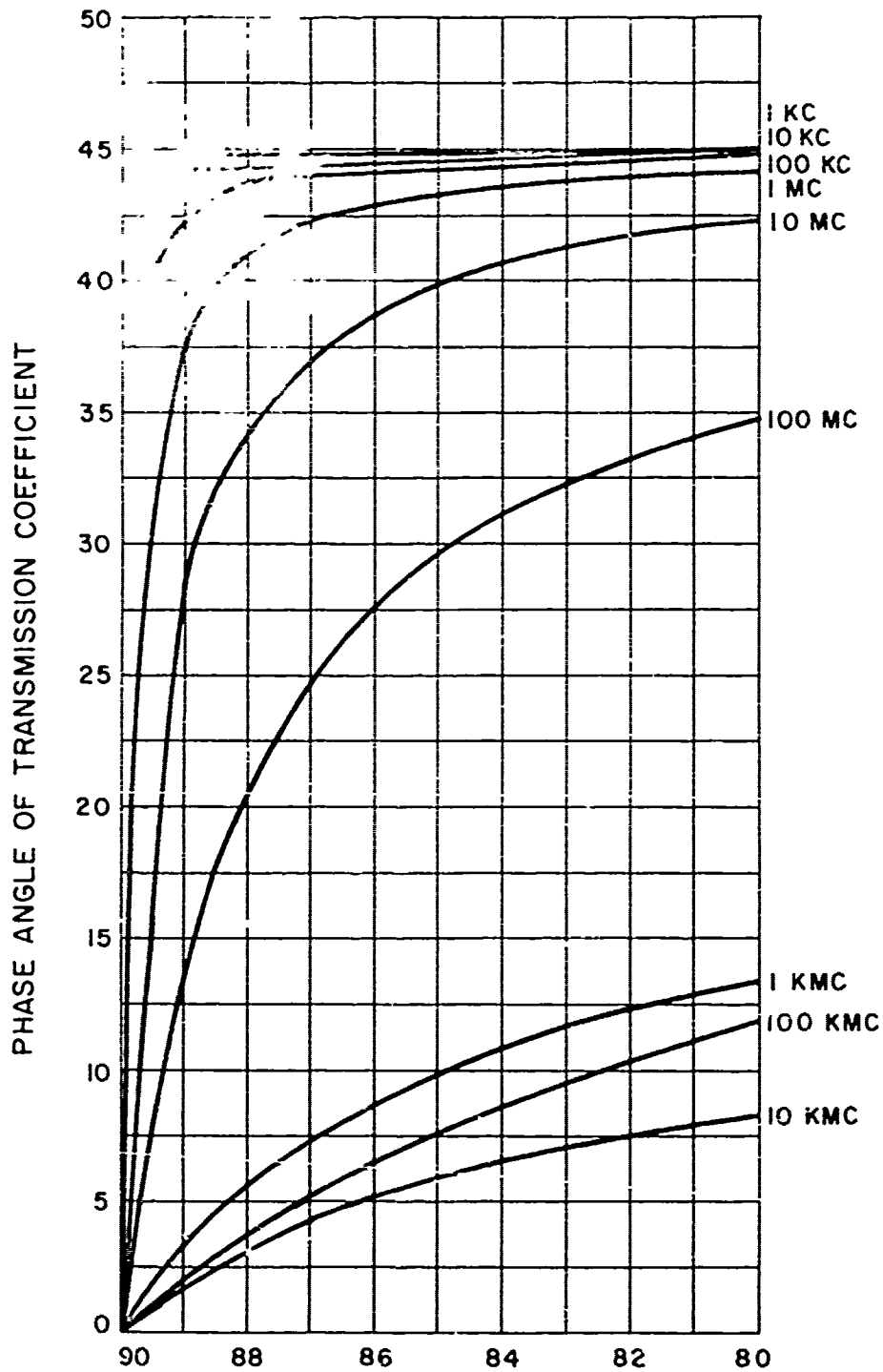.ERTICAL POLARIZATION



FIGURE 9

5.  Curves 7, 8 and 9 (figures 10, 11 and 12) repeat those of the preceding paragraph for horizontal polarization of the incident wave.  In this case, the transmission coefficient falls rather rapidly toward zero as the angle of incidence increases.  It should be noted that the points at zero angle of incidence, at corresponding frequencies, are identical for both horizontal and vertical polarization. For a wave directed perpendicular to an interface, the sense of polarization is lost.

It is noted that as frequency increases the transmission coefficient increases, as does also the attenuation within the sea water medium.  In the region of the frequency spectrum, where we may expect to obtain 10 to 50 per cent of the incident field strength on the under side of the interface, the attenuation is so high that the signals are useless.  In the region where attenuation becomes more nearly reasonable, the losses through the interface become large.

6.  Curve 10 (figure 13) shows the total attenuation to be expected when loss through the interface and loss through sea water to any selected depth are accounted for. Vertical polarization of the incident signal was chosen because the transmission coefficient is virtually independent of angle of incidence.  In addition the curves obtained will represent the most favorable limit for total attenuation.  Horizontally polarized signals will give higher values for all angles of incidence.

The following functions were obtained graphically:

$$\alpha \text{ (interface)} = 13.25 \ f^{-.0667} \tag{26}$$

$$\alpha \text{ (sea water)} = .0037 \ D \ \sqrt{f} \ ; \tag{27}$$

where f is the frequency in cycles per second, D is the depth of penetration in meters and $\alpha$ is attenuation in nepers.  These values of attenuation agree with the results shown in reference 1.  The frequency at which the total attenuation is a minimum for any fixed depth D is given by:

$$f = \left[\frac{478}{D}\right]^{1.76} \tag{28}$$

## TRANSMISSION COEFICIENT FOR
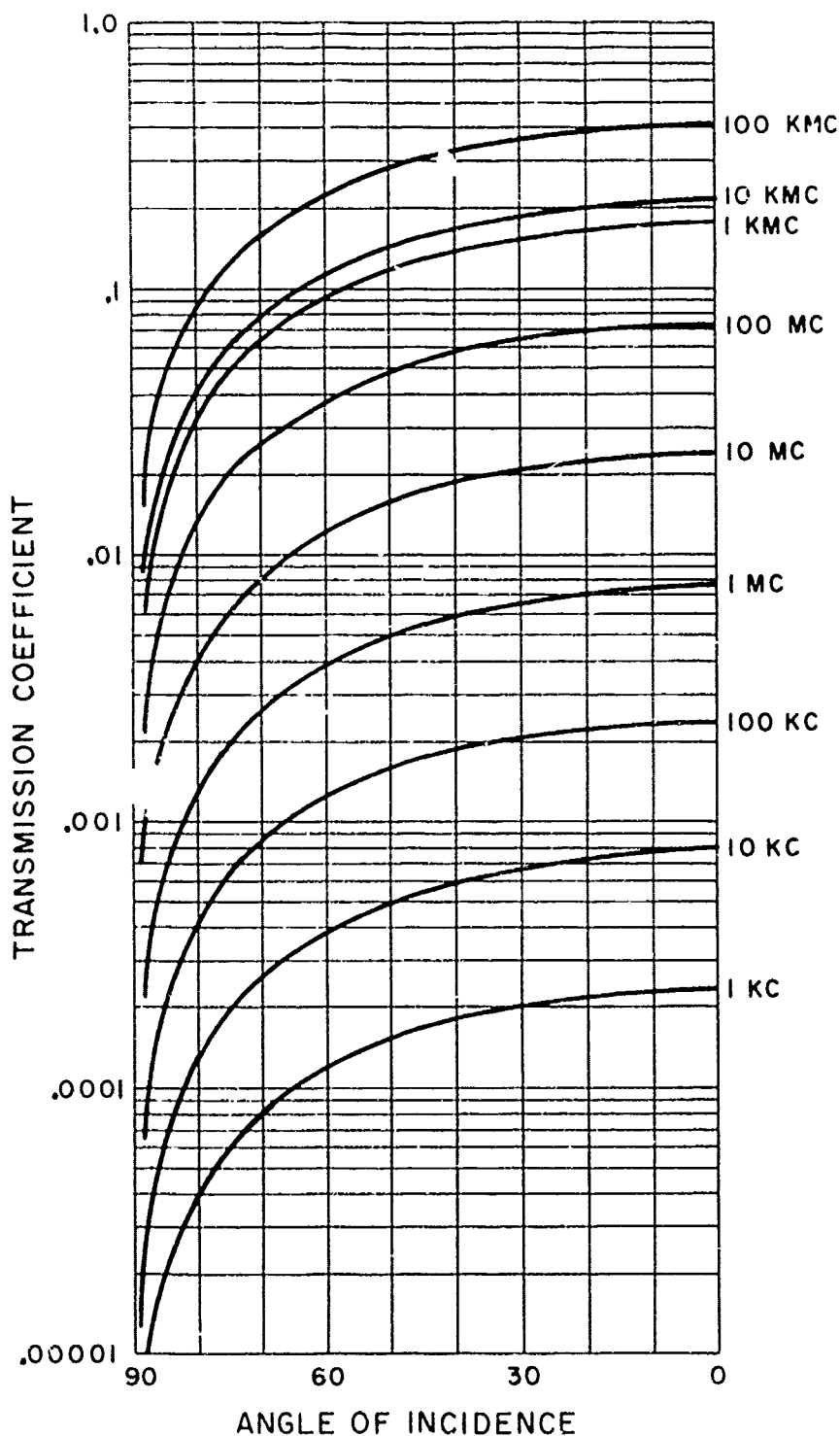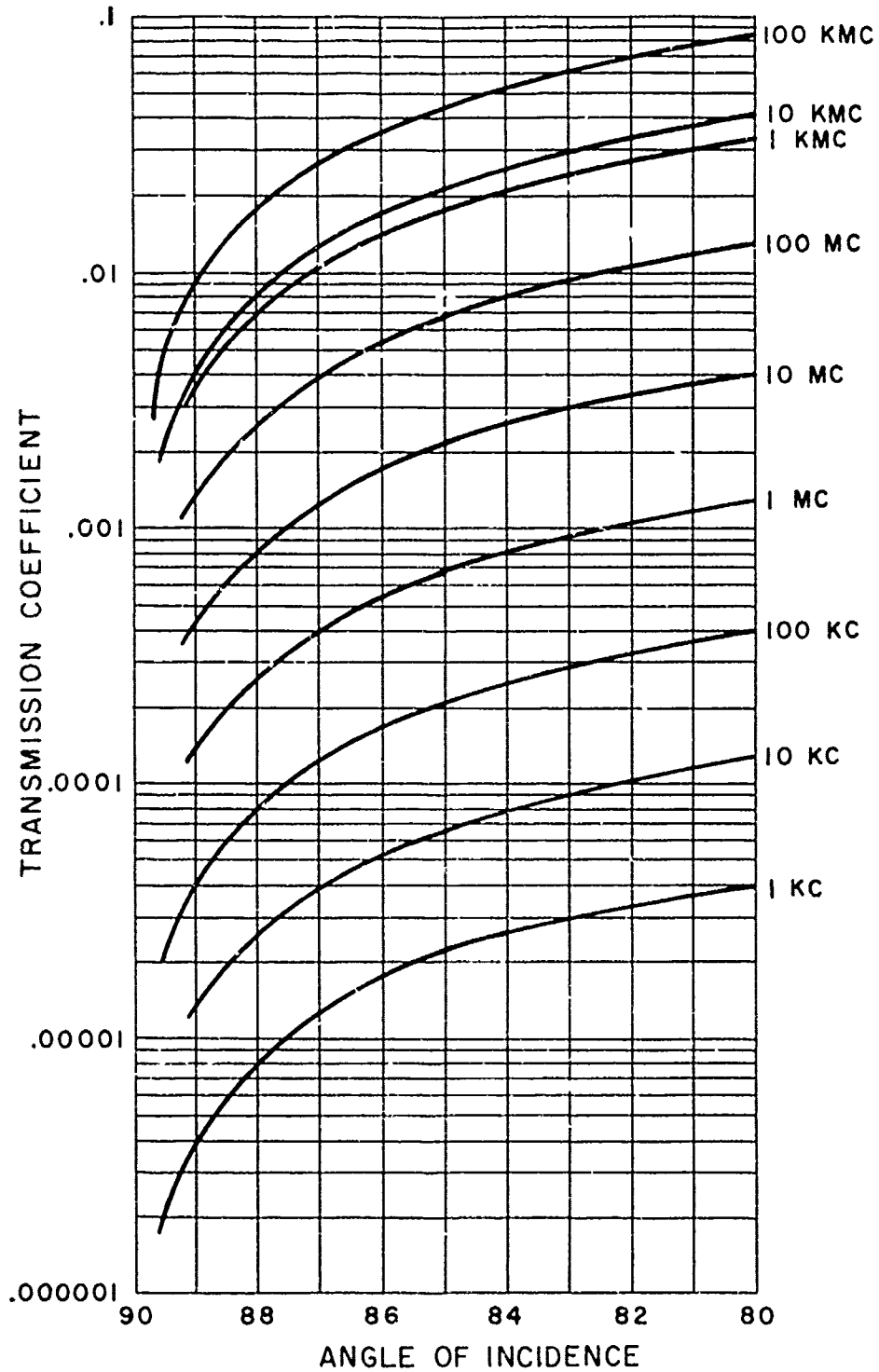## HORIZONTAL POLARIZATION



FIGURE 10

T.C. FOR HORIZONTAL POLARIZATION



FIGURE 11

PHASE ANGLE OF T.C. FOR
HORIZONTAL POLARIZATION
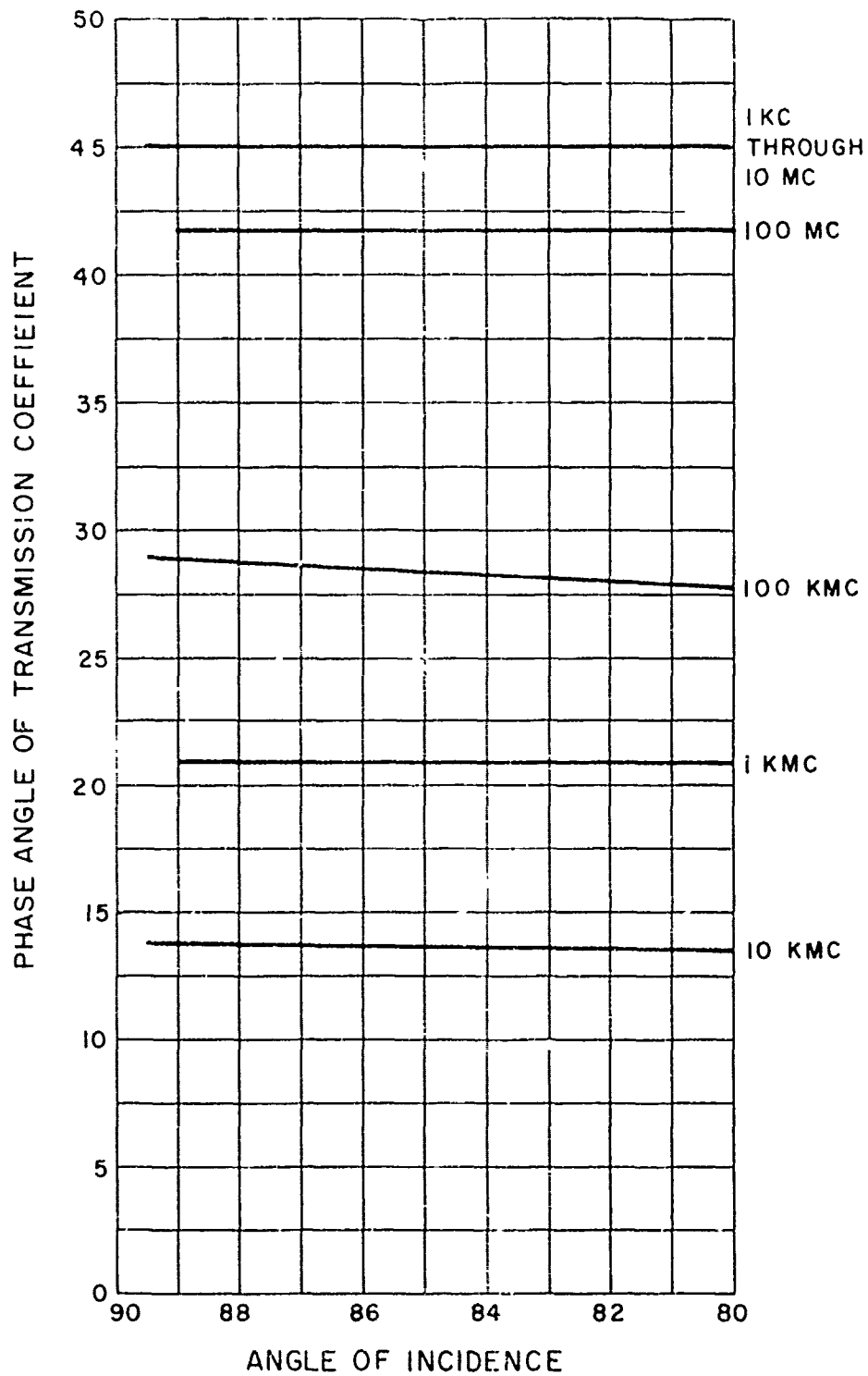


FIGURE 12

TOTAL ATTENUATION THROUGH
THE INTERFACE AND SEAWATER
OF FIXED DEPTH
(VERTICAL PROPAGATION)

TOTAL $\alpha$ FOR 100 METER PENETRATION

PENETRATION TO D = 100 METERS

LOSS THROUGH INTERFACE

D = 10 METERS

D = I METER

$\alpha$ IN NEPERS

FREQUENCY

FIGURE 13

HROUGH
WATER

TOTAL α FOR 100 METER PENETRATION

TOTAL α FOR 10 METER PENETRATION

TOTAL α FOR 1 METER

LOSS THROUGH INTERFACE

= 10 METERS

D = 1 METER

KC | 10 KC | 100 KC | MC
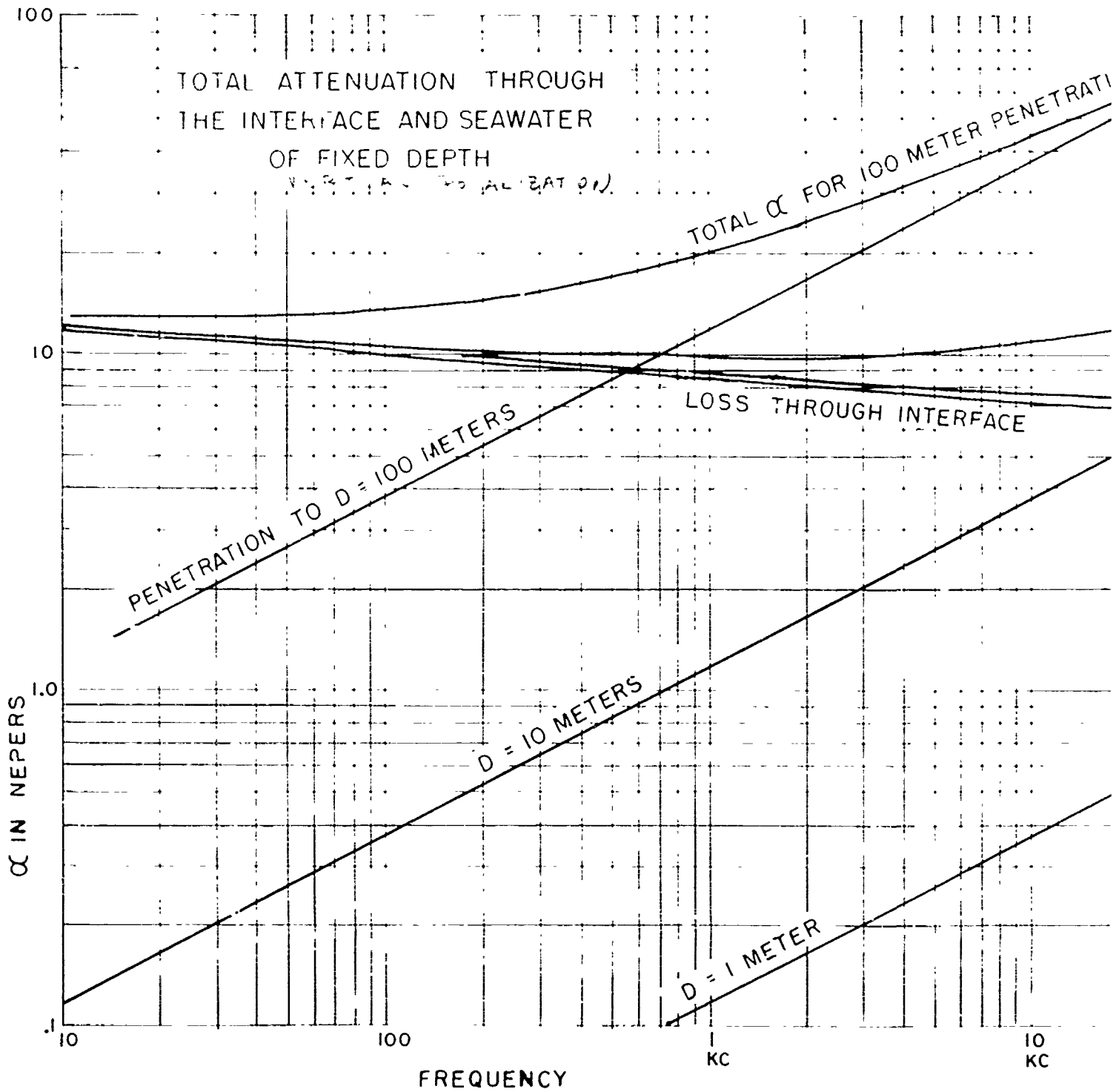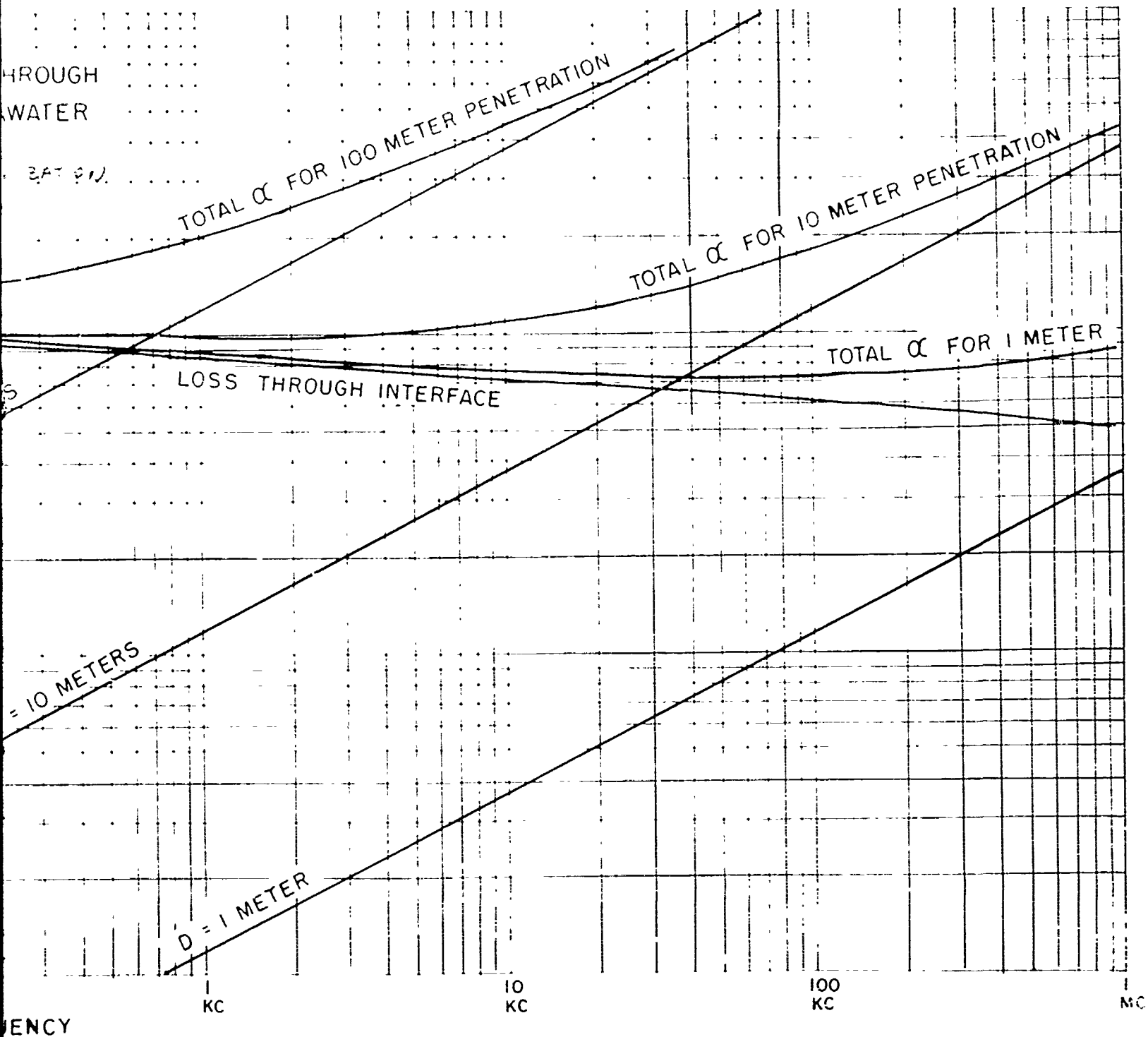
ENCY

The table below gives some representative values.  These
are rather optimistic minima for total attenuation to the
depth selected.  Frequencies different from those given
will increase the total  $\alpha$  , as will the use of horizontal
polarization.

| D | f for $\alpha$ Min. | $\alpha$ Total at f |
|---|---|---|
| 100 m. | 16 cps | 13 nepers (113 db) |
| 10 m. | 900 cps | 9.8 nepers (85 db) |
| 1 m. | 52 kcs | 7.2 nepers (62.5 db) |

CONCLUSIONS

The conclusions which may be drawn from this brief
survey are:

1.   That there are probably no "holes" or "windows"
in the electromagnetic spectrum of sea water below 100 kilo-
megacycles which may be used for communication with or
direct surveillance of submerged vehicles.

2.   That radio control or communications systems to
be developed should employ, wherever possible, vertically
polarized transmitting antennae, to maximize the signal
passed through the air-sea interface and minimize the depend-
ence of this signal on angle of incidence.

3.   That in the selection of a carrier frequency for
proposed underwater vehicle control systems, the minimum
interface-sea water attenuation formula be considered.  This
formula, (28) in the body of this report, is

$$f \quad min. = \left[ \frac{478}{D} \right]^{1.76} \quad ;$$

where D is the required depth of penetration in meters.

In general we may confirm, for the case of electromagnetic
waves, a conclusion drawn by acousticians for sound waves;
that is, sea water is a very difficult medium to use for the
transmission of signals.

## References

1. "The Submerged Reception of Radio Frequency Signals"
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2. "Electrical Properties of Sea Water" (Reflection and
   Attenuation Characteristics at V. H. F.) by J. A. Saxton
   and J. A. Lane, Wireless Engineer, October 1952.

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   John Wiley and Sons, Inc., 1954. Table 8.1, pages 22,
   23.

4. "Summary Technical Report of the Committee on Propaga-
   tion", NDRC, Volume 1, pub. 1946. Figure 2, page 33.

5. Eshbach "Handbook of Engineering Fundamentals", Second
   Edition, John Wiley and Sons, 1952.

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