

AD-A051 369

TRACOR INC WASHINGTON D C
ACOUSTIC ATTENUATION IN THE DEEP OCEAN BELOW 2000 HZ, (U)
FEB 70 J T GOTTWALD

F/6 8/10

UNCLASSIFIED

TRACOR-T-70-WA-2001-U

NL

| OF |
AD
A051 369



END
DATE
FILMED

4-78

DDC

MOST Project - 2

3
1

14 TRACOR-
TRACOR Document No. -T-78-WA-2001-U

000522

AD A 051369



6 ACOUSTIC ATTENUATION IN THE DEEP OCEAN
BELOW 2000 Hz

Good

By

10 J. T. GOTTWALD

12 26p.

11 10 Feb 1978

AD No.
DDC FILE COPY

DDC
RECEIVED
MAR 16 1978
D

000522

88-11

1735 Eye Street North West, Washington, D.C. 20006, AC 202/659-2400
Home Office: TRACOR Inc., 6500 Tracor Lane, Austin, Texas 78721 AC 512 / 926-2800

TRACOR

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

388 404



TRACOR Document No. T-70-WA-2001-U

ACOUSTIC ATTENUATION IN THE DEEP OCEAN
BELOW 2000 Hz

10 February 1970

By
J. T. GOTTWALD

DDC
RECEIVED
MAR 16 1978
D

ACCESSION for	
DTIC	White Section <input checked="" type="checkbox"/>
DDC	Ref Section <input type="checkbox"/>
UNANNOUNCED	<input type="checkbox"/>
JUSTIFICATION	
Per Hr. on file	
BY	
DISTRIBUTION/AVAILABILITY CODES	
Dist.	AVAIL. and/or SPECIAL
A	

i

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited



TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
1	INTRODUCTION	1
2	SUMMARY	2
3	SUMMARY OF ATTENUATION MECHANISMS	3
4	SUMMARY OF MEASURED ATTENUATION COEFFICIENTS FOR THE DEEP OCEAN	14
5	USEFUL EXPRESSIONS FOR ATTENUATION BELOW 2.0 KHz	17
6	BIBLIOGRAPHY	21



LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	ATTENUATION IN FRESH AND SALT WATER AT 5°C COMPARED WITH ABSORPTION ALONE AT 5°C.	6
2	ATTENUATION IN SEA WATER AT 5°C COMPARED WITH THE EQUATION OF SCHULKIN AND MARSH AT 5°C.	8
3	SUMMARY OF ATTENUATION MEASUREMENTS BELOW 100 KHz	9
4	ATTENUATION AS A FUNCTION OF DEPTH FOR A TYPICAL DEEP OCEAN THERMAL PROFILE	12
5	MEASURED ATTENUATION VERSUS FREQUENCY	15
6	SEVEN EMPIRICAL EXPRESSIONS FOR ACOUSTIC ATTENUATION AT LOW FREQUENCIES	18
7	ATTENUATION COEFFICIENT VERSUS FREQUENCY	20



1. INTRODUCTION

All acoustic energy propagated in the deep ocean is ultimately degraded into some form of heat energy. The sources of the dissipation are generally divided into two categories: those due to dissipation of acoustic energy in the transmitting medium and those associated with conditions at the boundaries of the medium. In the deep ocean where long paths exist apart from boundary reflection, the dissipation of acoustic energy into the medium itself is of extreme importance.

Attenuation is the term used to describe the decrease in acoustic energy by means other than spreading. Attenuation is caused by absorption in the medium along the propagation path, by scattering from the propagation path, and by leakage from the path through the interaction of the path size and the acoustic wavelength. The absorbed energy is converted to heat and is lost as acoustic energy. The scattered energy and the energy lost through leakage may be rescattered, absorbed at a boundary or absorbed in the medium. Each of these mechanisms is predominate over a unique part of the acoustic spectrum.



2. SUMMARY

This report presents a brief summary of existing acoustic attenuation mechanisms and attenuation data. An empirical relation between the attenuation and frequency is developed which fits the available data below 2000 Hz to within 16%. This expression is given by

$$\alpha = 0.0265f^{3/4} = 0.0165f \text{ to the } 3/4 \text{ power}$$

where f is in KHz and α is in dB/Kyd. This expression was developed from the data of Thorp, Kibblewhite, et-al., and Urick. No attempt was made to correlate the attenuation coefficient at low frequencies with temperature, depth or salinity since the quantity of available data is not sufficient and the scatter of the data is too large.



3. SUMMARY OF ATTENUATION MECHANISMS

The three principal attenuation mechanisms which result in conversion of acoustic energy into heat energy and a resulting decrease in available acoustic energy are as follows:

(a) Viscous losses, resulting from relative motion occurring between various portions of the medium during the compressions and expansions that accompany transmission of an acoustic wave.

(b) Heat conduction losses which occur when heat flows from the high pressure to the low pressure areas accompanying the propagation of an acoustic wave.

(c) Molecular exchange losses associated with changes in the molecular structure of the medium which are associated with the finite time that is required for the changes to take place. Each of these absorption mechanisms has been treated in detail by several authors (*References 1, 2, 3).

An expression for the absorption of acoustic energy by fluids due to viscous effects was originally derived theoretically by Lord Rayleigh. This expression was derived upon the assumption that the bulk or volume coefficient of viscosity associated with uniform compression of a fluid should be zero. This resulted in an expression for the absorption α of the form

$$\alpha = \frac{2\omega^2 \eta}{3\rho C^3} \quad (1)$$

where η is the shear coefficient of viscosity, ρ_0 is the density of the fluid; C is the velocity of sound in the fluid and ω is the circular frequency of the acoustic wave.

*Numbers in parenthesis in the text of this memorandum indicate references contained in the bibliography at the end of the memorandum.

TRACOR

It was later discovered that the assumption of a vanishing volume coefficient of viscosity was in error, producing absorption coefficients approximately 3 to 6 times smaller than measured for pure water. Inclusion of a non-vanishing volume coefficient of viscosity results in an expression for α in water of the form

$$\alpha = \frac{\omega^2}{2\rho_0 C^3} \left[\frac{4}{3}\eta + \eta' \right] \quad (2)$$

where η' is the volume coefficient of viscosity.

Direct measurement of the volume coefficient of viscosity indicates that η' in water is approximately three times the coefficient of shear viscosity. Substitution of measured values for ρ_0 , C , η and η' into Equation 2 results in satisfactory agreement between theoretical values and measured values for pure water but does not explain the observed absorption for sea water.

Another mechanism which provides for conversion of acoustic energy into heat energy in the fluid is heat conduction. During the compression of the fluid, resulting from the passage of a sound wave, the temperature is raised and a temperature gradient is established locally. This leads to a flow of heat by conduction from the high pressure (higher temperature) region to the low pressure (lower temperature) region. For most fluids, the magnitude of this effect is small enough for all practical frequencies that a fairly simple theoretical equation results and the expression can be added to the viscous losses which occur. The resulting expression is given in Equation 3

$$\alpha = \frac{\omega^2}{2\rho_0 C^3} \left[\frac{4}{3}\eta + \eta' + \frac{\kappa(\gamma-1)}{C_p} \right] \quad (3)$$

TRACOR

where κ is the thermal conductivity of the fluid, C_p is the specific heat at constant pressure and γ is the ratio of the specific heat at constant pressure to the specific heat at constant volume. As indicated, the conversion of acoustic energy into heat at normal frequencies is very small compared to the conversion by means of viscous effects. The ratio of the conversion by viscous effects to the conversion by heat conduction at 4°C is 3×10^3 . For all practical purposes, the effects of heat conduction can be neglected in water.

Figure 1 contains a graph of Equation 2 for a temperature of 5°C for fresh water. Also included in Figure 1 is a plot of the measured attenuation in fresh water at 5°C , and a plot of the measured attenuation in sea water at 5°C . The agreement between Equation 2 and fresh water is within the range of the experimental error of the measurements and it is apparent from the curve for sea water at 5°C that below 400 KHz there are additional processes producing absorption in sea water beyond those present in fresh water.

It is natural to attribute this additional absorption to the presence of dissolved salts in sea water and to refer to it as a type of chemical relaxation. Laboratory measurements by Leonard (4) and co-workers have shown that the excess acoustic absorption of sea water as compared to fresh water is caused almost entirely by the presence of dissolved MgSO_4 . Liebermann showed theoretically (5), that the ionic relaxation mechanism together with viscosity should yield a frequency dependent absorption coefficient of the form

$$\alpha = A \frac{S f_t f^2}{f_t^2 + f^2} + B f^2 / f_t^2 \quad (4)$$

Schulkin and Marsh (6) developed a fit between this equation and some 30 thousand measurements made at sea between 2 and 25 KHz

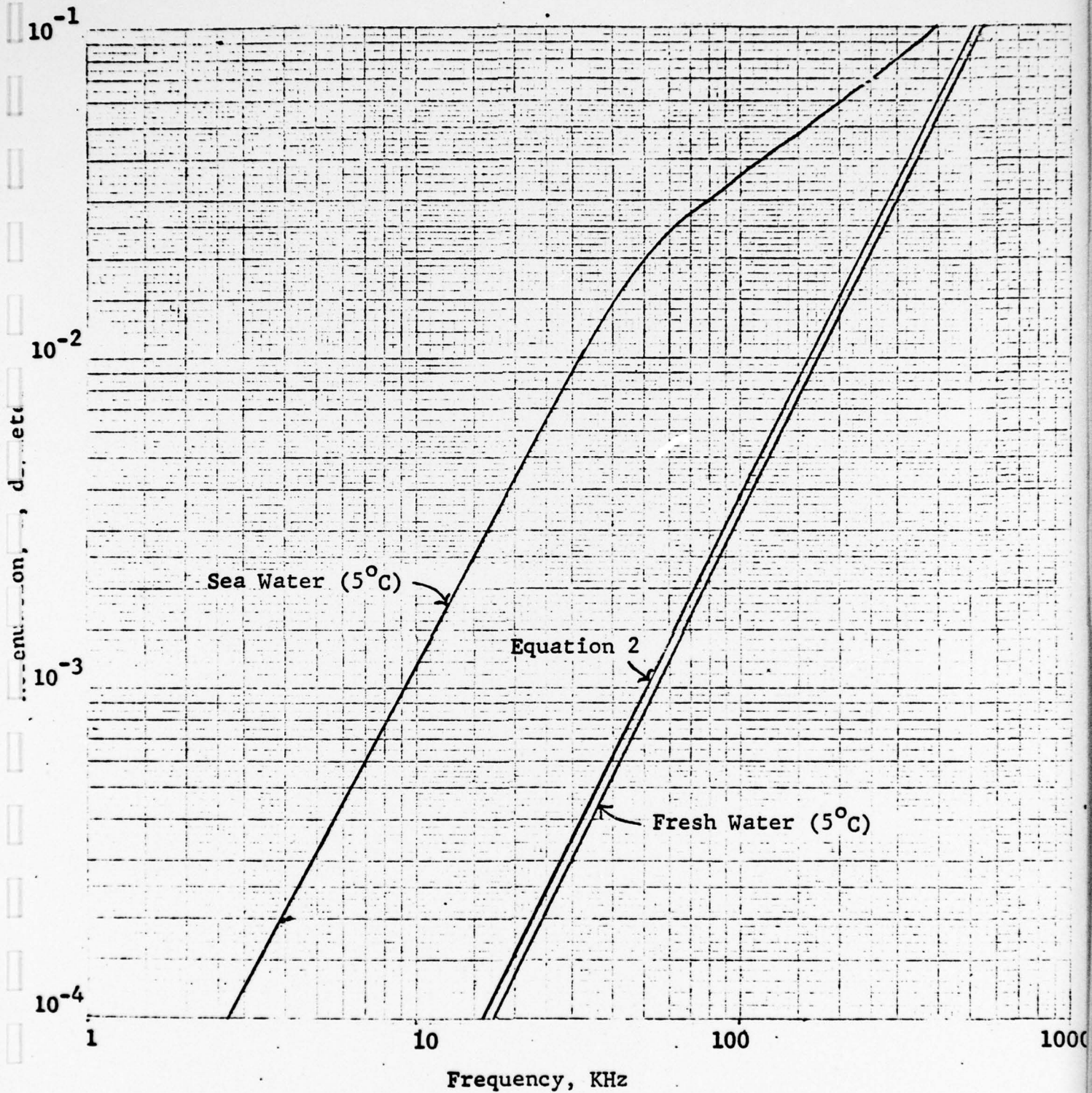


Figure 1 - Attenuation in Fresh and Salt Water at 5°C compared with absorption alone at 5°C.



out to ranges of 25 Kyds. The following values for the terms in Equation 4 were developed:

$$A = 1.36 \times 10^{-2}$$

$$B = 2.68 \times 10^{-2}$$

S = Salinity in parts per 1000 of sea water, ‰

f = Frequency in KHz

f_t = Temperature dependent relaxation given by

$$f_t = 21.9 \times 10^6 - \left(\frac{1520}{T+273} \right) \quad (4a)$$

At high frequencies ($f \gg f_t$) the second term in Equation 4 becomes dominant. This is the term associated with viscous absorption and is proportional to the square of the frequency. When f has a value in the neighborhood of f_t , the absorption varies in a very complicated fashion; both with frequency and temperature. Figure 2 presents the same measured curve for sea water at 5°C that is presented in Figure 1 and, in addition, presents the attenuation in dB per meter at 5°C as computed from Equation 4. It must be pointed out that Equation 4 is useful only for frequencies above 2 KHz and no attempt should be made to apply this equation in determining attenuation of sound in sea water at frequencies below 2 KHz.

The attenuation of acoustic energy from frequencies of 5 KHz up appears to be well understood in terms of viscous attenuation, heat loss, and chemical relaxation due to $MgSO_4$. However, for frequencies below approximately 5 KHz, measured attenuations depart from the theoretically derived expressions based upon the afore mentioned physical mechanisms, indicating that additional processes are involved in acoustic attenuation below frequencies of around 5 KHz. This is graphically illustrated in the compilation by Thorp (7) which is reproduced as Figure 3. It is apparent in Figure 3 that below 5 KHz, the measured attenuation data departs from the relaxation absorption curve of Schulkin

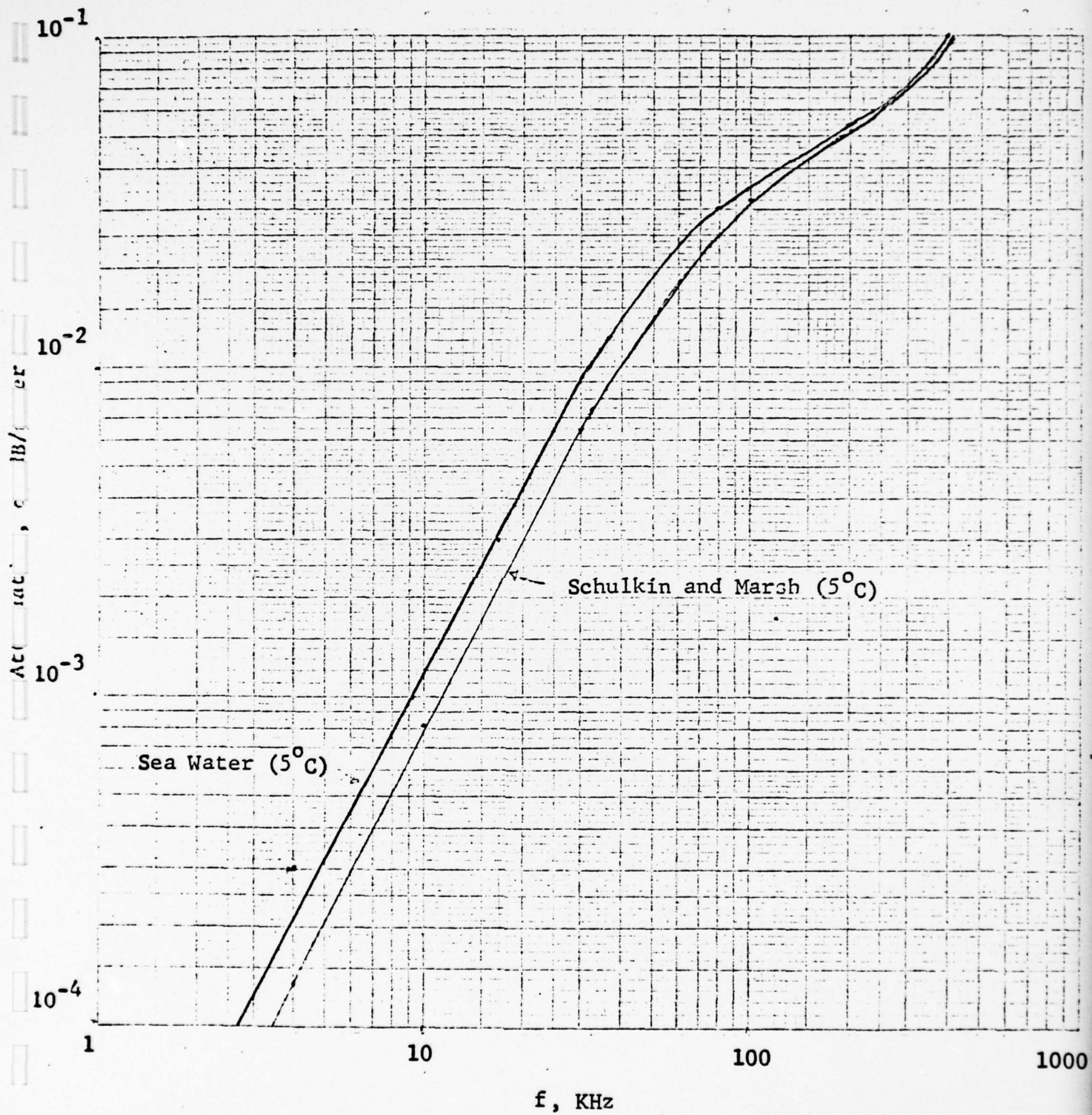


Figure 2 - Attenuation in Sea Water at 5°C compared with the equation of Schulkin and Marsh at 5°C. -8-

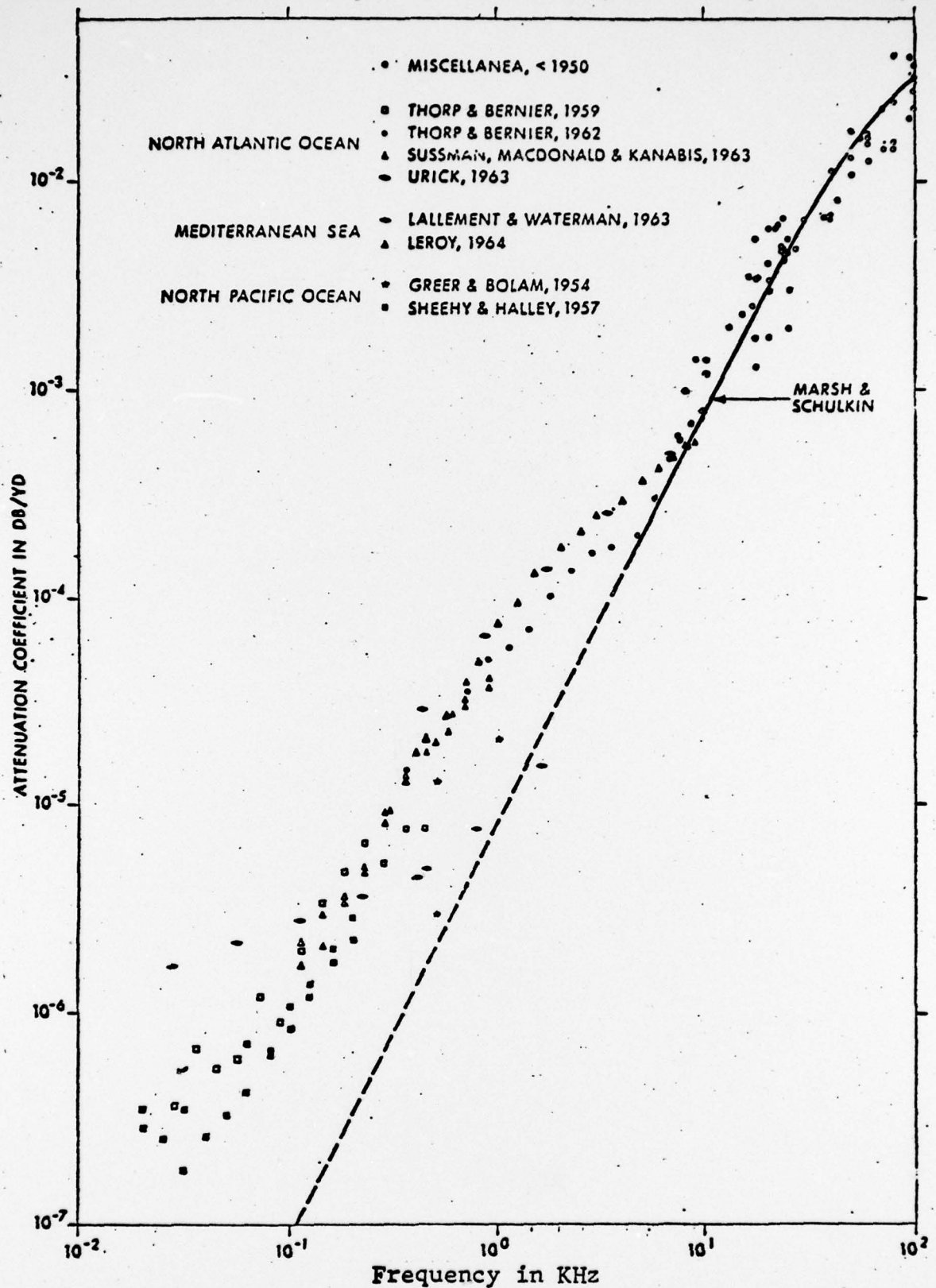


Figure 3 - Summary of attenuation measurements below 100 KHz. Origin and geographical area in which data were obtained since 1954 are indicated. The relaxation absorption curve for a depth of 4000 ft, temperature of 40°F, and salinity of 35% from Marsh and Schulkin, is shown for comparison.



and Marsh by approximately one decade. It is also apparent that at least one set of measurements, i.e., Urick (1963), varies from the general trend of the measured data particularly below 100 Hz. Subsequent measurements of very low frequency attenuation coefficients by Kibblewhite et-al., and Urick indicate that below about 500 Hz additional physical mechanisms are involved in the attenuation process.

Measurements of attenuation at very low frequencies require the use of extremely long propagation paths. These paths exist only in the deep ocean and involve 3 modes of propagation:

- (a) RSR Modes
- (b) SOFAR Modes
- (c) Bottom Reflected Modes.

In general, Bottom Reflected Modes will be unimportant at very long ranges. The attenuation suffered via the RSR and SOFAR Modes in contrast will be very small and, in fact, at long ranges, the energy received will be mainly due to a finite number of trapped RSR and SOFAR Modes. If a shallow source is considered, then the relative degree of excitation of SOFAR Modes would be expected to be small and RSR Modes would predominate. As the frequency decreases, the number of trapped RSR Modes would tend to decrease and more energy would be lost by defraction and scattering into the bottom. However, temperature and salinity inhomogeneities can cause attenuation through a net transfer of energy from trapped to untrapped modes; this mechanism would be expected to become more efficient as the frequency increased. As a result, at very low frequencies, it would be expected that the attenuation would demonstrate a minimum at some particular frequency with the attenuation increasing both for decreasing and increasing frequency. This, in fact, has been observed by Kibblewhite et-at., and Urick in their recent measurements (8, 9, 10, 11, 12). Urick (8) discusses the scattering and leakage problem theoretically as applied to the SOFAR channel. Kibblewhite, Denham and Barker (10) discuss the leakage problem and the scattering problem as applied



to the RSR propagation paths. The resulting analyses are essentially identical except in the various details concerning the size of the tracks which are traversed by the rays and the actual path length involved for a given range, but the physical mechanisms involved are identical for both the SOFAR and the RSR propagation modes. Thus it appears that a theoretical explanation for the observed attenuation coefficients at very low frequencies is available.

The effect of pressure or depth on absorption has been investigated theoretically and experimentally using the resonator decay method. In the range of hydrostatic pressure found in the sea, the effect of pressure is to reduce the absorption coefficient as shown in Equation 5

$$\alpha_d = \alpha_0(1 - 1.93 \times 10^{-5} d) \quad (5)$$

where α_d is the absorption coefficient at a depth d , α_0 is the absorption coefficient at zero depth, and d is the depth in feet. When Equation 5 is combined with Equation 4 and the attenuation is computed as a function of depth for a typical velocity profile in the deep ocean, the curve of Figure 4 results. This curve is computed for a frequency of 4 KHz and salinity 35 parts per thousand. This figure illustrates the combined effects of temperature and pressure variations upon the attenuation coefficient. In the upper 3 to 4 thousand feet, the predominant factor is the decreasing temperature which causes an increase by a factor of 2 in the attenuation coefficient. Below 3000 feet the temperature becomes constant and the principal factor is the increase in depth or pressure which causes a decrease in the attenuation coefficient of about 15% of the value at 4000 feet. Figure 4 particularly illustrates the errors which can be encountered if near surface attenuation values are used in figure of merit computations for RSR or Reliable Acoustic Paths systems. Since,

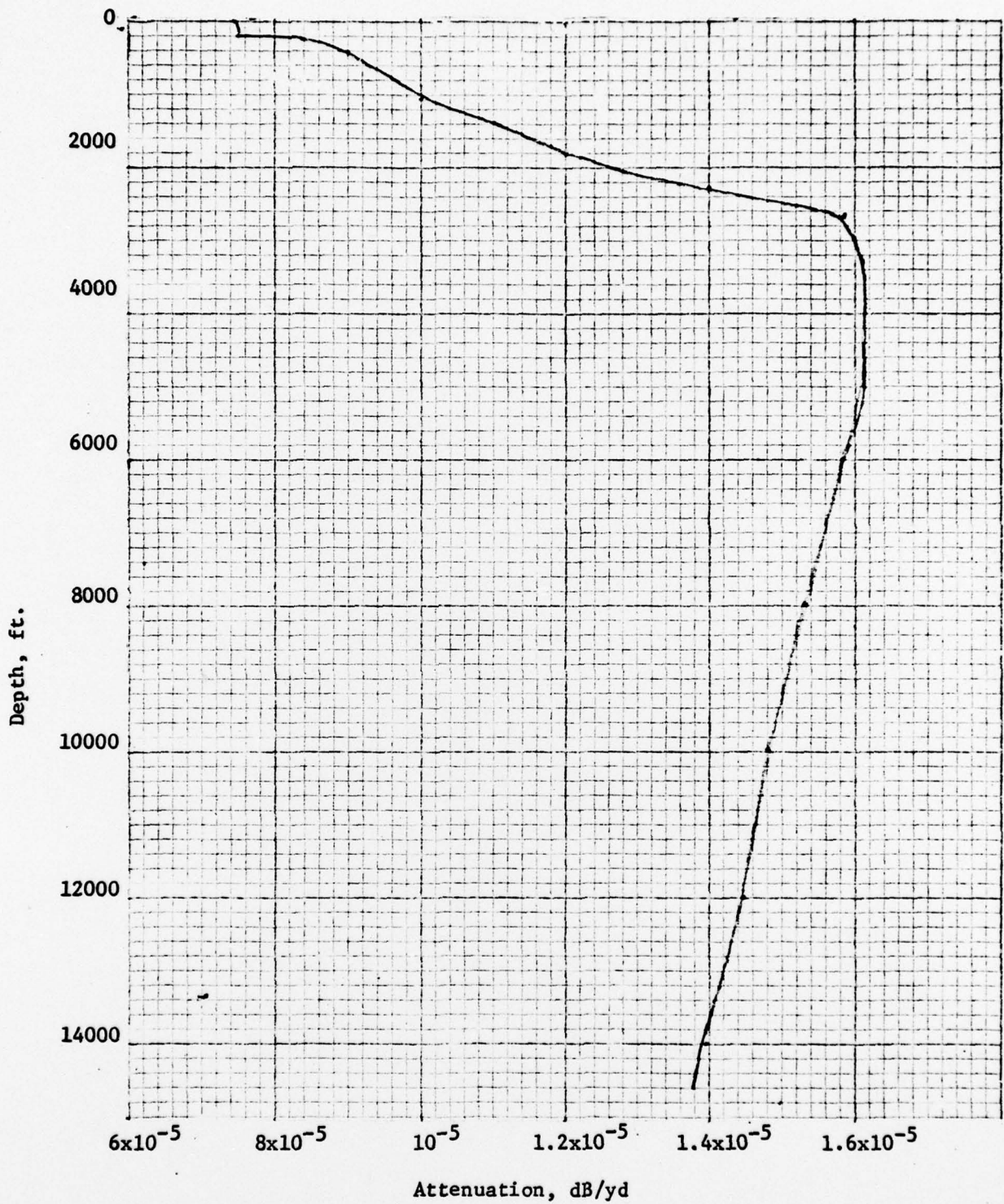


Figure 4 - Attenuation as a function of depth for a typical deep ocean thermal profile (computed from Equation 5) $f_o = 4$ KHz

TRACOR

in those cases, approximately 80% of the traveled path lies below 2000 feet, the use of near surface attenuation coefficients would result in an error of a factor of 2 in the correct attenuation value.

In reference to Equation 5, and Figure 4, it should be pointed out that these results are known to be applicable for attenuation at frequencies above 2 KHz. Below this frequency other mechanisms predominate in the attenuation and, as yet, the effect of pressure at extremely low frequencies has not been fully investigated or documented.

In summary, there are three principal mechanisms which produce attenuation of acoustic energy in the ocean. These are:

(1) Absorption of energy by means of viscous and molecular exchange phenomena.

(2) Scattering of acoustic energy by means of thermal and chemical inhomogeneities in the water.

(3) Leakage of acoustic energy from propagation modes. Absorption appears to be the predominant cause of attenuation above 2 KHz. In the region from 10 Hz to 2 KHz the predominant mechanism appears to be scattering and below 10 Hz leakage appears to be the predominant mechanism.



4. SUMMARY OF MEASURED ATTENUATION COEFFICIENTS FOR THE DEEP OCEAN

Thorp (7) has provided a summary of some of the measured values for deep ocean sound attenuation prior to 1965. Since that time, Urick and Kibblewhite, et-al., have provided a large number of measured values of deep ocean sound attenuation. As was noted in the previous section, below 5 KHz the measured values deviate significantly from the values as computed from Schulkin and Marsh. Subsequent measurements have shown that the deviation is even greater in the frequency region below 1 KHz. Figure 5 is a summary of the measured values reported by Urick and Kibblewhite et-al. The value of the attenuation as computed from Equation 4 and plotted in Figure 3, is also plotted in Figure 5 for reference purposes. It will be noted that for frequencies below 100 Hz, the error arising from using Equation 4 will amount to a factor of 10 to 20. The large spread of the data between 10 Hz and 1 KHz is indicative of at least 2 factors:

(1) The size of the attenuation coefficient in this frequency band requires the use of extremely long propagation paths for measurements. The propagation loss introduced by spreading, must be subtracted from the net propagation loss to obtain the propagation loss or attenuation over the path, thus the propagation over the path must be well understood. It is not too difficult to correct for propagation in the SOFAR or deep sound channel provided that the velocity profile information is available, but bottom contour information must be available and the effect of near surface channeling must be accounted for so that an adequate description of spreading loss can be included in the experiment.

(2) The value of the attenuation coefficient at low frequencies necessitates extreme care in the calibration of the equipment used in the measurements. Any slight inaccuracies, errors or systematic shifts in the calibration of the equipment

- - Urick, 1963 (SOFAR)
- - Urick, 1964 (RSR)
- - Kibblewhite, et-al., 1965 (SOFAR)
- △ - Urick, 1966 (SOFAR)
- - Kibblewhite, et-al., 1967 (RSR)
(Two values indicate measurements in two different areas)
- ▲ - Thorp, 1965 (RSR)

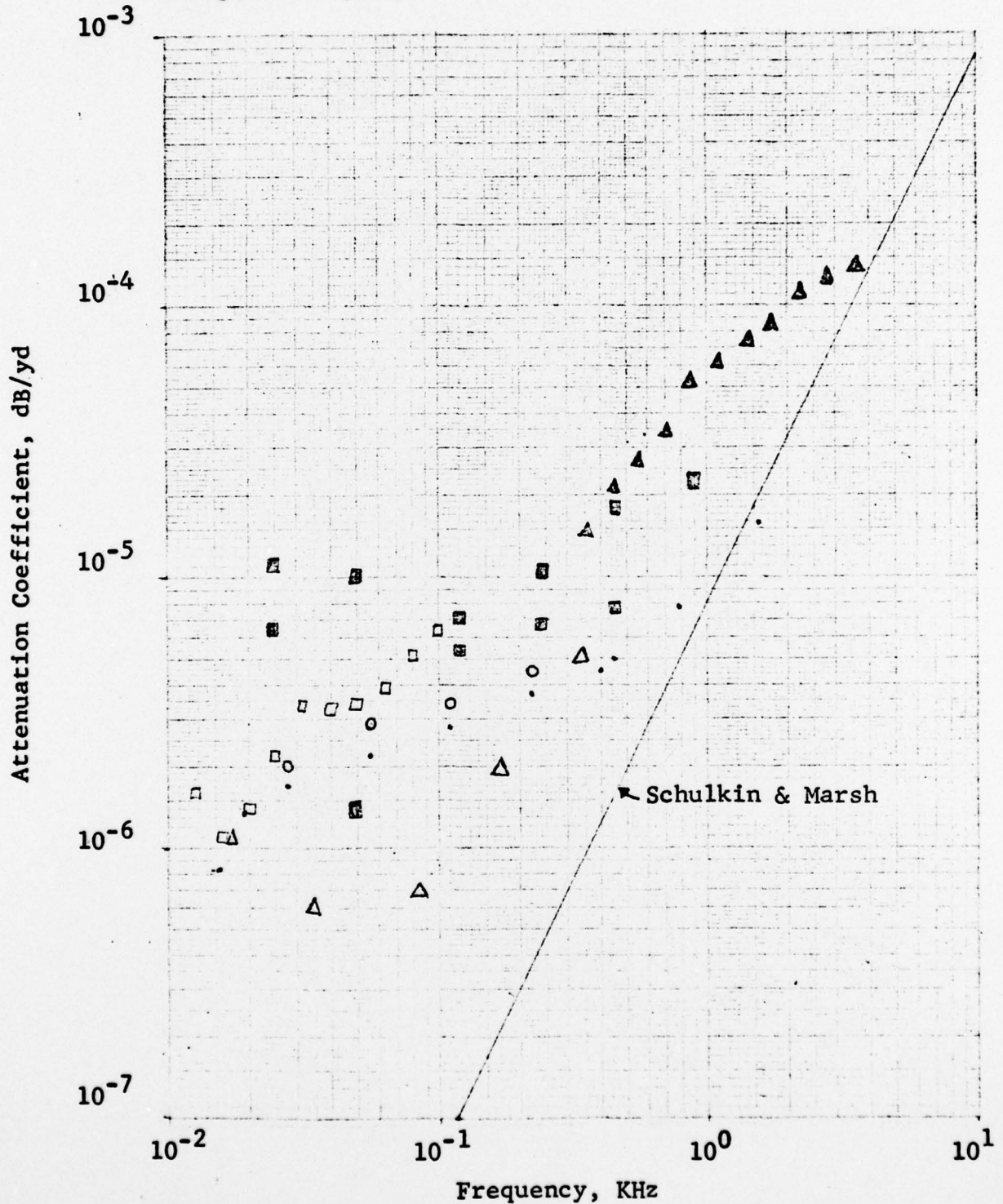


Figure 5 - Measured Attenuation Versus Frequency

TRACOR

will produce fairly large inaccuracies in the measured attenuation coefficient, and the spread observed in Figure 5 is probably due in some measure to slight inaccuracies in the calibration of the equipment used. This is further confirmed by the apparent randomness of the measured values in any given octave.

A third factor which was initially believed to cause an error was the use of explosive sources in the experiments. The measurements of Thorp were made using a coherent source and the general agreement between those measurements and the other measurements plotted in Figure 5 indicates use of explosives does not induce any undesirable or unknown effects into the measurements.

It will be noted that the results of the work by Sheehy and Halley (13) is not included in Figure 5. The reason for this is that the results of Sheehy and Halley were relative rather than absolute measures of the attenuation and they are, therefore, of little aid in determining the absolute value of the attenuation coefficient. Those results do, however, have a form very similar to those results plotted in Figure 5, and if the value of attenuation obtained by Sheehy and Halley is normalized so that attenuation coefficient is 1.8×10^{-6} dB/yd at 40 Hz, then the other values cluster among those values plotted.



5. USEFUL EXPRESSIONS FOR ATTENUATION BELOW 2.0 KHz

As a result of each set of measurements indicated in Figure 5, each observer postulated an empirical relation between attenuation and frequency. These postulated relations are plotted in Figure 6 for comparison purposes. The length of each curve in Figure 6 defines the frequency range over which the various expressions are valid. While each of the seven expressions presented in Figure 6 represents, to some extent, the measured data as obtained by various observers, none of these expressions satisfies an average value for the entire data sample. The expression proposed by Thorp satisfies the measured data between the frequencies 300 Hz and 1500 Hz fairly well. The two expressions from Urick fit Urick's data fairly well and the one expression from Kibblewhite et-al., fits the upper value of their measured data fairly well. None of these expressions, however, are general enough or agree well enough with the body of data to be used over an appreciable range of frequencies, such as 10 Hz to 1 KHz or even perhaps 5 KHz. A least square fit of the data in Figure 5 to a power function

$$\alpha = af^d$$

was performed. The resulting attenuation expression is given by

$$\alpha = 1.49f^{3/4} \times 10^{-7} \text{ dB/yd (f in Hz)}. \quad (6)$$

The correlation between Equation 6 and the data of Figure 5 is 84.5%. It is recommended that Equation 6 be used to compute underwater acoustic attenuation coefficients in the frequency range from 10 Hz to 2000 Hz until additional data becomes avail-

1 α - Low Frequency Limit of Schulkin & Marsh (50°C)

$$\alpha = 10^{-5} f^2 \text{ dB/yd, } f \text{ in KHz}$$

2 α - Sheehy & Halley

$$\alpha = 3.3 \times 10^{-5} f^{3/2} \text{ dB/yd, } f \text{ in KHz}$$

3 α - Thorp,

$$\alpha = 5.42 \times 10^{-5} f^{3/2} \text{ dB/yd, } f \text{ in KHz}$$

4 α - Urlick (1964),

$$\alpha = (1.5 + 8.1f) \times 10^{-6} \text{ dB/yd, } f \text{ in KHz}$$

5 α - Urlick (1963),

$$\alpha = (5.6f^{1/3} + 8.5f^2) \times 10^{-6} \text{ dB/yd}$$

6 α - Horton,

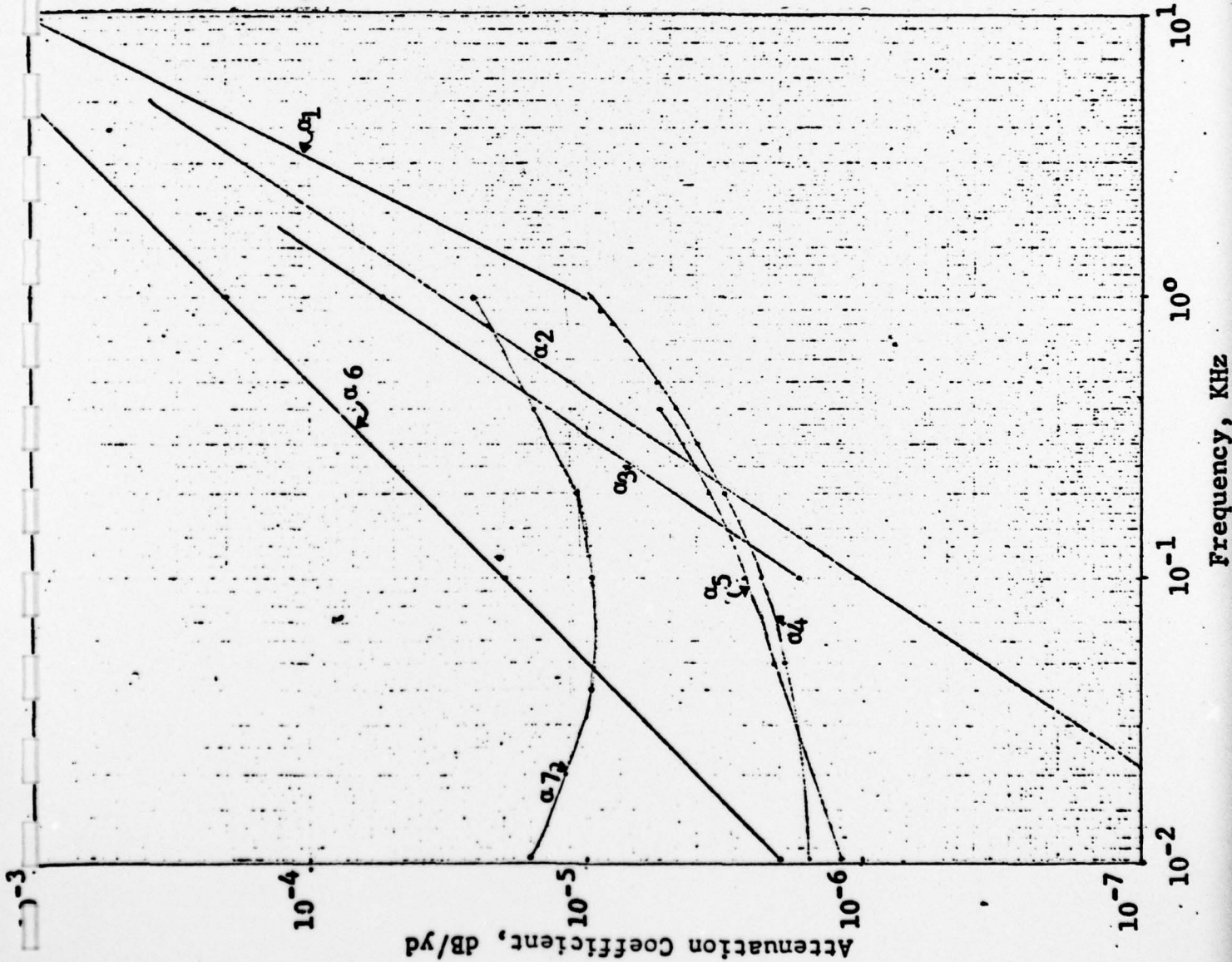
$$\alpha = 2f \times 10^{-4} + 1.5f^2 \times 10^{-7} \text{ dB/yd,}$$

7 α - Kibblewhite et-al.,

$$\alpha = \frac{89}{f} + 6.8 + 1.87f \times 10^{-2} \times 10^{-6} \text{ dB/yd, } f \text{ in Hz}$$

Figure 6

Seven empirical expressions for acoustic attenuation at low frequencies.



TRACOR

able whereby a better expression may be developed.

Figure 7 is a plot of Equation 6 and the data from Figure 5.

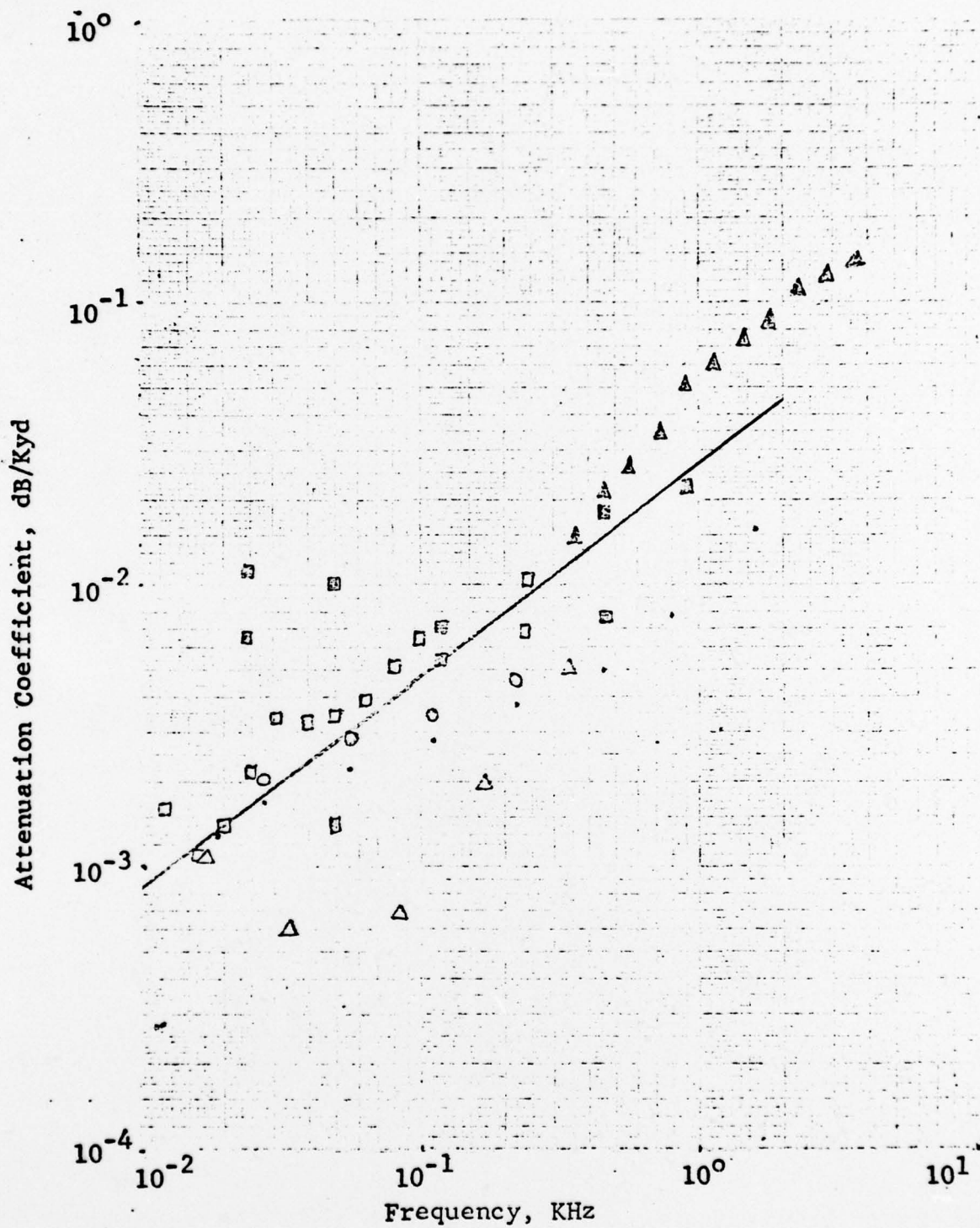


Figure 7 - Attenuation Coefficient Versus Frequency
 Showing The Expression $.0265f^{3/4}$ dB/Kyd



6. BIBLIOGRAPHY

- (1) Kinsler, L. E. and Frey, A. R.,
"Fundamentals of Acoustics"
John Wiley & Sons, Inc., 1962
- (2) Lindsay, R. B.,
"Mechanical Radiation"
McGraw-Hill Book Company, Inc., 1960
- (3) Urick, R. J.,
"Principles of Underwater Sound for Engineers",
McGraw-Hill Book Company, 1967
- (4) Wilson and Leonard,
"Journal of the Acoustical Society of America"
26, 223 (1954)
- (5) Liebermann,
"Physics Review"
75, 1415 (1949)
- (6) Schulkin and Marsh
"Sound Absorption in Sea Water"
Journal of the Acoustical Society of America.
34, 864 (1962)
- (7) Thorp
"Deep-Ocean Sound Attenuation in the Sub- and Low- Kilocycle
per Second Region"
Journal of the Acoustical Society of America,
38, 648 (1965)
- (8) Urick, R. J.
"Low-Frequency Sound Attenuation in the Deep Ocean"
Journal of the Acoustical Society of America.
35, 1413 (1963)
- (9) Urick, R. J.
"Attenuation over RSR Paths in the Deep Sea"
Journal of the Acoustical Society of America
36, 786 (1964)
- (10) Kibblewhite, Denham and Barker
"Long-Range Sound-Propagation Study in the Southern Ocean -
Project Neptune"
Journal of the Acoustical Society of America
38, 629 (1965)



- (11) Urick, R. J.
"Long-Range Deep-Sea Attenuation Measurement"
Journal of the Acoustical Society of America
39, 904 (1966)
- (12) Kibblewhite and Denham
"Long-Range Sound Propagation in the South Tasman Sea"
Journal of the Acoustical Society of America
41, 401 (1967)
- (13) Sheehy and Halley
"Measurement of the Attenuation of Low-Frequency Underwater
Sound"
Journal of the Acoustical Society of America
29, 464 (1957)
- (14) Murphy, Garrison and Potter
"Sound Absorption at 50 to 500 Kc from Transmission
Measurements in the Sea"
Journal of the Acoustical Society of America
30, 871 (1958)
- (15) Thorp
"Analytic Description of the Low-Frequency Attenuation
Coefficient"
Journal of the Acoustical Society of America
42, 270 (1967)
- (16) Brown and Raff
"Theoretical Treatment of Low-Frequency Sound Attenuation
in the Deep Ocean"
Journal of the Acoustical Society of America
35, 2007 (1963)