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WYLE LABORATORIES - RESEARCH STAFF

REPORT WR 72-11

CONTINUED INVESTIGATION INTO THE ANOMALOUS BEHAVIOR OF SOUND ABSORPTION BY MOLECULAR RELAXATION

research report

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CONTINUED INVESTIGATION INTO THE ANOMALOUS BEHAVIOR OF SOUND ABSORPTION BY MOLECULAR RELAXATION

By

L. B. Evans

Work Performed Under Contract No. DAH C04-69C-0088

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B. Oral Presentations (Continued)

"Rates Important for Atmospheric Acoustics," L.B. Evans. Paper presented at the Molecular Energy Transfer Symposium, University of Mississippi, April 1972.

C. Company Reports

"Investigation of Anomalous Behavior of Sound Absorption by Molecular Relaxation," L.B. Evans and L.C. Sutherland, Wyle Laboratories - Research Staff Technical Memorandum 70-4, May 1970.

"Absorption of Sound in Air," L.B. Evans and L.C. Sutherland, Wyle Laboratories - Research Staff Report WR 70-14, July 1970.

"Tables for Absorption and Velocity of Sound in Still Air at 68° F (20° C)," L.B. Evans and H.E. Bass, Wyle Laboratories - Research Staff Report WR 72-2, January 1972.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT DURING THIS REPORTING PERIOD:

Dr. Landon B. Evans — Principal Investigator

Mr. L. C. Sutherland

Mr. G. Rister

Mr. D. Lister

ABSTRACT

This report is a summary of the progress made in the understanding of the absorption of sound in air due to molecular relaxation. The objectives and the results of the project are stated. All of the significant publications stemming from this study are contained in appendices. These appendices give the theory of predicting sound absorption in air, the experimental basis of the theory, a set of tables for absorption at 20° C, and a set of analytical expressions which will reproduce the tables.

TABLE OF CONTENTS

1.0 INTRODUCTION

A basic characteristic of sound propagation is the attenuation with distance due to various irreversible processes which remove energy from an acoustic wave and convert it to heat. Prediction of sound propagation in air over long distances has become a matter of increasing practical significance in several areas including:

- Prediction of community noise levels around airports
- Analysis or acoustic detection of tactical equipment or aircraft
- Evaluation of very low frequency sound in the atmosphere generated by rocket engines or from natural sources such as tidal motion, earthquakes, wind storms, etc.
- Investigation of the vertical propagation of sonic disturbances from signaling grenades or sonic booms.

Where it is necessary to evaluate sound propagation over a substantial number of wavelengths, the absorption of sound by the atmosphere must be considered. Propagation characteristics are dependent upon (a) atmospheric conditions, (b) the position of the source relative to the ground, and (c) the terrain/vegetation features adjacent to the sound path. These factors, which ultimately affect the intensity of the sound arriving at the observer, can be classified under two main headings as follows:

Spreading Losses

- Uniform spherical spreading (Inverse Square Law) losses
- Non-uniform spreading
  - reflection by finite boundaries
  - refraction by non-uniform atmosphere
  - diffraction (scattering) by non-stationary atmosphere

Absorption Losses

- Absorption by ground and ground cover
- Absorption by atmosphere
  - classical absorption
  - molecular relaxation absorption

Of these sound propagation effects, different ones may be the controlling factor for different atmospheric meteorological conditions and for varying source-receiver placement; however, for any type of condition or any type of sound propagation path, the absorption due to classical and molecular effects are fixed for a homogeneous atmosphere and are functions only of the propagation path distance, the humidity content, gas impurities, and the temperature. Before the more variable propagation effects can be accurately assessed, it is necessary, therefore, to establish the proper values for these fixed absorption losses.

To establish the proper values for the losses due to molecular relaxation in air an extensive program has been conducted under Army sponsorship. In this project the following tasks have been completed:

- an extensive literature survey
- a set of sound absorption experiments in humid air to help define the anomalies
- the first successful measurement of the vibrational relaxation time of humid nitrogen at room temperature
- an extension of a theoretical model to enable the prediction of sound absorption in air at room temperatures
- development of an analytical technique to predict air absorption at room temperature
- definition of the problems needing further study to enable prediction at any temperature

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- design of an experimental apparatus to enable accurate acoustic measurement of the kinetic rate constants important in air as a function of temperature.

2.0 BACKGROUND

Sound absorption in a gas due to molecular relaxations is a chemical dynamics problem. The key factors which are needed for predictions of the acoustic absorption are the binary collision rate constants of the constituent molecules of air. These rate constants can be determined in many different ways with acoustic techniques being one method. The problem of predicting the sound absorption in air is then a problem of determining the energy transfer rates of the binary collisions which occur in air.

The theoretical model which has been developed (see Appendix B) assumes that air is composed of four gases — i.e., nitrogen, oxygen, carbon dioxide, and water vapor. By applying energy transfer rates for the binary collisions which are inherent in such a system, absorption of sound in the gas mixture can be predicted. To predict accurately the sound absorption in air, twenty-four binary collision rates are required. With the exception of one, all of these rates are fairly well defined at room temperature; however, almost none of the important rates are well defined as a function of temperature, and for this reason a new experimental apparatus was designed.

At different frequencies and humidities different rates are the controlling mechanism for sound absorption. For example, at relative humidities less than 20% the vibration — vibration (V-V) energy exchange between O_2 and CO_2 controls the absorption; at greater relative humidities nominal amounts of CO_2 have almost no effect on the maximum absorption. At these humidities the binary rates for N_2/H_2O and O_2/H_2O collisions are extremely important and they are the controlling mechanisms. However, the CO_2 rates are still important since they act as a catalyst or open energy path for energy transfer among the various other molecules.

Parametric studies using the theoretical model have shown that to extend the predictions from room temperature to other temperatures many of the binary energy transfer rates must be measured as a function of temperature. These rates can be subdivided into two broad areas (1) those that require low frequency experiments, and (2) those that require high frequency experiments. The new apparatus was designed to make measurements on the rate constants which require low frequency experiments and knowledge of these rates should be adequate for accurate prediction of sound absorption in air as a function of temperature and humidity.

Appendices A and B contain reprints of journal articles which have been published during this project. Appendix C contains a Wyle Research Staff Report WR 72-2, January 1972. The appendix to this report contains a preprint of another journal article which has been accepted for publication in the Journal of the Acoustical Society of America. These three journal articles along with the Wyle Report represent the state-of-the-art in predicting the absorption of sound in air due to molecular relaxation processes. These appendices contain the theory of the prediction technique, the experimental basis for rate constants used, a set of tables giving absorption as a function of humidity at 20° C, and a set of analytical expressions which will reproduce the tables and are easily programmable.

APPENDIX A

VIBRATIONAL RELAXATION IN MOIST NITROGEN

L. B. Evans

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Vibrational Relaxation in Moist Nitrogen

L. B. Evans

Wyle Laboratories, 7800 Governors Drive, Huntsville, Alabama 35807

The vibrational relaxation time of a nitrogen-water-vapor mixture has been determined at room temperature. The relaxation time for one molecule of nitrogen in pure water vapor, τ_{AB}, was found to be 8.85 μsec.

Vibrational relaxation times in nitrogen are of practical importance for two reasons: (1) CO_2 lasers and (2) sound absorption in the atmosphere. Most previous measurements of relaxation times in both pure N_2 and N_2 with admixtures have been surveyed recently by Taylor and Bitterman.[1] Since the vibrational specific heat of nitrogen is very small at room temperature, all of the previously reported data have been at elevated temperatures in both pure N_2 and mixtures. In this work, the vibrational relaxation time of a N_2-H_2O mixture has been measured at 29°C.

I. EXPERIMENTAL PROCEDURE

Since the vibrational specific heat of nitrogen at room temperatures is only approximately $0.002R$, where R is the universal gas constant, detection of an effect due to vibration requires an experimental system in which all other effects can either be reduced to small values themselves or be accurately determined. A system which will allow this is a large hard-surfaced sound reverberation chamber which has facilities for environmental control. For these measurements a

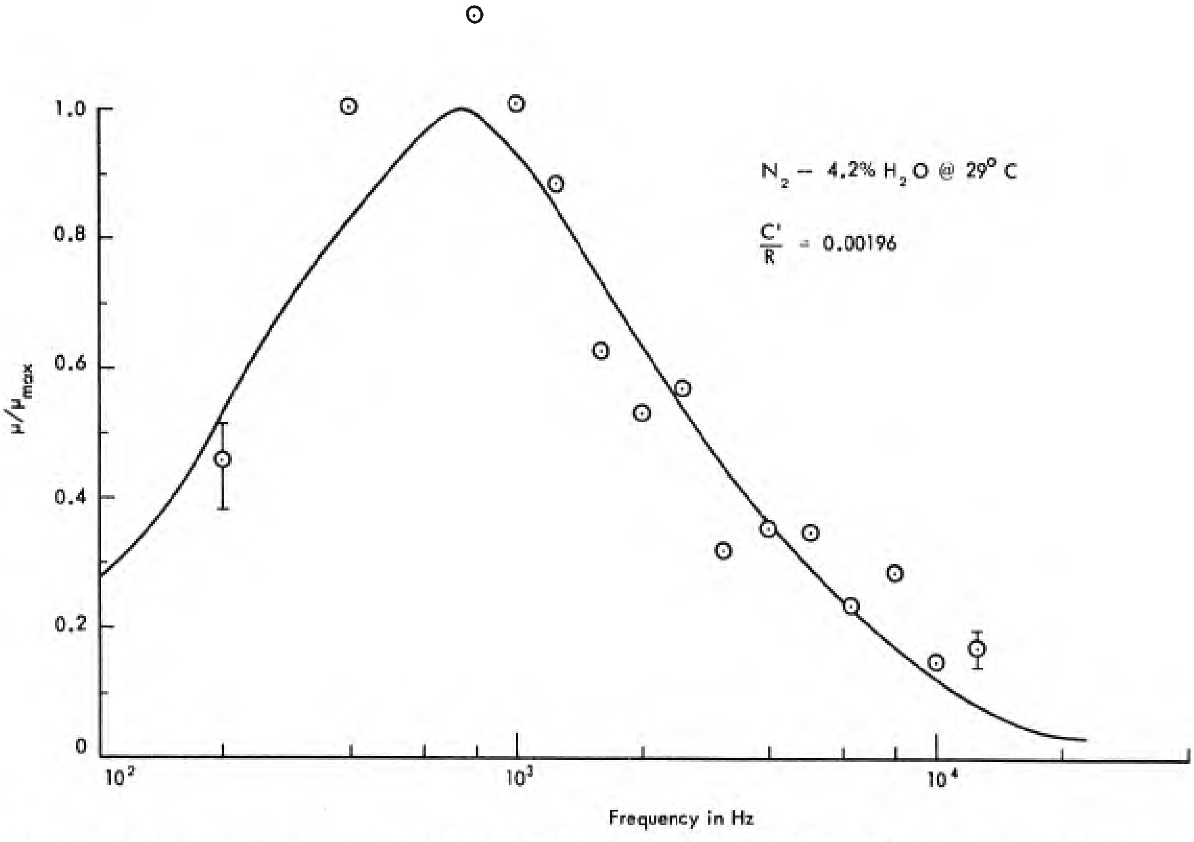

FIG. 1. Sound absorption versus frequency for a N_2 and 4.2 mole% H_2O mixture at 29°C. Circles are experimental data and the solid curve is single relaxation theory.

500-ft³ high-altitude simulation chamber was utilized. The experimental technique employed is very similar to that described by Harris.[2] The main difference is the size of the reverberation chamber. The chamber had vacuum capabilities and was purged twice with pure N_2 to further reduce impurities. The humidity in the chamber was monitored by three Phys-Chemical Research Corporation type PCRC-11 electro-humidity transducers. A circulating fan was employed to ensure that the gases were uniformly mixed.

The acoustic source was a wide-range high-fidelity driver, and a General Radio crystal microphone was used for the receiver. The placement of the driver and microphone were determined by a sound survey in the chamber with the chosen placements being those which gave the greatest received nodal density. The chamber was excited with wide band noise, and the reverberation decay times were obtained by $\frac{1}{3}$ oct band analysis over the frequency range of 200 Hz to 12.5 kHz, with the center frequency of each band chosen as the decay frequency. Any $\frac{1}{3}$ oct bands which did not produce a linear decay in decibels per second were discarded. To calibrate the chamber and determine the wall losses, measurements were made on pure N_2. These calibration measurements were then subtracted from the values mea-decay times were then subtracted from the values mea-sured in the N_2 H_2O mixture with the difference being attributed to absorption by the vibrational modes of nitrogen.

II. RESULTS

The normalized intensity absorption [μ/μ_{max}, where $\mu = 2\alpha\lambda$ and $\mu_{max} = 4\pi C'/(35R)$] versus frequency for a

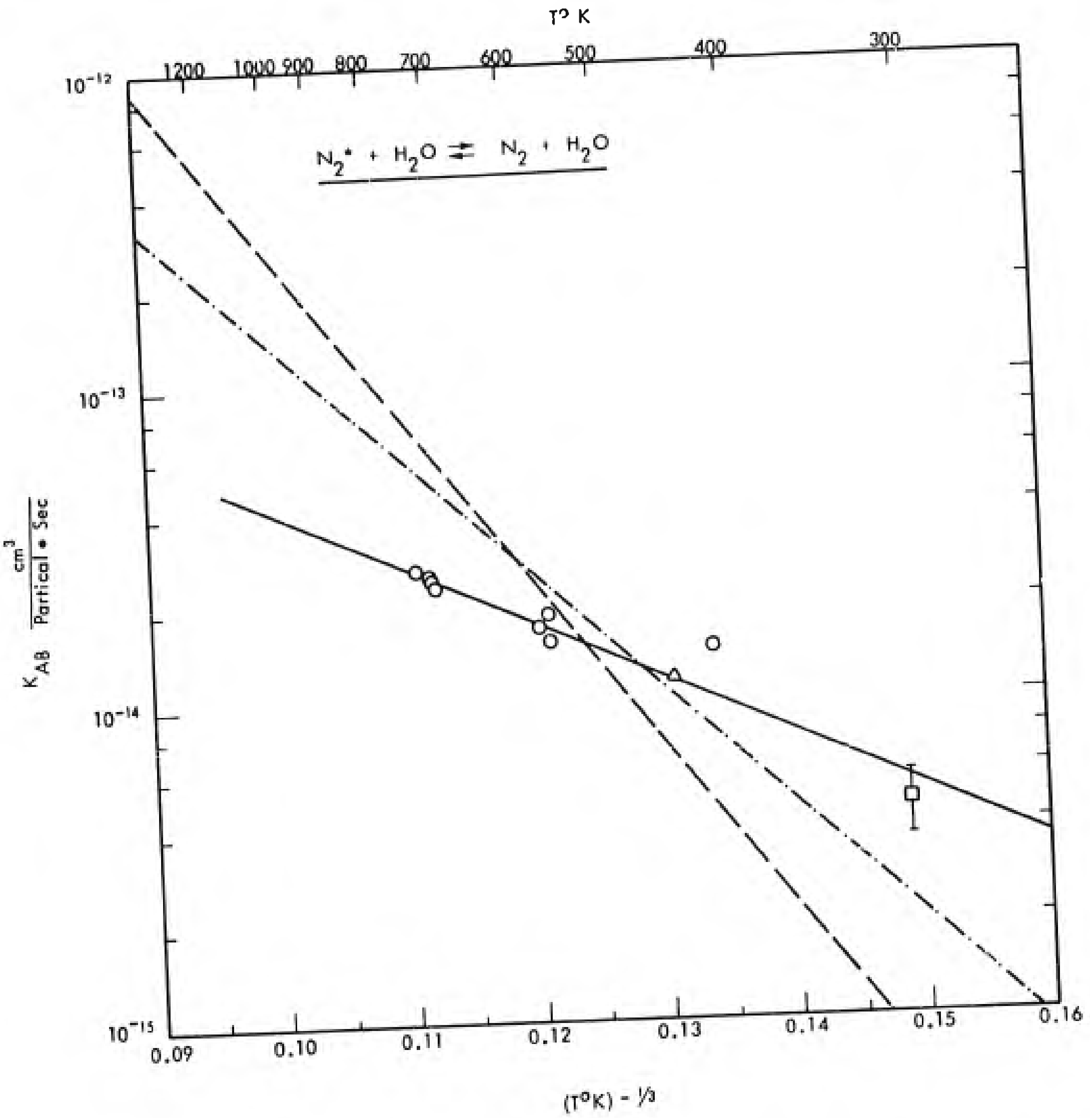

FIG. 2. Temperature dependence of the rate constants for nitrogen–water-vapor mixtures. △: Henderson *et al.*; ○: Huber and Kantrowitz; □: this work; (— — —): Taylor and Bitterman (V–T); (—·—·—): Taylor and Bitterman (V–V); (——): best fit—this work.

N_2 and 4.2 mole% H_2O mixture at 29°C is shown in Fig. 1. The solid curve is single relaxation theory. Even though the experimental data is quite scattered, there is a definite peak in the points and the maximum absorption occurs at approximately 760 Hz, which is equivalent to a relaxation time, τ, of 2.1×10^{-4} sec. If a linear relationship is assumed for the shift of relaxation frequency, f_m, with mole percent water vapor, h, then the frequency of maximum absorption is given by

$$f_m = 180h \pm 40h.$$

The error bounds in the above equation have been determined by taking the worst possible fit of single relaxation theory to the experimental data.

The relaxation time for one molecule of nitrogen in pure water vapor, τ_{AB}, was found to be 8.85 μsec, which corresponds to a rate constant, K_{AB}, of 4.64×10^{-15} cm^3 part^{-1} sec^{-1}, where

$$1/\tau = (1-X_B)/\tau_{AA} + X_B/\tau_{AB},$$

or since the relaxation time of pure nitrogen, τ_{AA}, is much greater than τ_{AB},

$$1/\tau \approx X_B/\tau_{AB}; \quad \tau_{AA} \gg \tau_{AB},$$

where X_B is the mole fraction of water vapor. The rate constant K_{AB} is then given by

$$K_{AB} \approx 1/\tau X_B N_B,$$

where N_B is the molecular number density at one atmosphere pressure and temperature T given by $L(273/T)$, where L is Loschmidt's number.

Inspection of Taylor's and Bitterman's[1] compiled data for N_2–H_2O mixtures reveals that their best fit for either a vibration → translation (V–T) or a vibration → vibration (V–V) collision process does not adequately describe the low-temperature data. In Fig. 2 the combined data of Huber and Kantrowitz,[3] Henderson *et al.*,[4] and this work are depicted. The solid line is the best least-square fit to the points. The fit is quite good and falls within the error bounds of this work. The dashed line is Taylor's and Bitterman's best fit assuming a (V–T) process, and the dot dash line is their best fit for a (V–V) process. The best least-square fit to the data in Fig. 2 is given by

$$K_{AB} = (2.34\times10^{-12})e^{-40.8/T^{1/3}}\ \mathrm{cm^3\ part^{-1}\ sec^{-1}},$$

or the frequency of maximum absorption is given by

$$f_m = (2.74\times10^{7})(h/T)e^{-40.8/T^{1/3}}\ \mathrm{Hz},$$

where h is the mole percent water vapor and T is the temperature in degrees Kelvin. The above equations should be fairly accurate over the temperature range of 250°–500°K. The value of f_m produced by this equation agrees very well with the value deduced by Piercy[5] to account for the anomalous sound absorption in air at low frequencies.

The best fit to the data in this paper is not to be interpreted as meaning the fits of Taylor and Bitterman are wrong. It only indicates that their work was weighted by many data points at higher temperatures. There is no reason to indicate that the data over all temperatures should fit a straight line or be described by the Landau–Teller theory. There is a possibility that the best fit to all of the data will show an upward trend at lower temperatures owing to vibrational → rotational (V–R) energy transfer becoming more important at lower temperatures, since the rotational tangential velocity of water vapor becomes large in relation to its translational velocity at these temperatures.

ACKNOWLEDGMENTS

The author expresses his gratitude to L. C. Sutherland for suggesting the possibility of making these measurements. This work was sponsored by the U. S. Army Research Office, Durham, North Carolina.

[1] R. L. Taylor, and S. Bitterman, Rev. Mod. Phys. **41**, 26–47 (1969).

[2] C. M. Harris, J. Acoust. Soc. Amer. **40**, 148–159 (1966).

[3] P. W. Huber and A. Kantrowitz, J. Chem. Phys. **15**, 275–284 (1947).

[4] M. C. Henderson, K. F. Herzfeld, J. Bry, R. Coakley, and Gaston Carriere, J. Acoust. Soc. Amer. **45**, 109–114 (1969).

[5] J. E. Piercy, J. Acoust. Soc. Amer. **46**, 602–604 (1969).

APPENDIX B

ATMOSPHERIC ABSORPTION OF SOUND: THEORETICAL PREDICTIONS

L. B. Evans
H. E. Bass
L. C. Sutherland

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Atmospheric Absorption of Sound: Theoretical Predictions*

L. B. Evans

Wyle Laboratories, Huntsville, Alabama 35807

H. E. Bass

University of Mississippi, Department of Physics and Astronomy, University, Mississippi 38677

L. C. Sutherland

Wyle Laboratories, El Segundo, California 90245

By assuming that air is composed of four gases (i.e., nitrogen, oxygen, water vapor, and carbon dioxide) and applying energy transfer rates for the binary collisions inherent in such a system, absorption of sound in the atmosphere has been predicted. The calculated curves based upon 24 energy transfer mechanisms are compared with experimental data over the humidity range of 0–100% relative humidity. Agreement between theory and experiment is very good. By including classical absorption and rotational relaxation effects, the total atmospheric absorption is also predicted at 20°C. Calculations made for various concentrations of CO_2 indicate that low CO_2 levels (less than 0.1%) do not significantly affect absorption of audible sound at high humidities. At very low humidities, however, CO_2 is an important factor.

INTRODUCTION

A basic characteristic of sound propagation is the attenuation with distance due to various irreversible processes that remove energy from an acoustic wave and convert it to heat. Prediction of sound propagation in air over long distances has become a matter of increasing practical significance in several cases, including:

(1) Prediction of community noise levels around airports.
(2) Analysis or acoustic detection of tactical equipment or aircraft.
(3) Evaluation of very low-frequency sound in the atmosphese generated by rocket engines or from natural sources such as tidal motion, earthquakes, wind storms, etc.
(4) Investigation of the vertical propagation of sonic disturbances from signaling grenades or sonic booms.

Where it is necessary to evaluate sound propagation over a substantial number of wavelengths, the absorption of sound by the atmosphere must be considered. Propagation characteristics are dependent upon (a) atmospheric conditions, (b) the position of the source relative to the ground, and (c) the terrain/vegetation features adjacent to the sound path. The above-listed factors which affect the intensity of the sound arriving at the observer can be classified as follows:

A. Spreading Losses

(1) Uniform spherical spreading (inverse square law) losses.
(2) Nonuniform spreading.
    (a) Reflection by finite boundaries.
    (b) Refraction by nonuniform atmosphere.
    (c) Diffraction (scattering) by nonstationary atmosphere.

B. Absorption Losses

(1) Absorption by ground and ground cover.
(2) Absorption by atmosphere.
    (a) Classical absorption.
    (b) Molecular relaxation absorption.

Of these sound propagation effects, different ones may be the controlling factors for different atmospheric meteorological conditions and for varying source–receiver placement; however, for any type of condition or any type of sound propagation path, the absorption due to classical and molecular effects are fixed for a homogeneous atmosphere and are functions only of the propagation path distance, the humidity content, gas impurities, and the temperature. Before the more variable propagation effects can be accurately assessed, it is necessary, therefore, to establish the proper values for these fixed absorption losses.

Atmospheric absorption losses have two basic forms: (1) classical losses associated with the change of acoustical energy (or kinetic energy of molecules) into heat by fundamental gas transport properties, and (2) for polyatomic gases, relaxation losses associated with the change of kinetic or translational energy of the molecules into internal energy within the molecules themselves. The classical losses can be further subdivided into

$$\left.\begin{array}{l}\text{(a) Viscous losses}\\ \text{(b) Heat conduction losses}\end{array}\right\}\text{Stokes–Kirchhoff loss.}$$

(c) Diffusion losses
(d) Radiation losses

Only the Stokes–Kirchhoff losses are considered significant for air under normal atmospheric conditions. Diffusion losses contribute only about 0.3% more, and radiation losses are significant only at very low frequencies.

Relaxation absorption losses in polyatomic gases are known to have the following forms.

(1) Thermal relaxation between translational energy and vibrational energy states of the molecules.

(2) Thermal relaxation between a close vibrational resonance of two different molecules.

(3) Thermal relaxation between the vibration of one molecule and the rotation of a different molecule.

(4) Thermal relaxation between translational energy and rotational energy states of the molecules.

(5) Electromagnetic relaxation between translational energy and allowable electronic energy states of the molecule.

As far as is known, electromagnetic relaxation is significant for only one common gas, nitric oxide, NO, and then, only at very high ultrasonic frequencies.[1]

In the balance of this paper, a basic theoretical technique for predicting the total atmospheric absorption losses is presented along with supporting experimental data.

I. THEORETICAL METHOD

Investigations of sound-absorption mechanisms in air have been carried out by many different laboratories since the pioneering experimental work of Pielemeier[2] in 1929 and have culminated recently in the work of Harris,[3] Harris and Tempest,[4] Monk,[5] and Evans and Sutherland.[6] The theoretical treatment of the problem has lagged somewhat behind the experimental results. Kneser's 1933 theoretical treatment has largely been used to explain the experimental data.[7] However, it has always been recognized that this theory does not give an adequate description of the entire problem. Sutherland[8] and Piercy[9] have shown that at frequencies well below the maximum absorption there is a distinct systematic deviation from single relaxation theory. It is this area that this paper attempts to clarify.

In this paper, air is considered as a four-gas mixture, i.e., nitrogen, oxygen, carbon dioxide, and water vapor. By applying the energy transfer rates for the binary collisions inherent in such a system, absorption of sound in the atmosphere is predicted. The calculated curves are based upon 24 energy transfer mechanisms as shown in Tables I and II.

The theoretical prediction of total sound absorption also requires calculation of the losses due to classical effects and molecular relaxation. The classical absorption can be written as

$$\alpha_{cl}=\frac{2\pi^2 f^2}{\gamma P_0 V_0}\left(\tfrac{4}{3}\eta+\frac{\gamma-1}{C_p}\kappa+\gamma a_d D_{12}\rho\right), \qquad (1)$$

where α_{cl} is total classical absorption; P_0, gas pressure;

TABLE I. Rate constants and their values used in this work.

Rate	Value ($sec^{-1}\ atm^{-1}$)	Reference
$M0P_3{}^1$ (3,2,0)	6.0×10^4	a
$M0P_0{}^1$ (2,0,0)	3.0×10^4	a
$M0P_1{}^1$ (5,2,0)	3.0×10^5	e
$M0P_2{}^1$ (1,2,0)	4.5×10^8	a
$M1P_0{}^1$ (2,0,1)	1.8×10^5	a
$M1P_3{}^1$ (3,2,1)	1.5×10^5	a
$M1P_2{}^1$ (1,2,1)	4.5×10^8	a
$M2P_0{}^1$ (2,0,2)	3.4×10^4	a
$M2P_0{}^1$ (4,0,2)	1.0	a
$M2P_1{}^1$ (3,4,2)	1.8×10^7	a
$M2P_3{}^1$ (3,2,2)	6.0×10^4	a
$M2P_2{}^1$ (1,2,2)	4.5×10^8	a
$M3P_0{}^1$ (2,0,3)	4.2×10^8	b
$M4P_1{}^1$ (4,5,4)	1.5×10^2	a
$M4P_0{}^1$ (5,0,4)	40	a
$M4P_0{}^1$ (4,0,4)	1.0	a
$M5P_0{}^1$ (5,0,5)	63	c
$M6P_1{}^1$ (6,5,6)	4.6×10^7	c
$M6P_0{}^1$ (5,0,6)	1.1×10^6	c
$M6P_0{}^1$ (6,0,6)	6.0×10^4	c
$M7P_0{}^1$ (4,0,7)	1.0	a
$M8P_0{}^1$ (4,0,8)	1.13×10^5	d
$M8P_0{}^1$ (6,0,8)	1.4×10^6	c
$M9P_0{}^1$ (6,0,9)	1.0×10^9	c

[a] See Ref. 17.
[b] F. D. Shields and J. A. Burks, J. Acoust. Soc. Amer. 43, 510–515 (1968).
[c] See Ref. 5.
[d] See Ref. 15.
[e] Ref. 17 gives an estimated value of $\sim3\times10^6$ $sec^{-1}\ atm^{-1}$. However, for this work we have chosen a value of 3×10^5 $sec^{-1}\ atm^{-1}$, which agrees with results of Ref. 16.

TABLE II. Definition of collision processes.

Molecules colliding	A	Molecules colliding	A
CO_2/O_2	0	O_2/O_2	5
CO_2/CO_2	1	O_2/H_2O	6
CO_2/N_2	2	N_2/N_2	7
CO_2/H_2O	3	N_2/H_2O	8
O_2/N_2	4	H_2O/H_2O	9

f, sound frequency; γ, effective specific heat ratio of the gas; V_0, sound velocity at low frequencies; η, viscosity of the gas; C_P, effective specific heat of the gas at constant pressure; a_d, a molecular diffusion constant; D_{12}, diffusion coefficient for O_2 and N_2 mixture; ρ, gas density; and κ, thermal conductivity. For frequencies less than that at which rotational relaxation occurs, this expression can be evaluated in terms of the viscosity based on measured values for the above constants[10]:

$$\alpha_{cl}=(2\pi^2 f^2/\gamma P_0 V_0)(1.9)\eta. \qquad (2)$$

For frequencies greater than that at which rotational relaxation occurs, the general expression must be used and the effective values of the frequency dependent terms utilized.[11] Equation 2 was utilized to calculate classical losses in this study with γ taken as its low-frequency value.

The absorption due to thermal relaxation between translational and rotational energy states of the molecules was calculated assuming that the rotational relaxation of each molecule was the same in air as in the pure gas. This assumes that during a collision with unlike molecules, the probability of transferring rotational energy for each molecule is independent of the collision partner. This assumption, of course,

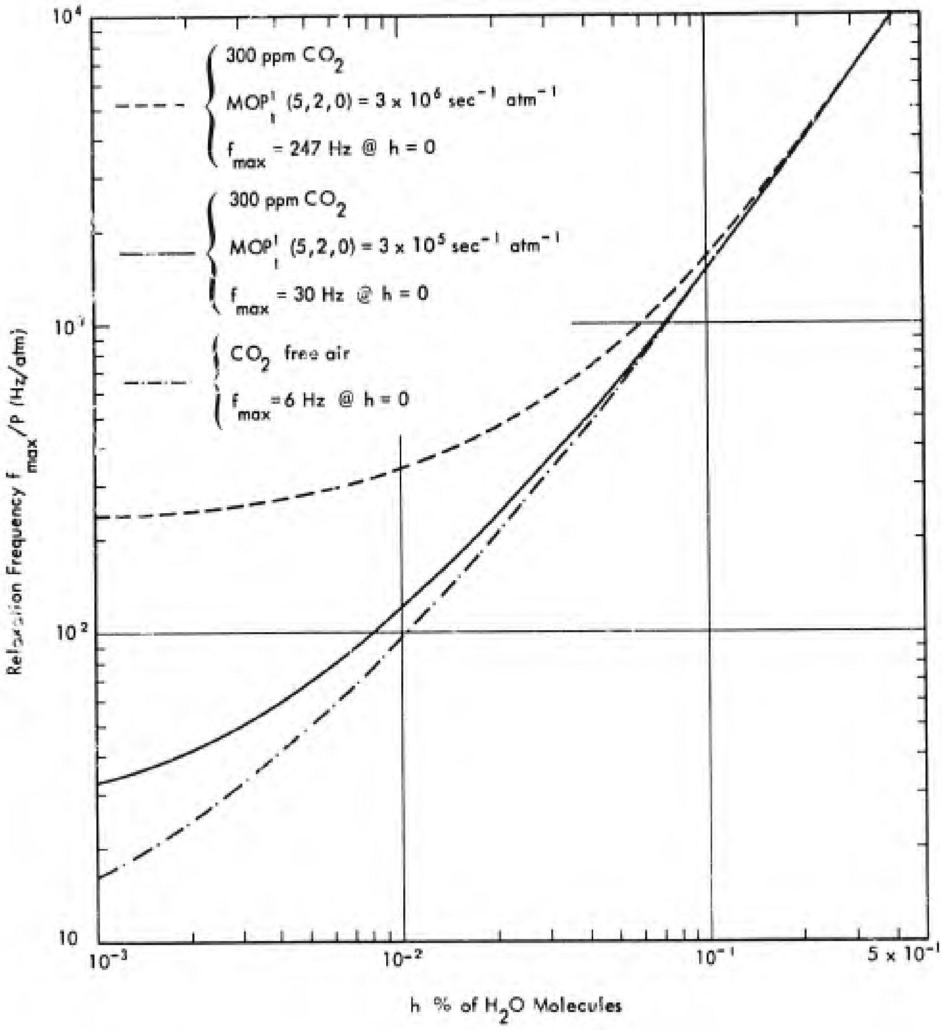

FIG. 1. Low-humidity plot of relaxation frequency as a function of percent H_2O molecules. The solid line represents the best calculation and has been calculated with $MOP_1{}^1$ (5,2,0)$=3\times10^5$ sec^{-1} atm^{-1} for 300 ppm CO_2. The dashed curve represents 300 ppm CO_2 and $MOP_1{}^1$ (5,2,0)$=3\times10^6$ sec^{-1} atm^{-1} and has been included to emphasize the importance of this rate of low humidities. The dot–dash curve represents CO_2 free air.

would be very poor for high frequencies. For the frequencies of interest, however, a change by a factor of 2 or 3 in the rotational relaxation time for any constituent molecule would lead to very little change in the total absorption. The effects of rotational relaxation were included by writing the effective specific heat as the sum of the contributions from the translational, ($\frac{3}{2}R$), vibrational, and rotational modes:

$$(C_v)_{\text{effective}}=\tfrac{3}{2}R+(C_v)_{\text{vibration}}$$
$$+R\sum_{j=1}^{n}x_j\frac{(f_j-3)}{2}\,\frac{1}{1+i\omega\tau_j},\quad(3)$$

where j represents the constituent molecules of air (i.e., CO_2, H_2O, O_2, and N_2); x_j is the concentration of molecule j; f_j, the number of degrees of freedom of molecule j; ω, 2π times the sound frequency; τ_j, the rotational relaxation time of molecule j; and n, the number of types of molecules considered.

For purposes of this study, only CO_2, N_2, O_2, and H_2O were considered; however, the method is quite general provided the above assumption regarding the effects of unlike collisions on the rotational relaxation times is valid.

The final term to be considered includes the sound loss due to the thermal relaxation between translational energy and vibrational energy states (V–T), between vibration of one molecule and the vibration of another

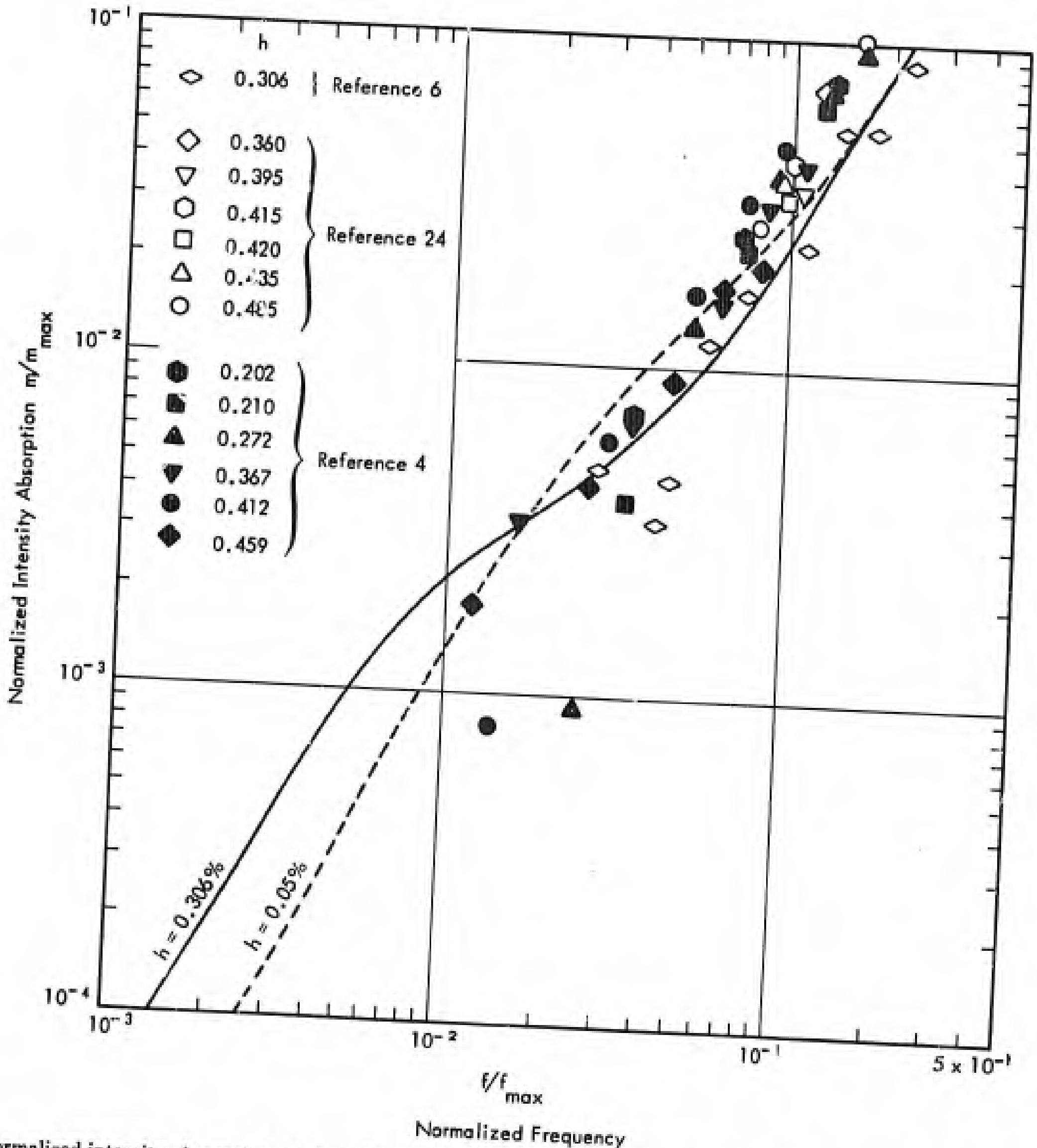

FIG. 2. Normalized intensity absorption as a function of normalized frequency for less than 0.5% H_2O molecules. The solid curve has been calculated for 11% relative humidity at 23°C ($h=0.306\%$ H_2O molecules). The dashed curve has been calculated for 1.8% relative humidity at 23°C ($h=0.05\%$ H_2O molecules).

(*V–V*), and between the vibration of one molecule and the rotation of the same or different molecule (*V–R*). The difference between (*V–T*) and (*V–R*) processes is only important when calculating energy transfer rates; so for these calculations, both processes will be considered as being (*V–T*). These vibrational relaxation processes are the dominant causes of loss at low acoustic frequencies.

The sound absorption due to vibrational relaxation was calculated using the method first advanced by Tanczos,[12] which was expanded to a two-component system by Shields[13] and later expanded by Shields and Bass[14] to allow for three-for-one (*V–V*) exchange between colliding molecules. The only information required to perform such calculations is the binary rate constants and the concentration of each gas present.

Shields's equations for expressing the acoustic absorption and dispersion as a function of the various energy transfer rates of importance were used as a starting point for these calculations. The only modifications required to expand the method to a four-component system was a change in Eq. 6 of Ref. 13. The modified equations become

$$k_{10}(I)=\sum_{i=1}^{n} x_i MAP_0{}^1(I,0,A),$$

$$k_0{}^a{}_b{}^0(I,J)=\sum_{i=1}^{n} x_i MAP_b{}^a(I,J,A),$$

where the terms have been defined in Ref. 13. These two expressions allow the effective vibrational specific heat

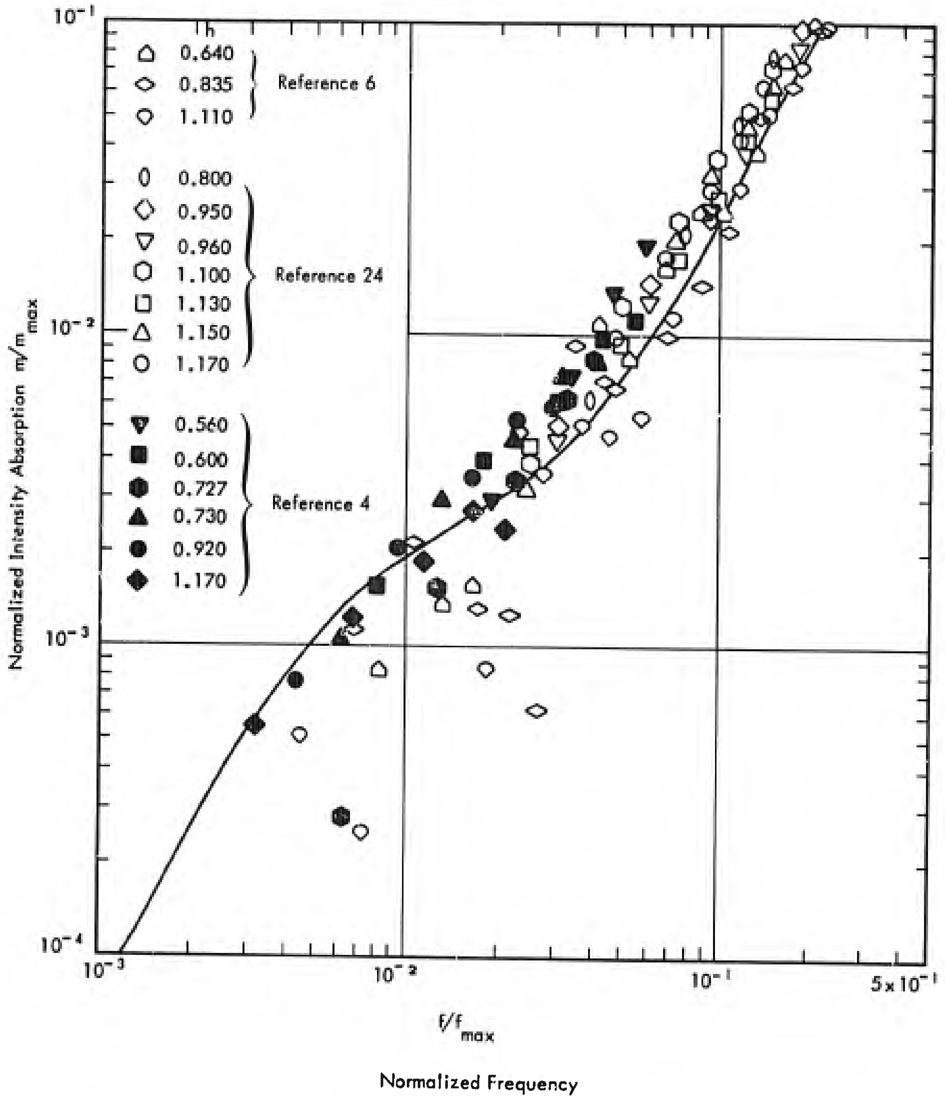

FIG. 3. Normalized intensity absorption as a function of normalized frequency for 0.5% to 1.2% H_2O molecules. The solid curve has been calculated for 23°C and represents an average value of the calculated curves in this humidity range. The difference in the calculated values over this range is about twice the line thickness.

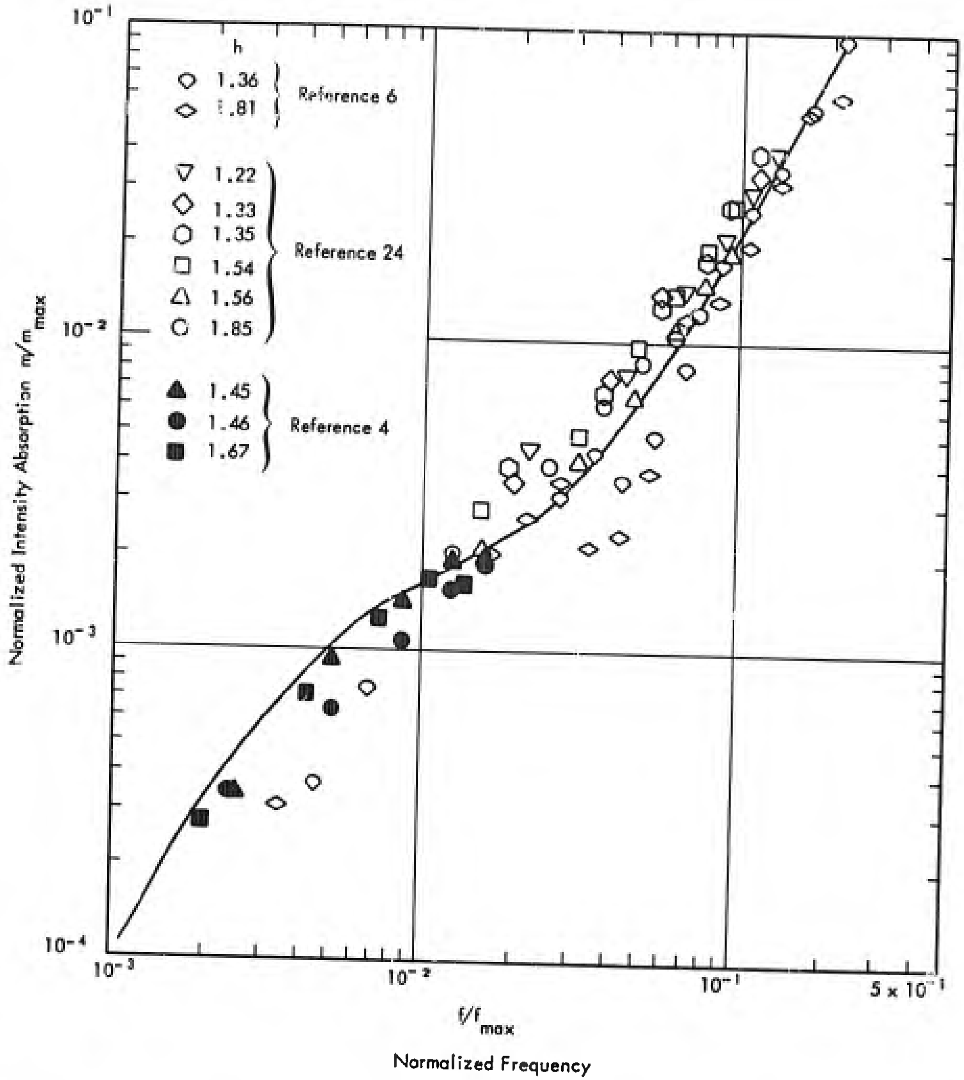

FIG. 4. Normalized intensity absorption as a function of normalized frequency for 1.2% to 1.9% H_2O molecules. The solid curve has been calculated for 23°C and represents an average value of the calculated curves in this humidity range. The difference in the calculated values over this range is about twice the line thickness.

to be calculated, which in turn can be used to determine the absorption and velocity of sound using Ref. 13.

A total of 24 energy transfer processes were considered. The rates for these processes are given in Table I. Rates are labeled as $MAP_b^a(I,J,A)$. The letter A indicates the type molecules involved in the collision. An index to the numbering system used is given in Table II. MA is the number of collisions of type A occurring each second in air at 1 atm of pressure. $P_b^a(I,J,A)$ is the probability that, during a collision between the molecules involved in type A collisions, mode I of the molecule will lose "a" quanta of vibrational energy, while mode J of the same molecule or the collision partner gains "b" quanta of energy. The modes are numbered as follows:

Mode 0—translational mode of any molecule;
Mode 1—symmetric stretching mode of CO_2 ($\nu_1 = 1388$ cm^{-1});
Mode 2—bending mode of CO_2 ($\nu_2 = 667$ cm^{-1}) (doubly degenerate);
Mode 3—asymmetric stretching mode of CO ($\nu_3 = 2349$ cm^{-1});
Mode 4—vibrational mode of N_2 ($\nu_4 = 2331$ cm^{-1});
Mode 5—vibrational mode of O_2 ($\nu_5 = 1580$ cm^{-1});
Mode 6—bending mode of H_2O ($\nu_6 = 1595$ cm^{-1}).

For example, $M2P_1^1$ (4,0,2) is the rate for the (V–T) process

$$N_2^* + CO_2 \rightarrow N_2 + CO_2,$$

and $M4P_1^1$ (4,5,4) is the rate for the (V–V) process

$$O_2 + N_2^* \rightarrow O_2^* + N_2,$$

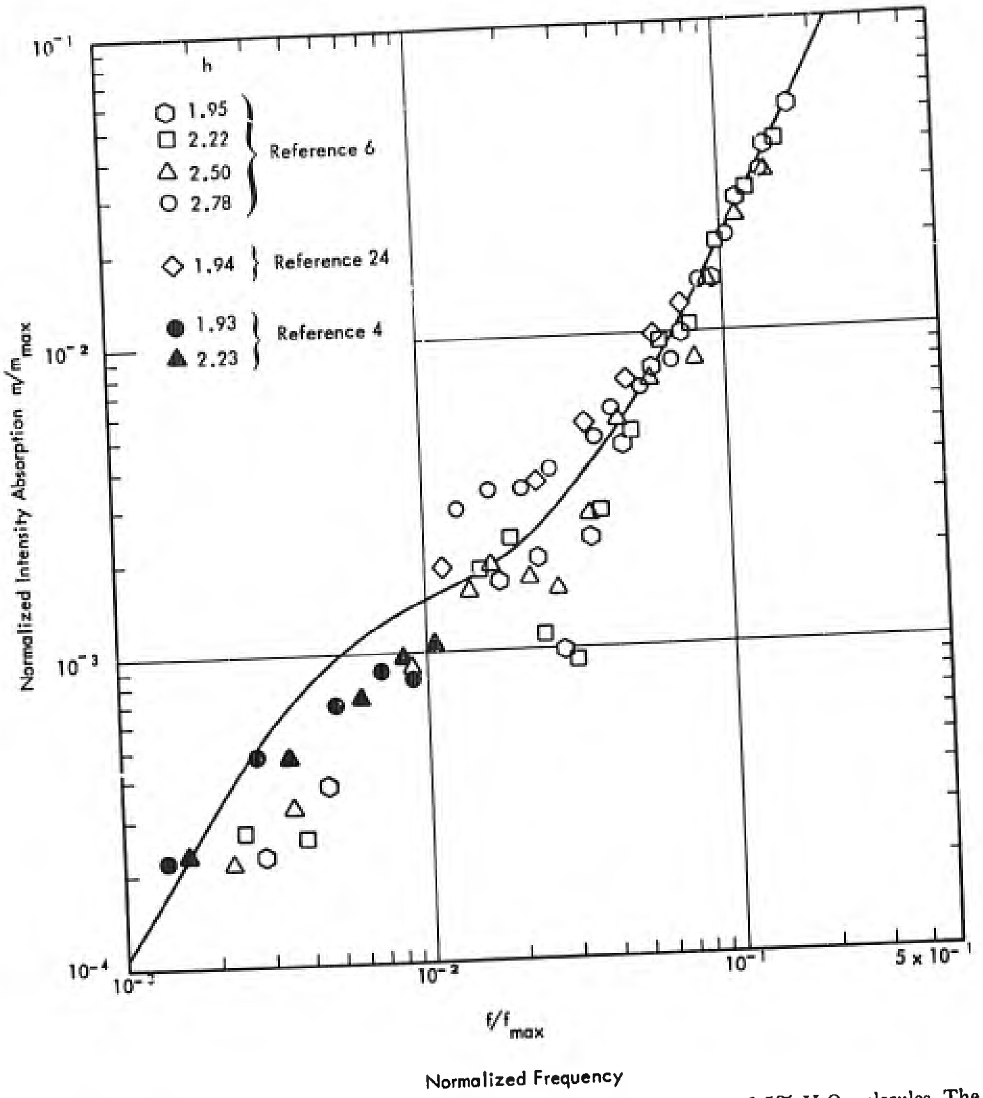

FIG. 5. Normalized intensity absorption as a function of normalized frequency for 1.9% to 2.5% H_2O molecules. The solid curve has been calculated for 23°C and represents an average value of the calculated curves in this humidity range. The difference in the calculated values over this range is about twice the line thickness.

where an asterisk indicates a vibrationally excited mode. The symmetric and asymmetric stretching modes of H_2O were not considered, since their contributions to the total specific heat is very small.

A rather large number of rates have been considered since at different humidity and frequency combinations different rates are the controlling mechanisms for the sound absorption. For example, at high humidities the effect of CO_2 is insignificant in concentrations below 1000 parts per million. However, in relatively dry air the CO_2 content controls the relaxation frequency of the mixture as shown in Fig. 1. The most important rates for the study are the $(V-T)$ and $(V-V)$ rates for O_2/H_2O collisions; the $(V-T)$ rate for H_2O/H_2O collisions; the $(V-T)$ and $(V-V)$ rates for N_2/H_2O collisions; and at low humidities the $(V-T)$ and $(V-V)$ rates for O_2/CO_2 interactions. It should be recognized that any of the above $(V-T)$ rates could very well be the result of a $(V-R)$ process followed by a rapid $(R-T)$ process.

Although only the absorption has been discussed, the velocity could also be calculated by the same method. The velocity, however, is less sensitive to the presence of relaxation.

The power of the theoretical method is its versatility. The same theoretical method and computer program could be used for any combination of gases. The effect of pollutants on the frequency dependence of sound absorption and the absorption of sound in alien atmospheres could readily be calculated provided the binary collision rates were known. In many cases, these rates can be found in the literature. Those not

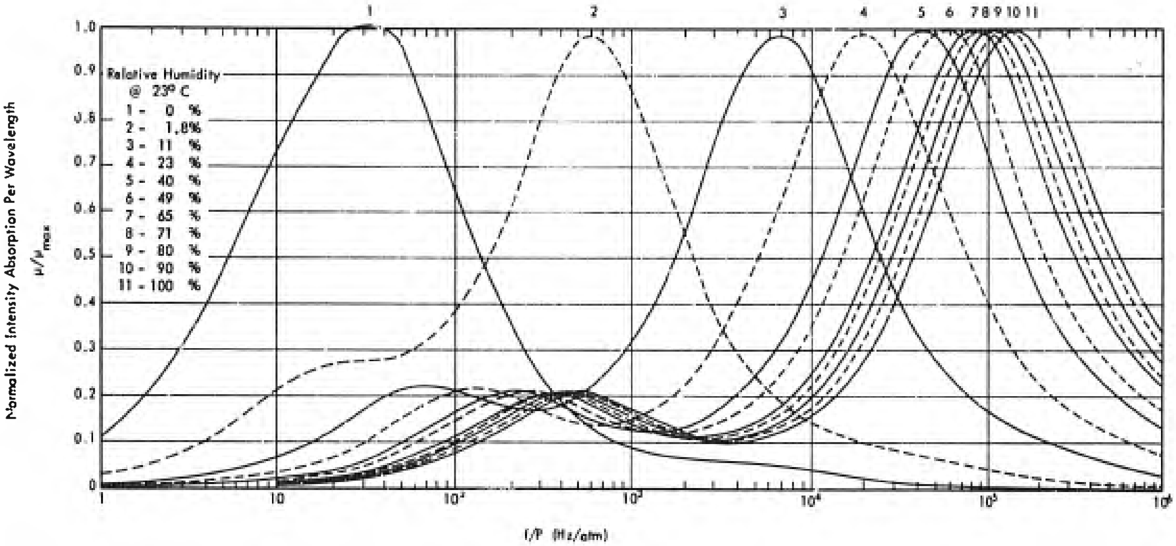

FIG. 6. Normalized molecular absorption per wavelength as a function of frequency. The curves are calculated for the indicated relative humidities at 23°C.

available in the literature can be measured in controlled laboratory conditions without being concerned with all the variables inherent in field measurements. The temperature dependence of the relaxation absorption can also be calculated if the temperature dependence of the individual transition rates are known. Additional laboratory measurements of the temperature dependence of the rates important in sound absorption must be made before more accurate theoretical predictions will be possible. A great deal of progress has been made towards developing theoretical expressions for energy transfer rates. Once such expressions are developed, calculations of sound absorption from molecular constants will be possible. This area clearly deserves additional attention.

II. RESULTS

The predicted curves are shown in Figs. 2–5 along with available experimental data. Of the three sets of data, that of Harris and Tempest is thought to be the most accurate. Agreement between theory and experiment is very good. The curves and data have been presented in the form, $m/m_{\max}$ vs $f/f_{\max}$, where m is the intensity attenuation coefficient and $m_{\max}$ is its value at the relaxation frequency $f_{\max}$. By normalizing both axes, data for the various different humidities can be plotted on the same graph. In each case the experimental data has been normalized by $f_{\max}$ predicted by Monk's expression and the value of $m_{\max}$ has been computed using the Planck–Einstein relationship for the specific heat of the oxygen content. An error in $f_{\max}$ will move a data point along a 45° line; an error in $m_{\max}$ will change the vertical position of the data point on the $m/m_{\max}$ scale; and hence both parameters affect the agreement between theory and experiment.

Figure 6 depicts the predicted curves of $\mu/\mu_{\max}$ vs f/p, where μ is the absorption per wavelength. It is readily obvious from these curves that sound absorption in air is a multiple relaxation process. The curves have been normalized by the major peak, which is due to the vibrational specific heat of oxygen; hence, as a result of the nitrogen relaxation $\mu/\mu_{\max}$ does not necessarily equal 1. The minor peak is not as easily explained. It is primarily due to the nitrogen content of air; however, its position in frequency is primarily a function of the water vapor content.[15]

Comparison between $f_{\max}$ and theory as a function of humidity is shown in Fig. 7 along with Monk's curve.[5] It is not surprising that Monk's results and the present work are identical at high humidities, since we have taken the rates which are important at high humidities from Monk's paper. However, there is considerable difference at lower humidities (Fig. 1). This work approaches a value of approximately 30 Hz for the relaxation frequency at zero humidity. This agrees very well with the values reported by Piercy[16] that were extracted from very low-temperature air data. There is some uncertainty in this 30-Hz prediction since the rate for $O_2/CO_2(\nu_2)(V\text{–}V)$ coupling is not well known. As shown in Fig. 1, a difference of one order of magnitude in this particular rate makes approximately the same difference in $f_{\max}$ at zero humidity. For this work, MOP_1^1 (5,2,0) was chosen to be 3.0×10^5 sec^{-1} atm^{-1} to agree with Piercy's[16] results. Taylor and Bitterman[17] suggest a value of 3.0×10^6 sec^{-1} atm^{-1}. The third curve in Fig. 1 emphasizes the importance of including the trace amounts (300 ppm) of CO_2. Without CO_2 the zero humidity relaxation frequency is approximately 6 Hz.

The acoustician is often faced with making corrections for atmospheric absorption and for these purposes

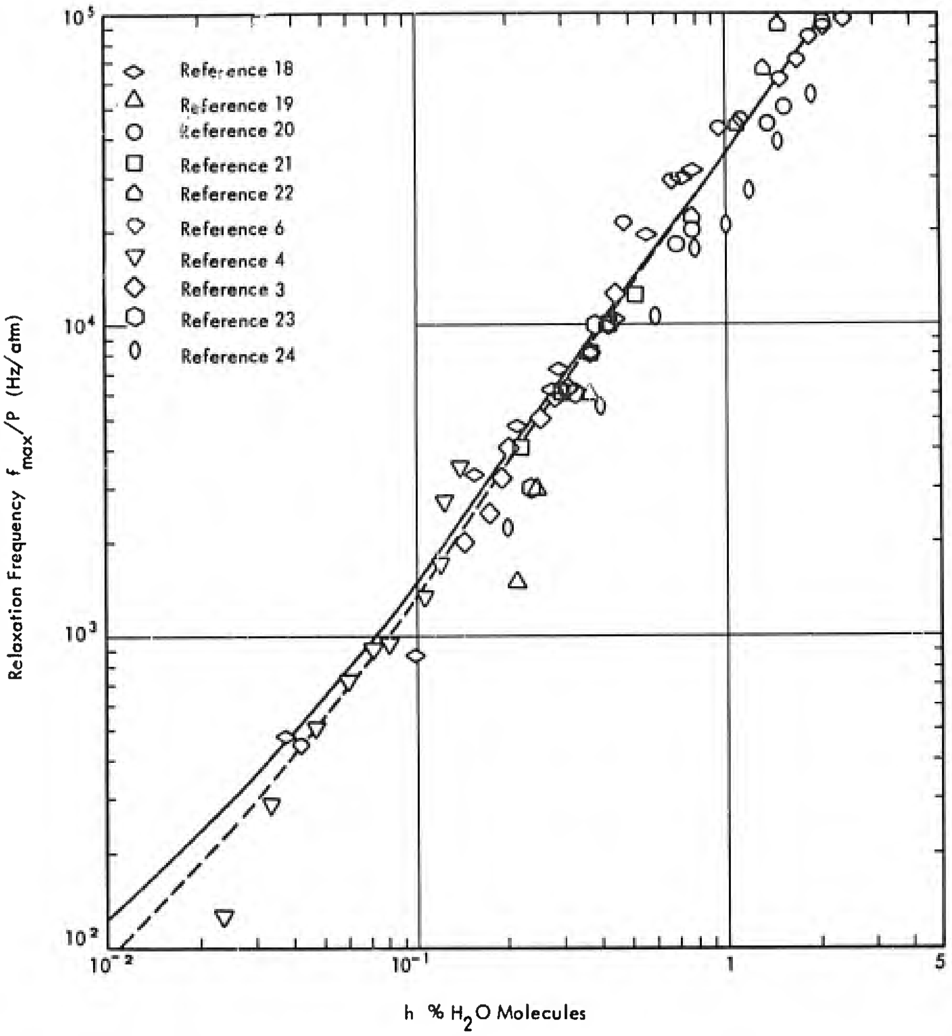

FIG. 7. Relaxation frequency as a function of percent H_2O molecules. The solid curve is from this work. The dashed curve is from Monk (Ref. 5).

Fig. 8 is included. These curves show the total absorption (i.e., classical, vibrational, and rotational absorption) in decibels/1000 ft vs f/p at 20°C. It is felt that the accuracy of these predicted curves will be well within any experimental error in field measurements and can be used without hesitation.

III. SUMMARY

The theoretical method developed allows the acoustic absorption to be calculated to an accuracy comparable to that of present experiments. If the need for more accurate predictions of sound absorption arises, then the transition rates required in the theory must be determined more accurately, especially those involving water vapor. Further, if the theoretical method is to be expanded to alien atmospheres, the necessary binary vibrational energy transfer rates must be determined experimentally or calculated. The ability of the theoretical technique to predict the temperature dependence of the sound absorption depends upon the temperature dependence of the various vibrational rates. Again, those rates involving water vapor need additional study. In order to make calculations of the absorption of sound in air, or any other calculation which requires transition rates, without *a priori* knowledge of the various transition rates, theoretical expressions for these rates must be developed. To date, there has been marginal success with (V–T) calculations and with (V–R) calculations, but none with (V–V) theory. These calculations also deserve additional study.

Some error may be introduced into the present calculations by exclusion of the trace amounts of H_2 and Ar which are present in the atmosphere. These constituents, particularly H_2, may have some import-

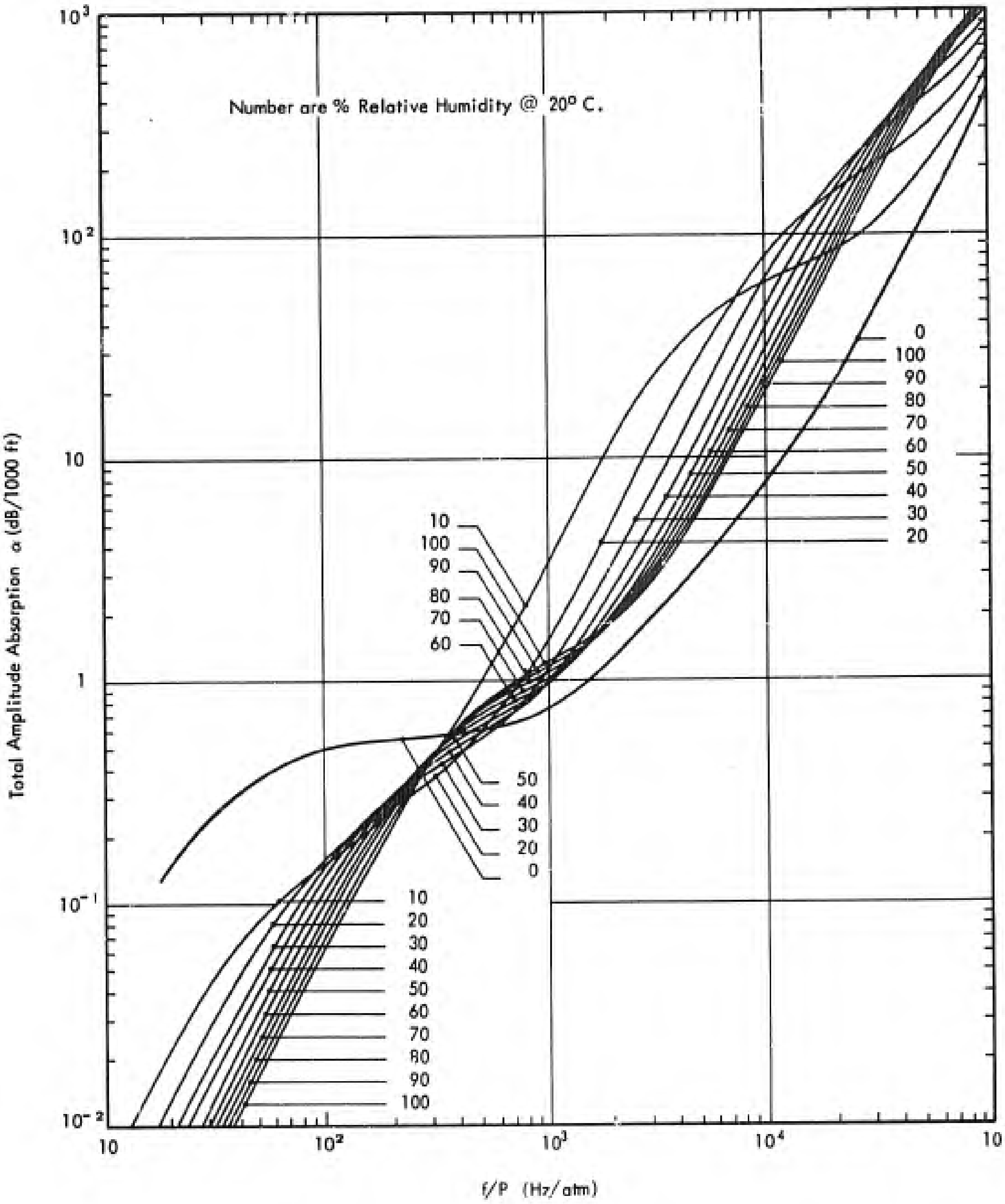

FIG. 8. Total absorption of sound in air as a function of frequency. The curves range from 0 to 100% relative humidity and are for 20°C.

ance at extremely low humidities. The uncertainty introduced by neglecting these two trace elements, however, is certainly no greater than that already present owing to the uncertainty in the transition rates.

These calculations were expedited by most of the needed transition rates being available in Taylor's and Bitterman's[17] excellent review article on the transition rates important for CO_2 lasers. Other reviews of this nature, where the various data sets are not only recorded but their accuracy assessed, are certainly needed.

It is felt by these authors that the method and curves presented can be used to predict atmospheric sound propagation reliably at 20°C and probably safely over a 5° spread around 20°C. Not until better information is available on the temperature dependence of many of the transition rates will accurate calculations as a function of temperature be possible.

ACKNOWLEDGMENTS

This work was sponsored by the Army Research Office–Durham. One of us (H.E.B.) wishes to express

his gratitude to the Committee on Faculty Research of the University of Mississippi and the Office of Naval Research for support. We all express our gratitude to Dr. F. D. Shields of the University of Mississippi for making available a copy of his computer program for a binary gas mixture.

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APPENDIX C

TABLES OF ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

L. B. Evans
H. E. Bass

Wyle Laboratories Research Staff Report WR 72-2, January 1972

WYLE LABORATORIES - RESEARCH STAFF

REPORT WR 72-2

TABLES OF ABSORPTION AND VELOCITY OF SOUND IN STILL AIR AT 68° F (20° C)

By

L. B. Evans
Wyle Laboratories, Huntsville, Alabama

H. E. Bass
Dept. of Physics & Astronomy
University of Mississippi

Work Performed Under Contract No. DAH C04-69C 0088

January 1972

WYLE LABORATORIES
RESEARCH DIVISION, HUNTSVILLE FACILITY

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ABSTRACT

Tables are presented for the absorption and velocity of sound in still air at 68° F (20° C). The absorption is presented in dB/1000 ft, dB/Km, and dB/sec. The velocity is presented in 1000 ft/sec. The tables cover the frequency range of 12 Hz - 1 MHz and for relative humidities of 0%-100%. An appendix is included which presents analytical expressions that will duplicate the tables within 3% over all frequencies and humidities.

INTRODUCTION

These tables and graphs are an interim step in the process of developing a comprehensive set of tables for absorption of sound in still air. They have been produced because of a need for such results which was expressed at the Helicopter Noise Symposium in Durham, North Carolina, September 1971. They should be viewed as an interim effort, and as being accurate only at the stated temperature. For those that need analytical expressions for the absorption and velocity such expressions are discussed in the Appendix.

The tables give the % relative humidity, temperature, one-third octave band center frequencies, absorption in dB/1000 ft, dB/Km, and dB/sec along with the velocity in 1000 ft/sec. They cover the frequency range of 12 Hz - 1 MHz and humidity range of 0% relative humidity to 100% relative humidity.

The tables have been produced from the theoretical technique which is described in Reference 1. The only modification which has been made is that the calculation technique for rotational relaxation has been replaced with a single rotational rate constant for air which has been taken from Reference 2. This modification affects the results only at the higher frequencies and brings the calculations into excellent agreement with experimental data at these frequencies. The agreement between the calculations and available experimental data in the audible frequency range can be viewed in Reference 1. At frequencies below 100 Hz no comparison has been made with experimental data because of the lack of such data.

For extremely dry air (less than 10% relative humidity) there is some difficulty in assessing the accuracy of the calculations below 100 Hz. However, the calculated values in this range reflect the best agreement with available data at higher frequencies.

The accuracy of the tables is different for different frequencies. For the range of 12 Hz - 100 Hz the calculated values may be in error as much as 50% with the error decreasing with increasing frequency. Over the rest of the frequency range the error in the calculations is less than 5% which is as good or better than experimental accuracy. The tables have been calculated for more digits than for which significance can be ascribed. This has been done for computational convenience. All of the absorption measurements should be regarded as significant to only one decimal place and the velocity (in 1000 ft/sec) is significant to four decimal places.

The velocity calculations include both relaxational and humidity effects and are in fair agreement with the experimental data in Reference 3.

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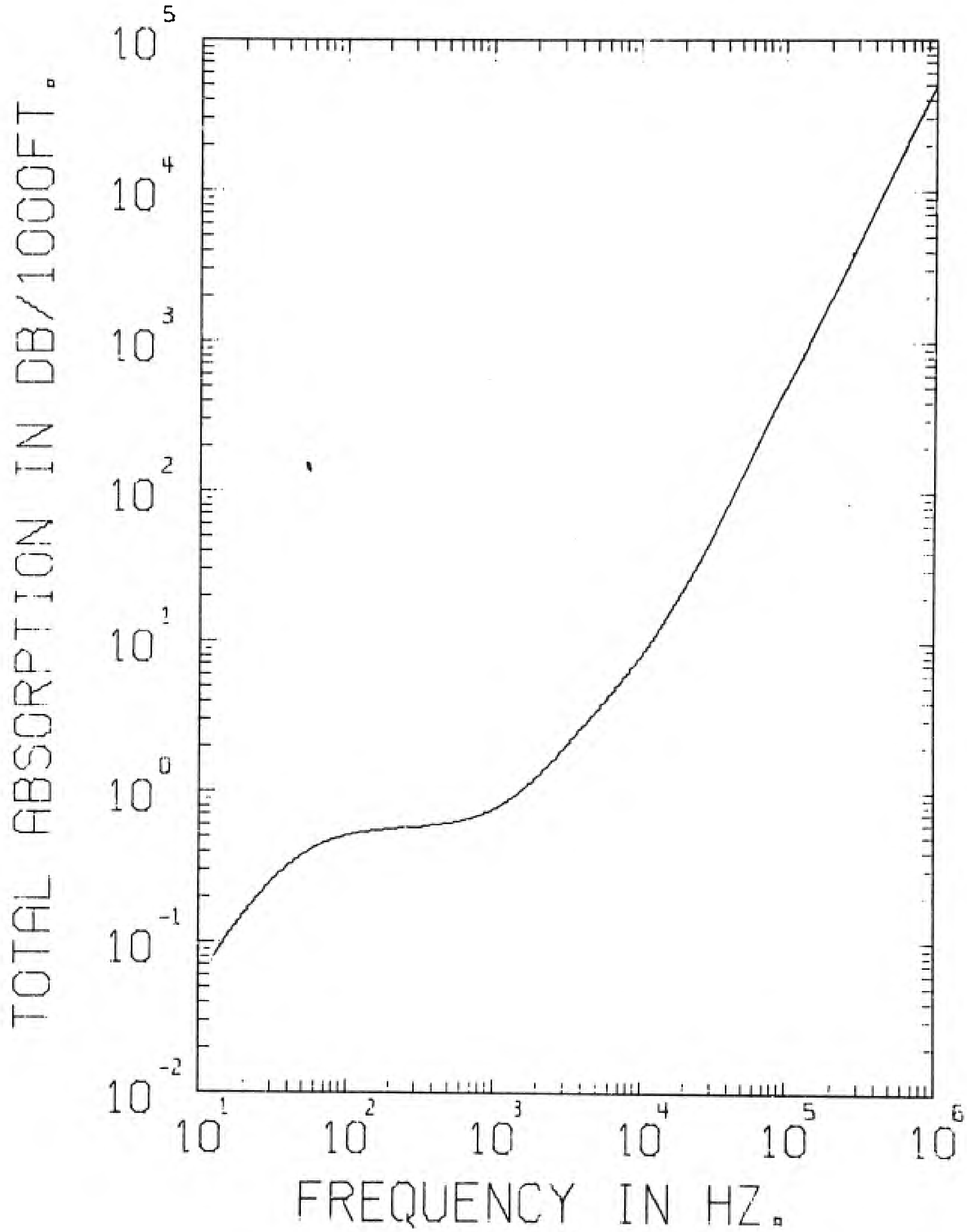
GRAPHS AND TABLES

LIST OF GRAPHS AND TABLES

SOUND ABSORPTION IN STILL AIR FOR 0% RELATIVE HUMIDITY.

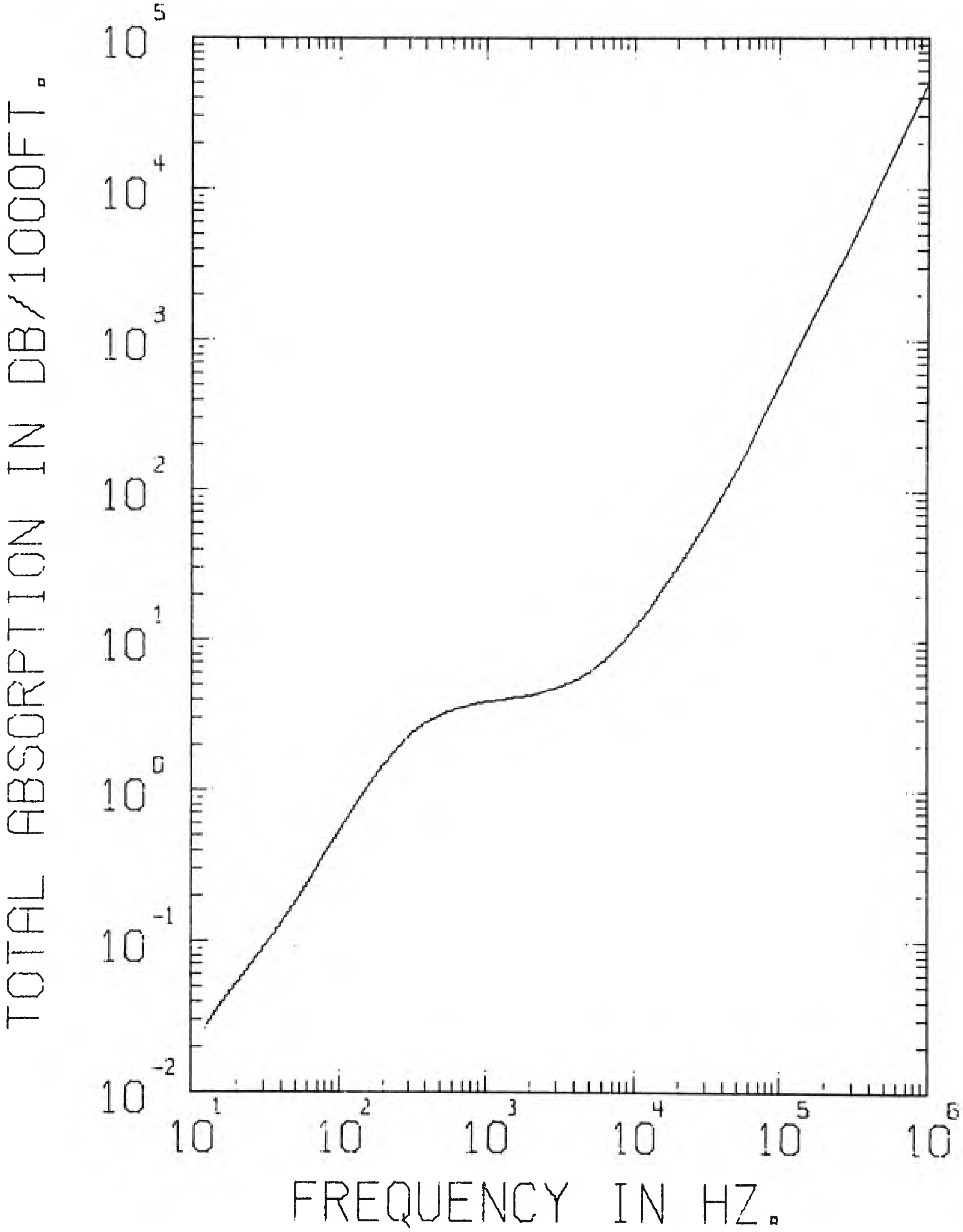


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 0.0%　　　TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.074	0.24	0.083	1.126826
16.	0.114	0.37	0.128	1.126861
20.	0.154	0.51	0.174	1.126892
25.	0.204	0.67	0.230	1.126928
31.	0.258	0.85	0.291	1.126967
40.	0.327	1.07	0.368	1.127013
50.	0.384	1.26	0.433	1.127050
63.	0.436	1.43	0.491	1.127085
80.	0.479	1.57	0.539	1.127112
100.	0.509	1.67	0.573	1.127131
125.	0.531	1.74	0.598	1.127145
160.	0.548	1.80	0.618	1.127154
200.	0.560	1.84	0.631	1.127161
250.	0.571	1.87	0.643	1.127164
315.	0.582	1.91	0.656	1.127167
400.	0.596	1.96	0.672	1.127169
500.	0.615	2.02	0.694	1.127170
630.	0.645	2.11	0.727	1.127171
800.	0.692	2.27	0.780	1.127172
1000.	0.759	2.49	0.855	1.127172
1250.	0.861	2.82	0.970	1.127172
1600.	1.032	3.38	1.163	1.127172
2000.	1.262	4.14	1.423	1.127173
2500.	1.588	5.21	1.790	1.127174
3150.	2.052	6.73	2.313	1.127177
4000.	2.696	8.84	3.039	1.127178
5000.	3.481	11.42	3.925	1.127180
6300.	4.541	14.89	5.118	1.127182
8000.	6.032	19.79	6.799	1.127183
10000.	8.013	26.28	9.032	1.127184
12500.	10.918	35.81	12.306	1.127186
16000.	15.901	52.15	17.923	1.127187
20000.	22.978	75.37	25.901	1.127187
25000.	33.967	111.41	38.288	1.127187
31500.	51.849	170.06	58.443	1.127188
40000.	81.405	267.01	91.759	1.127188
50000.	125.152	410.50	141.070	1.127188
63000.	196.544	644.66	221.542	1.127188
80000.	314.677	1032.14	354.700	1.127188
100000.	489.613	1605.93	551.885	1.127188
125000.	762.945	2502.46	859.982	1.127188
160000.	1247.652	4092.30	1406.338	1.127188
200000.	1947.377	6387.39	2195.059	1.127188
250000.	3040.696	9973.48	3427.435	1.127188
315000.	4825.242	15826.79	5438.953	1.127188
400000.	7778.418	25513.21	8767.734	1.127188
500000.	12151.711	39857.61	13697.258	1.127188
630000.	19289.883	63270.81	21743.316	1.127188
800000.	31102.625	102016.56	35058.496	1.127188
1000000.	48595.793	159394.19	54776.578	1.127188

SOUND ABSORPTION IN STILL AIR
FOR 1% RELATIVE HUMIDITY.

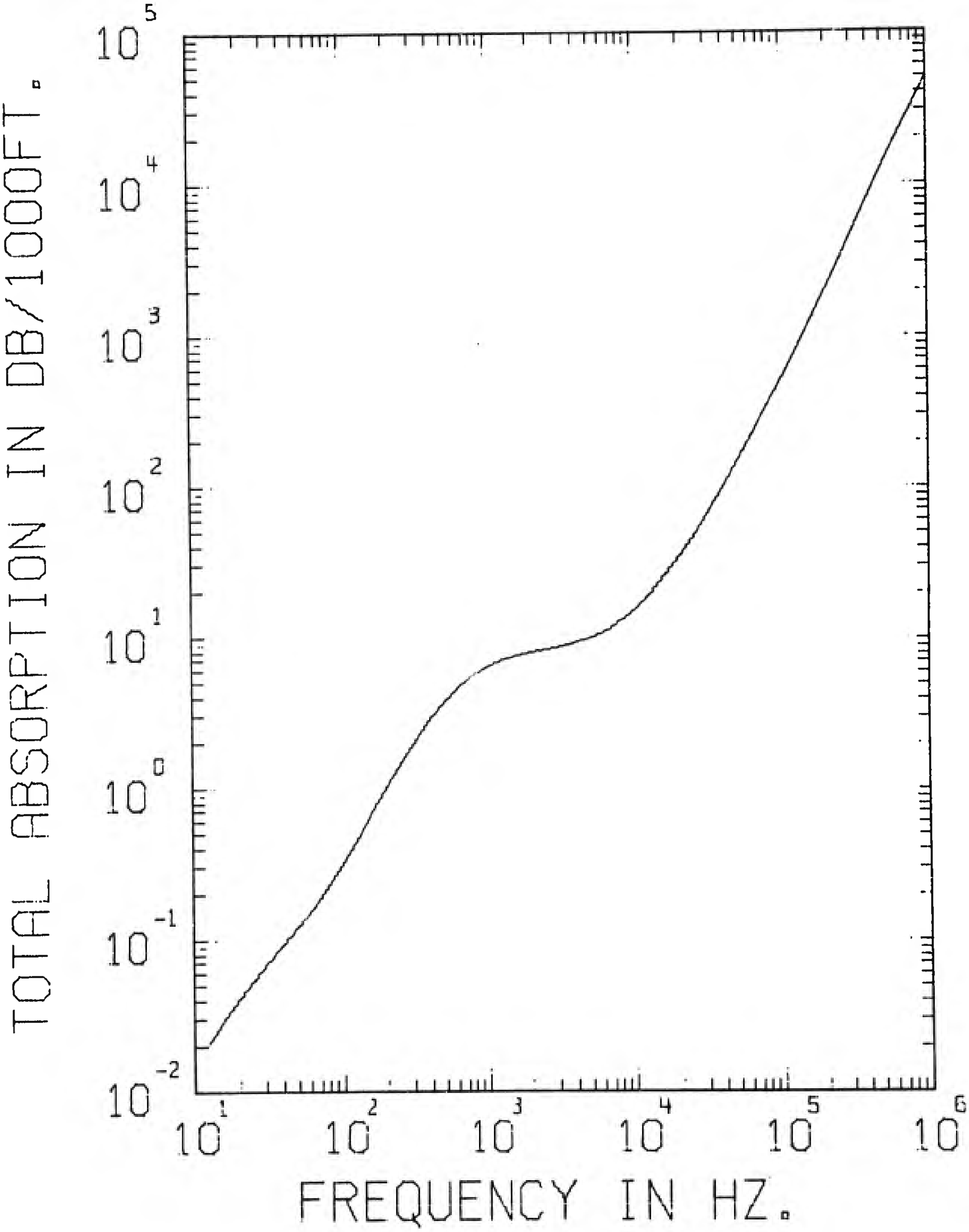


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 1.0% TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.026	0.08	0.029	1.126817
16.	0.039	0.13	0.044	1.126827
20.	0.053	0.17	0.060	1.126836
25.	0.071	0.23	0.080	1.126844
31.	0.094	0.31	0.105	1.126852
40.	0.132	0.43	0.149	1.126861
50.	0.182	0.60	0.206	1.126868
63.	0.260	0.85	0.293	1.126877
80.	0.380	1.25	0.428	1.126889
100.	0.543	1.78	0.612	1.126904
125.	0.771	2.53	0.869	1.126925
160.	1.109	3.64	1.250	1.126955
200.	1.490	4.89	1.679	1.126988
250.	1.921	6.30	2.165	1.127027
315.	2.381	7.81	2.683	1.127066
400.	2.822	9.26	3.181	1.127105
500.	3.173	10.41	3.576	1.127133
630.	3.462	11.35	3.902	1.127158
800.	3.689	12.10	4.158	1.127176
1000.	3.854	12.64	4.344	1.127189
1250.	3.994	13.10	4.502	1.127196
1600.	4.147	13.60	4.674	1.127201
2000.	4.310	14.14	4.859	1.127206
2500.	4.531	14.86	5.107	1.127208
3150.	4.864	15.95	5.483	1.127209
4000.	5.394	17.69	6.080	1.127210
5000.	6.155	20.19	6.938	1.127211
6300.	7.361	24.14	8.297	1.127213
8000.	9.277	30.43	10.457	1.127213
10000.	11.970	39.26	13.493	1.127214
12500.	15.911	52.19	17.936	1.127216
16000.	22.356	73.33	25.200	1.127218
20000.	30.916	101.41	34.850	1.127221
25000.	43.375	142.27	48.893	1.127222
31500.	62.618	205.39	70.584	1.127224
40000.	93.309	306.05	105.180	1.127225
50000.	137.853	452.16	155.391	1.127226
63000.	209.833	688.25	236.529	1.127227
80000.	328.377	1077.08	370.155	1.127227
100000.	503.565	1651.69	567.632	1.127228
125000.	777.061	2548.76	875.924	1.127228
160000.	1261.978	4138.96	1422.424	1.127228
200000.	1961.658	6434.24	2211.236	1.127228
250000.	3055.001	10020.40	3443.682	1.127228
315000.	4839.539	15873.68	5455.262	1.127228
400000.	7792.676	25559.97	8784.117	1.127228
500000.	12165.891	39904.12	13713.727	1.127228
630000.	19303.926	63316.87	21759.918	1.127228
800000.	31116.449	102061.94	35075.324	1.127228
1000000.	48609.227	159438.25	54793.668	1.127228

SOUND ABSORPTION IN STILL AIR FOR 2% RELATIVE HUMIDITY.

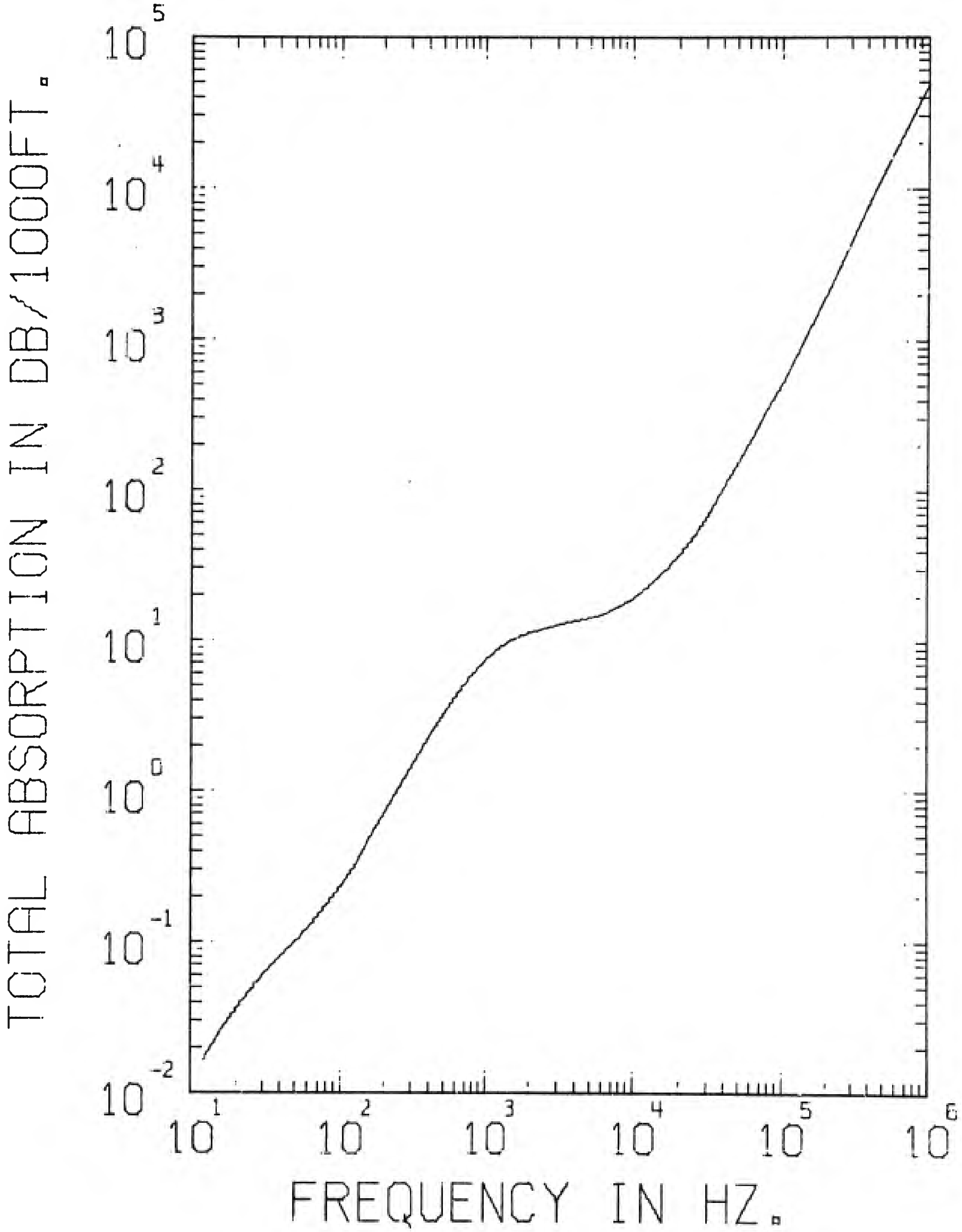


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 2.0% TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.020	0.07	0.023	1.126850
16.	0.031	0.10	0.035	1.126859
20.	0.042	0.14	0.047	1.126866
25.	0.055	0.18	0.062	1.126875
31.	0.070	0.23	0.079	1.126883
40.	0.094	0.31	0.106	1.126890
50.	0.122	0.40	0.138	1.126895
63.	0.164	0.54	0.185	1.126901
80.	0.231	0.76	0.260	1.126905
100.	0.325	1.07	0.367	1.126911
125.	0.468	1.53	0.527	1.126919
160.	0.707	2.32	0.797	1.126929
200.	1.028	3.37	1.159	1.126944
250.	1.479	4.85	1.667	1.126963
315.	2.106	6.91	2.374	1.126988
400.	2.927	9.60	3.298	1.127024
500.	3.811	12.50	4.296	1.127061
630.	4.770	15.65	5.376	1.127100
800.	5.707	18.72	6.433	1.127139
1000.	6.465	21.20	7.287	1.127171
1250.	7.083	23.23	7.983	1.127195
1600.	7.620	24.99	8.589	1.127214
2000.	8.014	26.29	9.034	1.127227
2500.	8.373	27.46	9.438	1.127235
3150.	8.771	28.77	9.887	1.127241
4000.	9.292	30.48	10.474	1.127246
5000.	9.981	32.74	11.251	1.127248
6300.	11.046	36.23	12.452	1.127250
8000.	12.756	41.84	14.379	1.127251
10000.	15.228	49.95	17.166	1.127252
12500.	18.998	62.31	21.415	1.127254
16000.	25.464	83.52	28.704	1.127255
20000.	34.416	112.88	38.795	1.127256
25000.	47.749	156.62	53.825	1.127258
31500.	68.403	224.36	77.108	1.127259
40000.	100.906	330.97	113.748	1.127262
50000.	147.197	482.81	165.930	1.127264
63000.	220.803	724.23	248.904	1.127266
80000.	340.695	1117.48	384.054	1.127267
100000.	516.817	1695.16	582.591	1.127268
125000.	790.975	2594.40	891.641	1.127268
160000.	1276.282	4186.20	1438.711	1.127268
200000.	1976.344	6482.40	2227.870	1.127269
250000.	3069.858	10069.13	3460.555	1.127269
315000.	4854.488	15922.72	5472.312	1.127269
400000.	7807.656	25609.11	8801.324	1.127269
500000.	12180.836	39953.14	13731.074	1.127269
630000.	19318.762	63365.53	21777.434	1.127269
800000.	31131.047	102109.81	35093.055	1.127269
1000000.	48623.480	159485.00	54811.730	1.127269

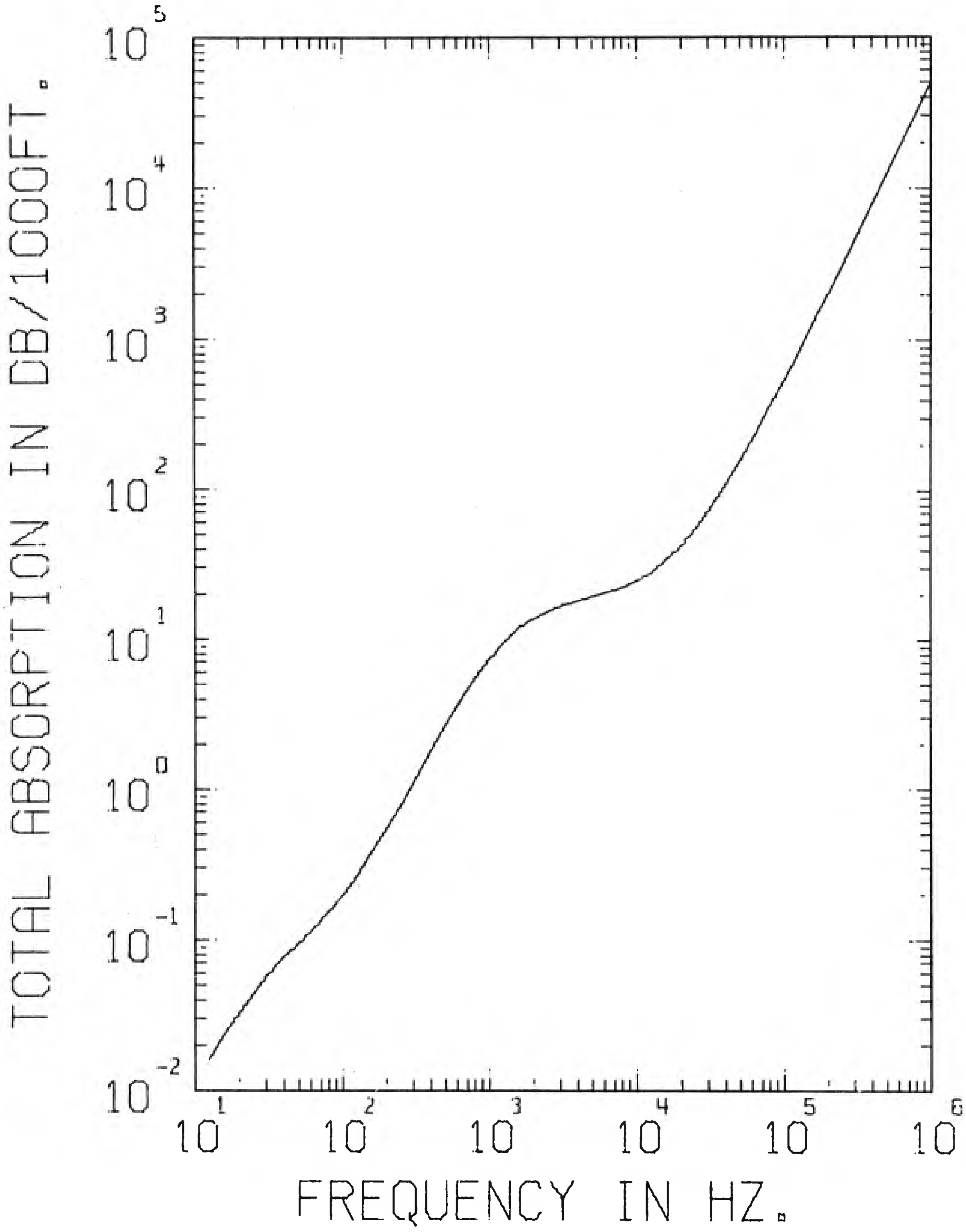
SOUND ABSORPTION IN STILL AIR FOR 3% RELATIVE HUMIDITY.



ABSORPTION AND VELOCITY OF SOUND IN STILL AIR
RELATIVE HUMIDITY = 3.0%   TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.017	0.06	0.019	1.126885
16.	0.027	0.09	0.030	1.126893
20.	0.037	0.12	0.041	1.126901
25.	0.049	0.16	0.055	1.126908
31.	0.063	0.21	0.071	1.126917
40.	0.082	0.27	0.092	1.126925
50.	0.103	0.34	0.116	1.126931
63.	0.133	0.44	0.150	1.126936
80.	0.177	0.58	0.200	1.126941
100.	0.239	0.79	0.270	1.126944
125.	0.334	1.09	0.376	1.126948
160.	0.496	1.63	0.559	1.126953
200.	0.722	2.37	0.814	1.126960
250.	1.060	3.48	1.195	1.126969
315.	1.575	5.16	1.775	1.126983
400.	2.338	7.67	2.635	1.127003
500.	3.305	10.84	3.725	1.127028
630.	4.568	14.98	5.148	1.127061
800.	6.090	19.98	6.864	1.127100
1000.	7.590	24.90	8.555	1.127139
1250.	9.027	29.61	10.175	1.127175
1600.	10.417	34.17	11.742	1.127212
2000.	11.448	37.55	12.904	1.127236
2500.	12.290	40.31	13.854	1.127254
3150.	13.035	42.75	14.694	1.127267
4000.	13.779	45.19	15.532	1.127276
5000.	14.574	47.80	16.429	1.127282
6300.	15.662	51.37	17.656	1.127286
8000.	17.311	56.78	19.515	1.127290
10000.	19.654	64.46	22.155	1.127291
12500.	23.228	76.19	26.185	1.127292
16000.	29.439	96.56	33.187	1.127294
20000.	38.206	125.32	43.070	1.127295
25000.	51.540	169.05	58.101	1.127296
31500.	72.583	238.07	81.823	1.127298
40000.	106.066	347.90	119.568	1.127300
50000.	153.794	504.44	173.372	1.127301
63000.	229.214	751.82	258.393	1.127303
80000.	351.010	1151.31	395.696	1.127306
100000.	528.698	1734.13	596.005	1.127307
125000.	804.106	2637.47	906.475	1.127308
160000.	1290.417	4232.57	1454.698	1.127309
200000.	1991.099	6530.80	2244.585	1.127310
250000.	3085.031	10118.90	3477.786	1.127310
315000.	4869.926	15973.35	5489.914	1.127310
400000.	7823.238	25660.22	8819.211	1.127310
500000.	12196.473	40004.43	13749.203	1.127310
630000.	19334.352	63416.66	21795.801	1.127310
800000.	31146.480	102160.44	35111.730	1.127310
1000000.	48638.613	159534.62	54830.785	1.127310

SOUND ABSORPTION IN STILL AIR
FOR 4% RELATIVE HUMIDITY.

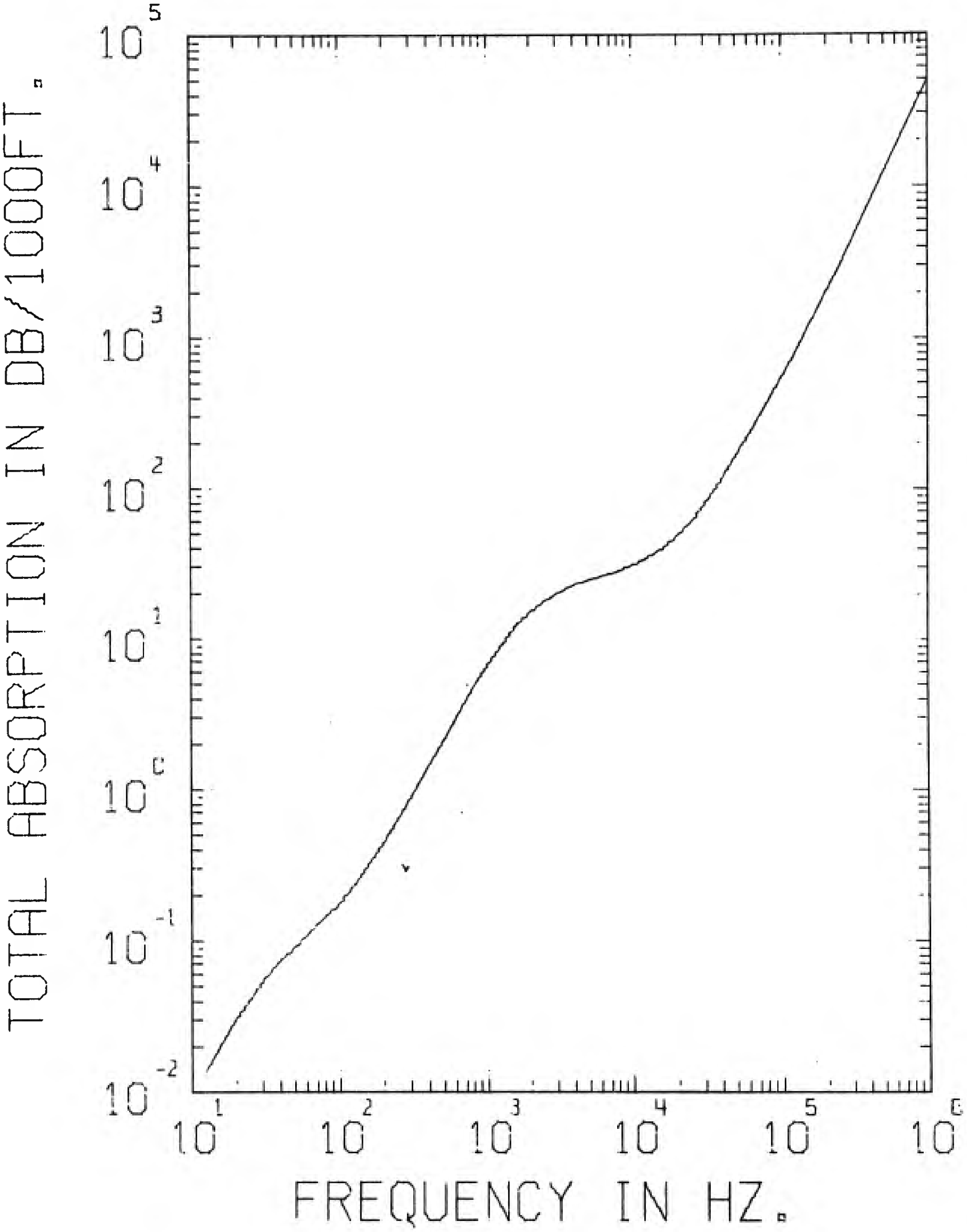


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 4.0%   TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.015	0.05	0.017	1.126923
16.	0.024	0.08	0.027	1.126929
20.	0.033	0.11	0.038	1.126936
25.	0.045	0.15	0.051	1.126944
31.	0.059	0.19	0.066	1.126951
40.	0.077	0.25	0.087	1.126961
50.	0.096	0.31	0.108	1.126967
63.	0.120	0.39	0.135	1.126972
80.	0.154	0.50	0.173	1.126978
100.	0.200	0.65	0.225	1.126981
125.	0.268	0.88	0.302	1.126985
160.	0.385	1.26	0.434	1.126987
200.	0.551	1.81	0.621	1.126992
250.	0.803	2.63	0.905	1.126996
315.	1.200	3.93	1.352	1.127004
400.	1.820	5.97	2.051	1.127015
500.	2.664	8.74	3.003	1.127031
630.	3.881	12.73	4.374	1.127053
800.	5.548	18.20	6.254	1.127083
1000.	7.452	24.44	8.400	1.127119
1250.	9.573	31.40	10.790	1.127156
1600.	11.950	39.19	13.470	1.127198
2000.	13.929	45.69	15.701	1.127234
2500.	15.634	51.28	17.623	1.127261
3150.	17.102	56.10	19.279	1.127285
4000.	18.392	60.33	20.733	1.127302
5000.	19.529	64.06	22.016	1.127314
6300.	20.832	68.33	23.484	1.127320
8000.	22.580	74.06	25.455	1.127326
10000.	24.920	81.74	28.093	1.127329
12500.	28.409	93.18	32.026	1.127332
16000.	34.436	112.95	38.821	1.127333
20000.	42.980	140.97	48.453	1.127334
25000.	56.095	183.99	63.238	1.127336
31500.	77.042	252.70	86.852	1.127337
40000.	110.771	363.33	124.876	1.127339
50000.	159.230	522.27	179.506	1.127341
63000.	235.977	774.00	266.026	1.127343
80000.	359.591	1179.46	405.383	1.127345
100000.	539.097	1768.24	607.749	1.127346
125000.	816.176	2677.06	920.115	1.127349
160000.	1303.986	4277.07	1470.048	1.127350
200000.	2005.672	6578.60	2261.094	1.127350
250000.	3100.310	10169.02	3495.137	1.127351
315000.	4885.695	16025.08	5507.891	1.127351
400000.	7839.312	25712.94	8837.652	1.127351
500000.	12212.672	40057.56	13767.977	1.127352
630000.	19350.574	63469.87	21814.902	1.127352
800000.	31162.605	102213.31	35131.215	1.127352
1000000.	48654.492	159586.69	54850.727	1.127352

SOUND ABSORPTION IN STILL AIR FOR 5% RELATIVE HUMIDITY.

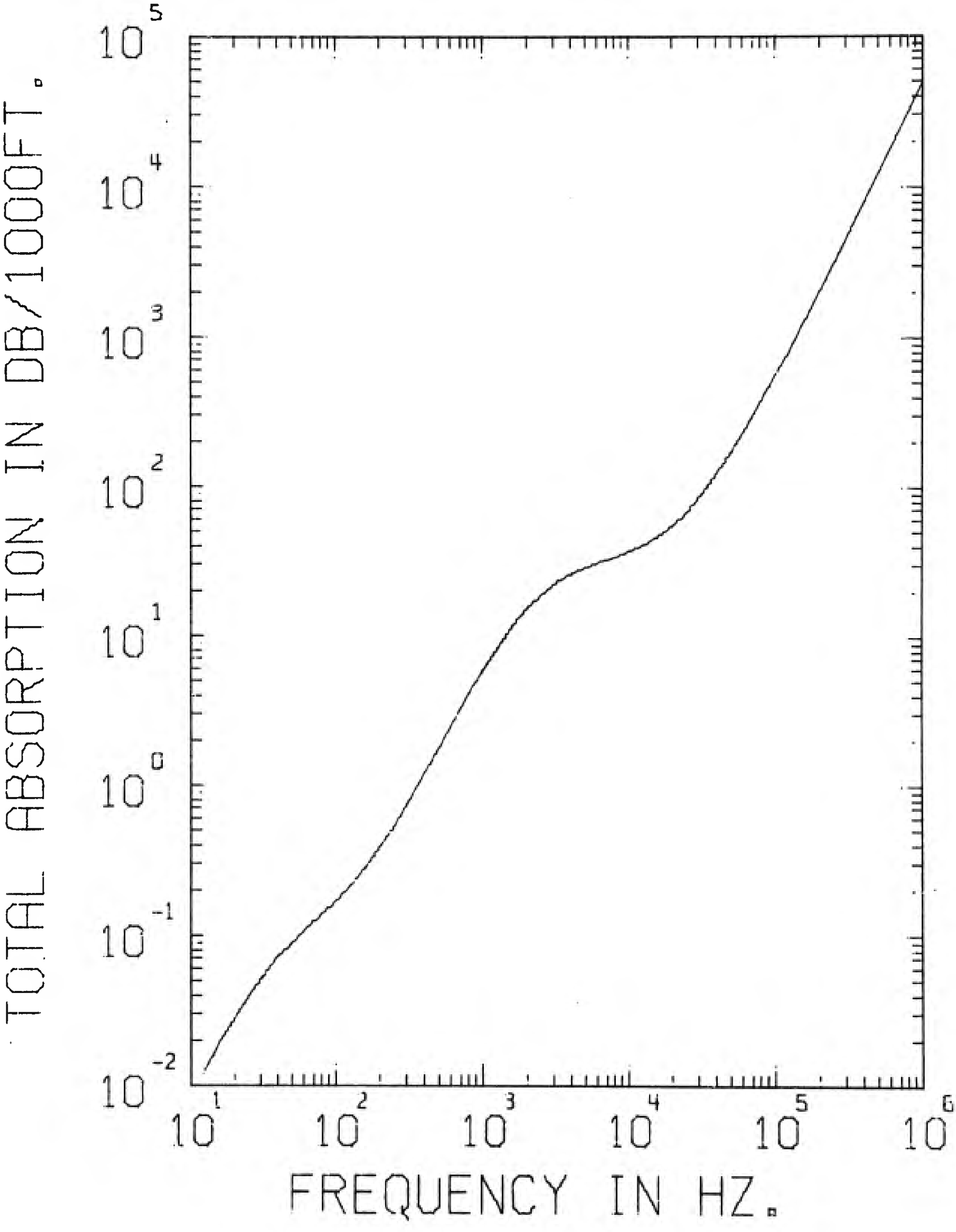


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 5.0%   TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (CB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.013	0.04	0.015	1.126963
16.	0.021	0.07	0.024	1.126967
20.	0.031	0.10	0.034	1.126973
25.	0.042	0.14	0.048	1.126980
31.	0.056	0.18	0.063	1.126987
40.	0.074	0.24	0.083	1.126996
50.	0.092	0.30	0.104	1.127004
63.	0.114	0.37	0.129	1.127009
80.	0.143	0.47	0.161	1.127015
100.	0.179	0.59	0.202	1.127019
125.	0.232	0.76	0.262	1.127022
160.	0.322	1.06	0.363	1.127025
200.	0.449	1.47	0.506	1.127028
250.	0.644	2.11	0.726	1.127031
315.	0.954	3.13	1.075	1.127035
400.	1.451	4.76	1.635	1.127043
500.	2.151	7.05	2.424	1.127052
630.	3.211	10.53	3.619	1.127067
800.	4.774	15.66	5.380	1.127088
1000.	6.732	22.08	7.588	1.127115
1250.	9.164	30.06	10.329	1.127147
1600.	12.259	40.21	13.818	1.127189
2000.	15.175	49.77	17.106	1.127228
2500.	17.945	58.86	20.229	1.127263
3150.	20.476	67.16	23.082	1.127295
4000.	22.685	74.41	25.573	1.127321
5000.	24.473	80.27	27.589	1.127338
6300.	26.245	86.08	29.587	1.127352
8000.	28.295	92.81	31.899	1.127360
10000.	30.781	100.96	34.701	1.127365
12500.	34.306	112.52	38.676	1.127369
16000.	40.263	132.06	45.391	1.127372
20000.	48.653	159.58	54.850	1.127373
25000.	61.552	201.89	69.393	1.127375
31500.	82.274	269.86	92.753	1.127376
40000.	115.903	380.16	130.666	1.127378
50000.	164.582	539.83	185.547	1.127379
63000.	242.070	793.99	272.905	1.127381
80000.	367.063	1203.97	413.821	1.127383
100000.	548.273	1798.34	618.115	1.127386
125000.	827.179	2713.15	932.552	1.127388
160000.	1316.839	4319.23	1484.590	1.127389
200000.	2019.879	6625.20	2277.191	1.127390
250000.	3115.528	10218.93	3512.417	1.127391
315000.	4901.645	16077.39	5526.066	1.127391
400000.	7855.758	25766.88	8856.508	1.127391
500000.	12229.379	40112.36	13787.301	1.127392
630000.	19367.410	63525.10	21834.656	1.127392
800000.	31179.379	102268.31	35151.375	1.127392
1000000.	48671.082	159641.12	54871.379	1.127392

SOUND ABSORPTION IN STILL AIR
FOR 6% RELATIVE HUMIDITY.

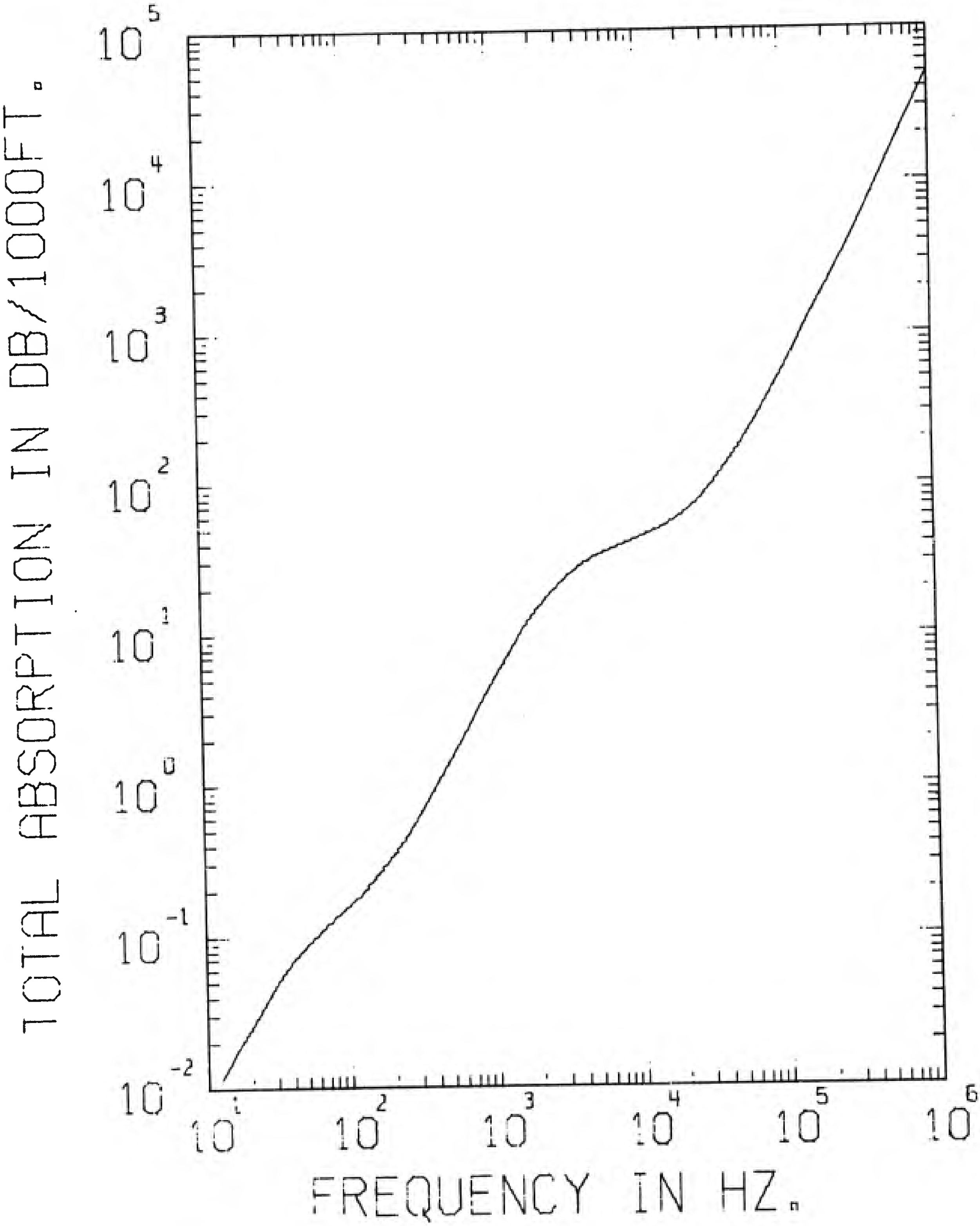


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 6.0% TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.012	0.04	0.013	1.127002
16.	0.020	0.06	0.022	1.127006
20.	0.028	0.09	0.032	1.127010
25.	0.040	0.13	0.045	1.127016
31.	0.053	0.17	0.060	1.127024
40.	0.072	0.24	0.081	1.127032
50.	0.090	0.30	0.102	1.127040
63.	0.112	0.37	0.126	1.127048
80.	0.138	0.45	0.155	1.127053
100.	0.169	0.55	0.190	1.127057
125.	0.213	0.70	0.240	1.127060
160.	0.285	0.93	0.321	1.127064
200.	0.386	1.27	0.435	1.127066
250.	0.541	1.78	0.610	1.127069
315.	0.790	2.59	0.891	1.127072
400.	1.193	3.91	1.345	1.127076
500.	1.771	5.81	1.996	1.127083
630.	2.671	8.76	3.011	1.127092
800.	4.053	13.29	4.568	1.127107
1000.	5.886	19.31	6.634	1.127127
1250.	8.333	27.33	9.393	1.127152
1600.	11.756	38.56	13.251	1.127189
2000.	15.338	50.31	17.290	1.127226
2500.	19.096	62.63	21.526	1.127265
3150.	22.833	74.89	25.739	1.127302
4000.	26.270	86.17	29.615	1.127336
5000.	29.038	95.24	32.736	1.127360
6300.	31.591	103.62	35.615	1.127378
8000.	34.204	112.19	38.561	1.127392
10000.	37.023	121.43	41.739	1.127400
12500.	40.730	133.60	45.920	1.127405
16000.	46.744	153.32	52.700	1.127410
20000.	55.074	180.64	62.091	1.127412
25000.	67.824	222.46	76.465	1.127414
31500.	88.324	289.70	99.578	1.127417
40000.	121.736	399.29	137.248	1.127418
50000.	170.364	558.79	192.072	1.127419
63000.	248.154	813.94	279.774	1.127420
80000.	374.034	1226.83	421.694	1.127422
100000.	556.627	1825.74	627.556	1.127425
125000.	837.279	2746.27	943.971	1.127427
160000.	1328.949	4358.95	1498.296	1.127429
200000.	2033.610	6670.24	2292.753	1.127430
250000.	3130.559	10268.23	3529.489	1.127431
315000.	4917.652	16129.89	5544.316	1.127432
400000.	7872.453	25821.64	8875.652	1.127432
500000.	12246.473	40168.43	13807.086	1.127434
630000.	19384.723	63581.93	21854.988	1.127434
800000.	31196.738	102325.25	35172.254	1.127434
1000000.	48688.320	159697.62	54892.855	1.127434

SOUND ABSORPTION IN STILL AIR FOR 7% RELATIVE HUMIDITY.

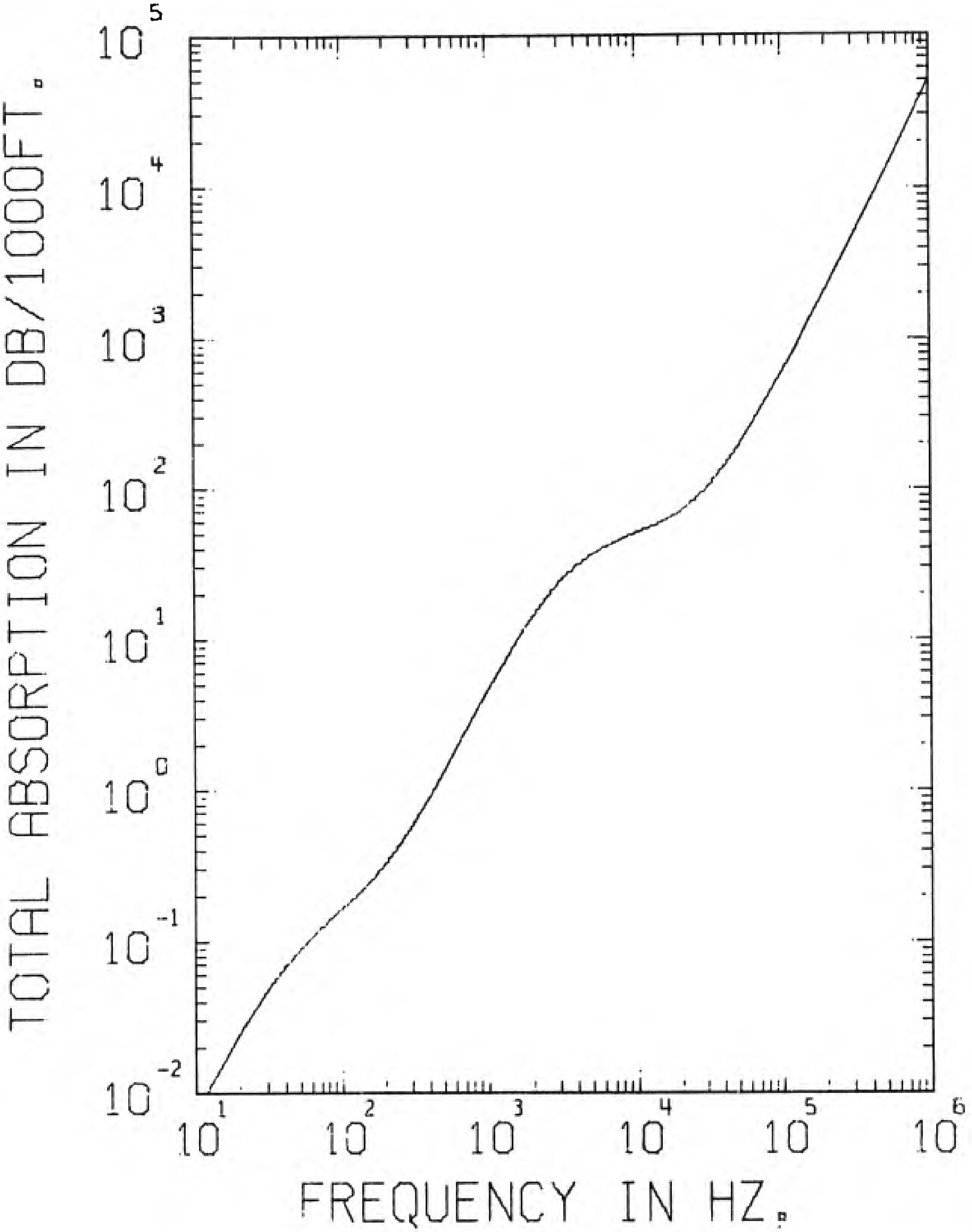


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 7.0% TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.011	0.03	0.012	1.127041
16.	0.018	0.06	0.020	1.127044
20.	0.026	0.09	0.029	1.127048
25.	0.037	0.12	0.042	1.127053
31.	0.051	0.17	0.057	1.127061
40.	0.070	0.23	0.079	1.127069
50.	0.089	0.29	0.100	1.127077
63.	0.110	0.36	0.124	1.127085
80.	0.135	0.44	0.152	1.127091
100.	0.164	0.54	0.184	1.127097
125.	0.201	0.66	0.227	1.127100
160.	0.262	0.86	0.295	1.127103
200.	0.345	1.13	0.389	1.127106
250.	0.473	1.55	0.533	1.127108
315.	0.677	2.22	0.764	1.127110
400.	1.010	3.31	1.139	1.127113
500.	1.493	4.90	1.683	1.127117
630.	2.256	7.40	2.543	1.127124
800.	3.456	11.34	3.896	1.127134
1000.	5.105	16.74	5.754	1.127149
1250.	7.413	24.31	8.355	1.127169
1600.	10.861	35.63	12.243	1.127198
2000.	14.775	48.46	16.655	1.127231
2500.	19.249	63.14	21.699	1.127269
3150.	24.099	79.05	27.167	1.127309
4000.	28.897	94.78	32.577	1.127347
5000.	32.911	107.95	37.104	1.127378
6300.	36.569	119.95	41.228	1.127402
8000.	40.049	131.36	45.152	1.127421
10000.	43.433	142.46	48.968	1.127433
12500.	47.503	155.81	53.557	1.127441
16000.	53.727	176.22	60.574	1.127447
20000.	62.105	203.70	70.020	1.127451
25000.	74.789	245.31	84.321	1.127454
31500.	95.125	312.01	107.249	1.127456
40000.	128.309	420.85	144.663	1.127457
50000.	176.766	579.79	199.296	1.127459
63000.	254.588	835.05	287.038	1.127460
80000.	380.952	1249.52	429.509	1.127462
100000.	564.556	1851.74	636.517	1.127464
125000.	846.723	2777.25	954.651	1.127466
160000.	1340.390	4396.48	1511.248	1.127469
200000.	2046.828	6713.59	2307.740	1.127471
250000.	3145.312	10316.62	3546.250	1.127472
315000.	4933.645	16182.35	5562.547	1.127473
400000.	7889.352	25877.07	8895.027	1.127473
500000.	12263.934	40225.70	13827.262	1.127474
630000.	19402.508	63640.22	21875.816	1.127474
800000.	31214.664	102384.06	35193.715	1.127474
1000000.	48706.199	159756.31	54914.965	1.127474

SOUND ABSORPTION IN STILL AIR FOR 8% RELATIVE HUMIDITY.

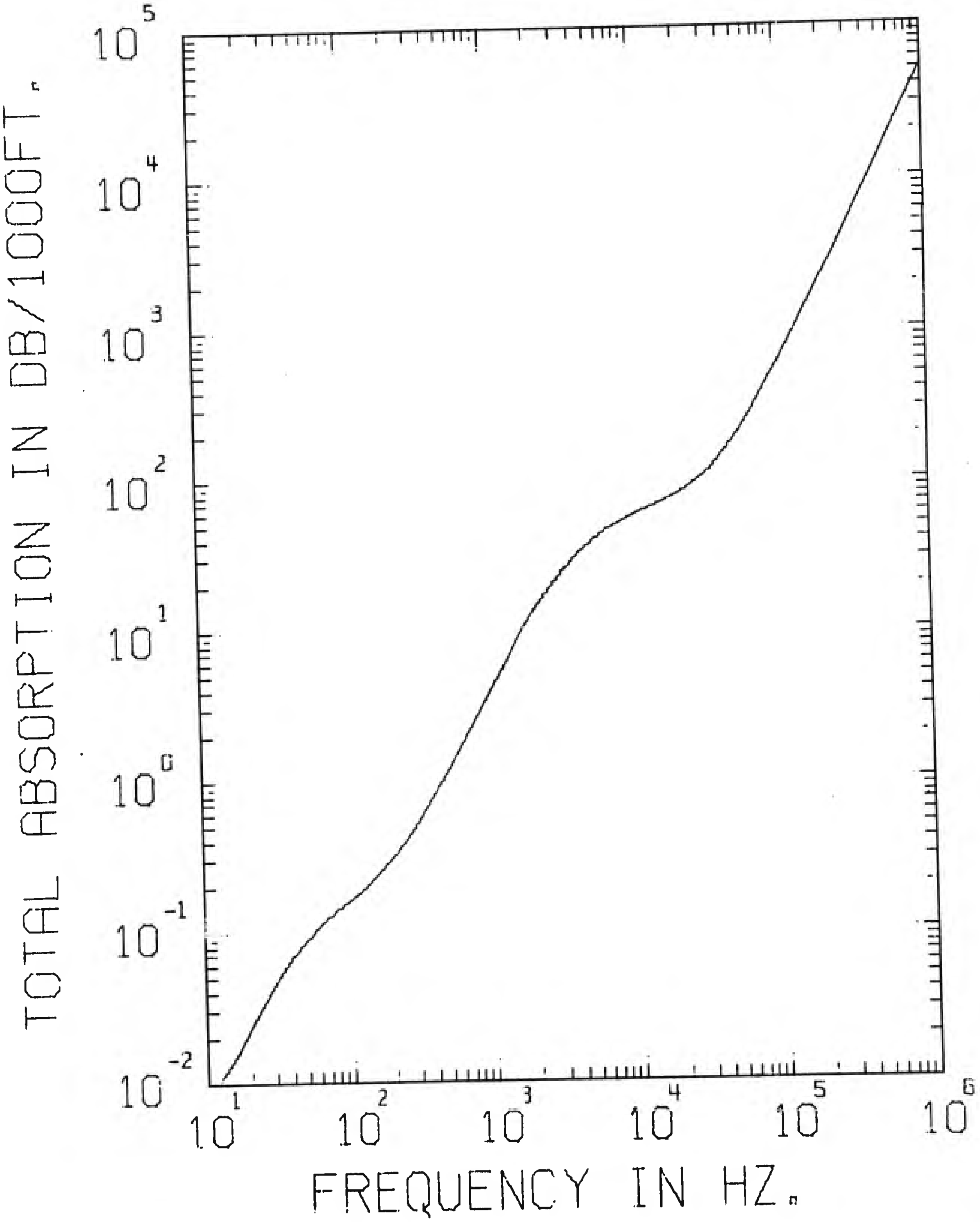


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 8.0% TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.010	0.03	0.011	1.127080
16.	0.016	0.05	0.019	1.127084
20.	0.024	0.08	0.027	1.127088
25.	0.035	0.12	0.040	1.127092
31.	0.048	0.16	0.055	1.127099
40.	0.068	0.22	0.076	1.127108
50.	0.087	0.29	0.098	1.127115
63.	0.109	0.36	0.123	1.127122
80.	0.134	0.44	0.151	1.127130
100.	0.161	0.53	0.182	1.127135
125.	0.195	0.64	0.220	1.127139
160.	0.248	0.81	0.279	1.127143
200.	0.319	1.04	0.359	1.127145
250.	0.426	1.40	0.480	1.127147
315.	0.598	1.96	0.674	1.127148
400.	0.878	2.88	0.990	1.127151
500.	1.286	4.22	1.450	1.127154
630.	1.938	6.36	2.185	1.127159
800.	2.979	9.77	3.358	1.127167
1000.	4.440	14.56	5.005	1.127177
1250.	6.551	21.49	7.384	1.127192
1600.	9.853	32.32	11.106	1.127215
2000.	13.831	45.36	15.590	1.127244
2500.	18.703	61.35	21.083	1.127278
3150.	24.407	80.05	27.514	1.127318
4000.	30.494	100.02	34.378	1.127358
5000.	35.889	117.71	40.461	1.127393
6300.	40.918	134.21	46.132	1.127424
8000.	45.583	149.51	51.392	1.127448
10000.	49.799	163.34	56.146	1.127464
12500.	54.448	178.59	61.389	1.127476
16000.	61.066	200.30	68.851	1.127484
20000.	69.618	228.35	78.494	1.127489
25000.	82.336	270.06	92.833	1.127492
31500.	102.584	336.47	115.663	1.127496
40000.	135.579	444.70	152.866	1.127498
50000.	183.833	602.97	207.271	1.127499
63000.	261.542	857.86	294.888	1.127501
80000.	388.102	1272.97	437.586	1.127502
100000.	572.376	1877.39	645.357	1.127505
125000.	855.766	2806.91	964.881	1.127506
160000.	1351.284	4432.21	1523.585	1.127509
200000.	2059.561	6755.36	2322.175	1.127510
250000.	3159.747	10363.96	3562.655	1.127513
315000.	4949.543	16234.50	5580.672	1.127513
400000.	7906.352	25932.83	8914.520	1.127514
500000.	12281.637	40283.76	13847.727	1.127515
630000.	19420.684	63699.84	21897.105	1.127515
800000.	31233.098	102444.50	35215.777	1.127515
1000000.	48724.590	159816.62	54937.695	1.127515

SOUND ABSORPTION IN STILL AIR FOR 9% RELATIVE HUMIDITY.

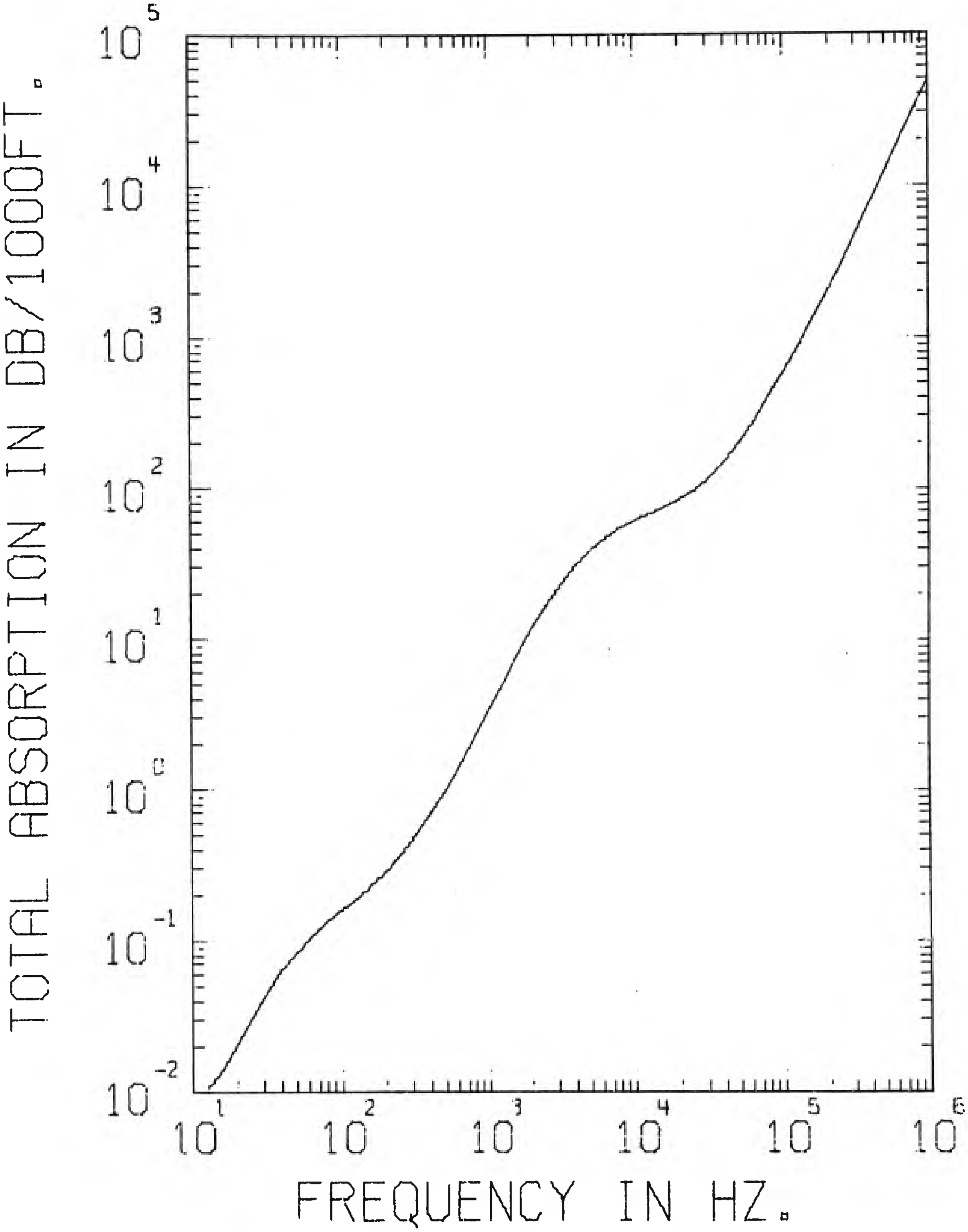


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 9.0% TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.009	0.03	0.010	1.127121
16.	0.015	0.05	0.017	1.127124
20.	0.023	0.07	0.026	1.127127
25.	0.033	0.11	0.037	1.127131
31.	0.046	0.15	0.052	1.127137
40.	0.066	0.22	0.074	1.127145
50.	0.086	0.28	0.097	1.127152
63.	0.109	0.36	0.123	1.127161
80.	0.134	0.44	0.151	1.127169
100.	0.160	0.53	0.181	1.127174
125.	0.192	0.63	0.216	1.127178
160.	0.239	0.78	0.269	1.127183
200.	0.301	0.99	0.339	1.127185
250.	0.393	1.29	0.443	1.127187
315.	0.540	1.77	0.609	1.127188
400.	0.780	2.56	0.879	1.127190
500.	1.130	3.71	1.274	1.127193
630.	1.693	5.55	1.908	1.127196
800.	2.600	8.53	2.931	1.127202
1000.	3.892	12.76	4.387	1.127211
1250.	5.797	19.01	6.534	1.127221
1600.	8.873	29.11	10.003	1.127239
2000.	12.745	41.80	14.367	1.127263
2500.	17.747	58.21	20.006	1.127294
3150.	23.992	78.69	27.047	1.127330
4000.	31.144	102.15	35.111	1.127371
5000.	37.893	124.29	42.721	1.127408
6300.	44.454	145.81	50.120	1.127444
8000.	50.582	165.91	57.030	1.127473
10000.	55.910	183.39	63.038	1.127494
12500.	61.387	201.35	69.215	1.127508
16000.	68.615	225.06	77.365	1.127521
20000.	77.492	254.17	87.374	1.127526
25000.	90.359	296.38	101.882	1.127531
31500.	110.609	362.80	124.716	1.127534
40000.	143.479	470.61	161.779	1.127538
50000.	191.543	628.26	215.972	1.127539
63000.	269.075	882.56	303.393	1.127541
80000.	395.645	1297.71	446.106	1.127542
100000.	580.315	1903.43	654.331	1.127544
125000.	864.632	2835.99	974.913	1.127547
160000.	1361.782	4466.64	1535.476	1.127549
200000.	2071.855	6795.68	2336.122	1.127551
250000.	3173.851	10410.23	3578.682	1.127552
315000.	4965.270	16286.08	5598.602	1.127553
400000.	7923.391	25988.72	8934.055	1.127555
500000.	12299.555	40342.54	13868.434	1.127556
630000.	19439.195	63760.55	21918.777	1.127556
800000.	31251.953	102506.37	35238.320	1.127556
1000000.	48743.488	159878.62	54961.051	1.127557

SOUND ABSORPTION IN STILL AIR FOR 10% RELATIVE HUMIDITY.

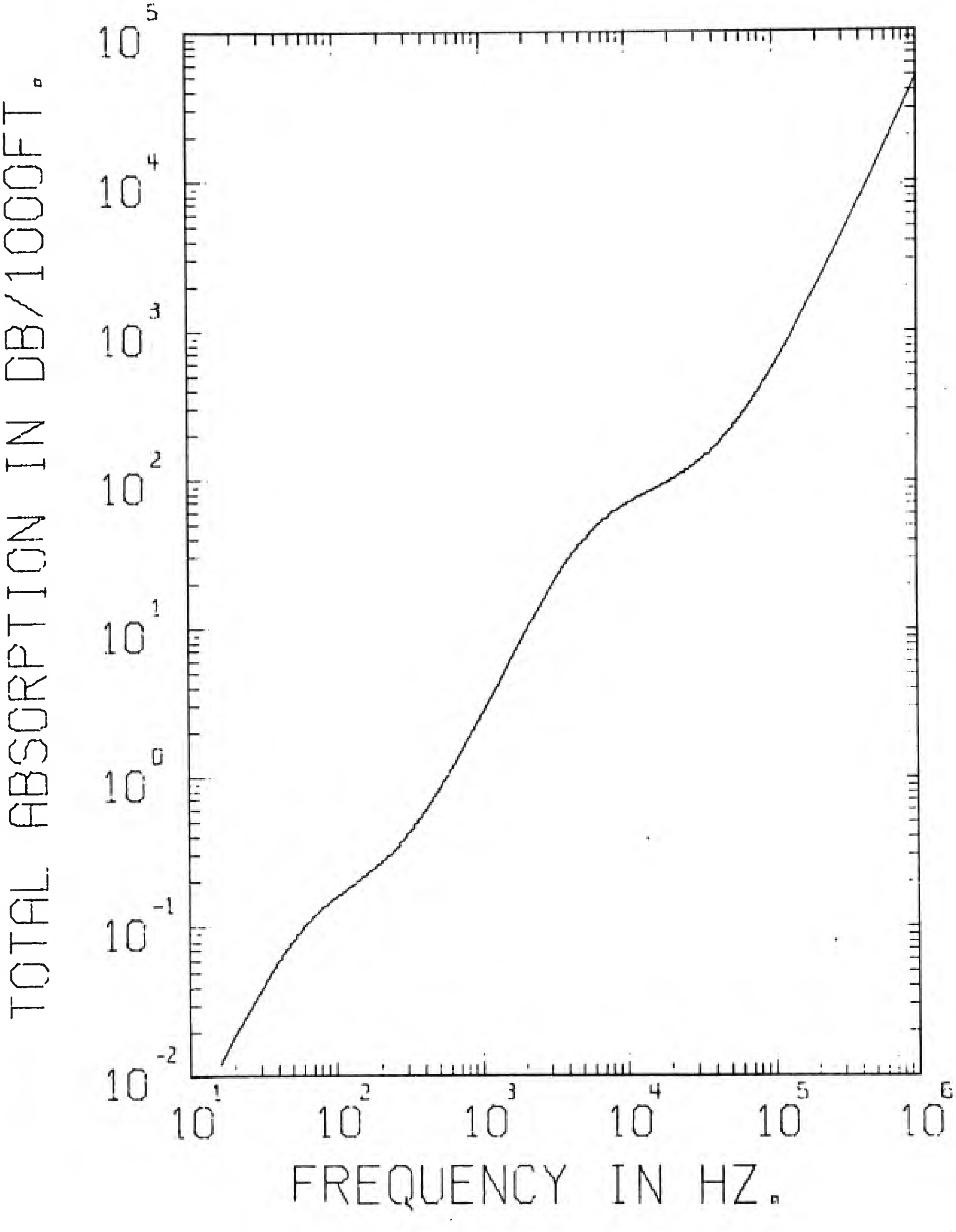


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 10.0%   TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.008	0.03	0.009	1.127161
16.	0.014	0.05	0.016	1.127163
20.	0.021	0.07	0.024	1.127167
25.	0.031	0.10	0.035	1.127170
31.	0.044	0.14	0.050	1.127175
40.	0.064	0.21	0.072	1.127183
50.	0.084	0.28	0.095	1.127191
63.	0.108	0.35	0.122	1.127199
80.	0.134	0.44	0.151	1.127207
100.	0.161	0.53	0.181	1.127213
125.	0.191	0.63	0.215	1.127217
160.	0.234	0.77	0.264	1.127221
200.	0.289	0.95	0.326	1.127225
250.	0.370	1.21	0.417	1.127227
315.	0.498	1.63	0.561	1.127228
400.	0.706	2.32	0.796	1.127230
500.	1.011	3.32	1.139	1.127233
630.	1.501	4.92	1.692	1.127234
800.	2.297	7.54	2.590	1.127238
1000.	3.442	11.29	3.880	1.127245
1250.	5.155	16.91	5.811	1.127254
1600.	7.984	26.19	9.000	1.127269
2000.	11.658	38.24	13.141	1.127287
2500.	16.602	54.45	18.716	1.127313
3150.	23.104	75.78	26.046	1.127346
4000.	31.023	101.76	34.975	1.127386
5000.	38.967	127.81	43.932	1.127424
6300.	47.085	154.44	53.087	1.127462
8000.	54.875	179.99	61.872	1.127497
10000.	61.578	201.98	69.431	1.127522
12500.	68.146	223.52	76.837	1.127540
16000.	76.231	250.04	85.955	1.127555
20000.	85.605	280.78	96.525	1.127563
25000.	98.754	323.91	111.352	1.127570
31500.	119.113	390.69	134.309	1.127573
40000.	151.938	498.36	171.321	1.127576
50000.	199.852	655.52	225.349	1.127579
63000.	277.191	909.19	312.555	1.127581
80000.	403.662	1324.01	455.162	1.127583
100000.	588.526	1930.37	663.613	1.127584
125000.	873.505	2865.10	984.953	1.127587
160000.	1372.027	4500.25	1547.082	1.127589
200000.	2083.789	6834.82	2349.661	1.127591
250000.	3187.622	10455.40	3594.337	1.127592
315000.	4980.809	16337.05	5616.328	1.127594
400000.	7940.414	26044.55	8953.578	1.127596
500000.	12317.617	40401.78	13889.293	1.127596
630000.	19457.973	63822.14	21940.746	1.127597
800000.	31271.176	102569.44	35261.277	1.127597
1000000.	48762.930	159942.37	54984.926	1.127597

SOUND ABSORPTION IN STILL AIR FOR 12% RELATIVE HUMIDITY.

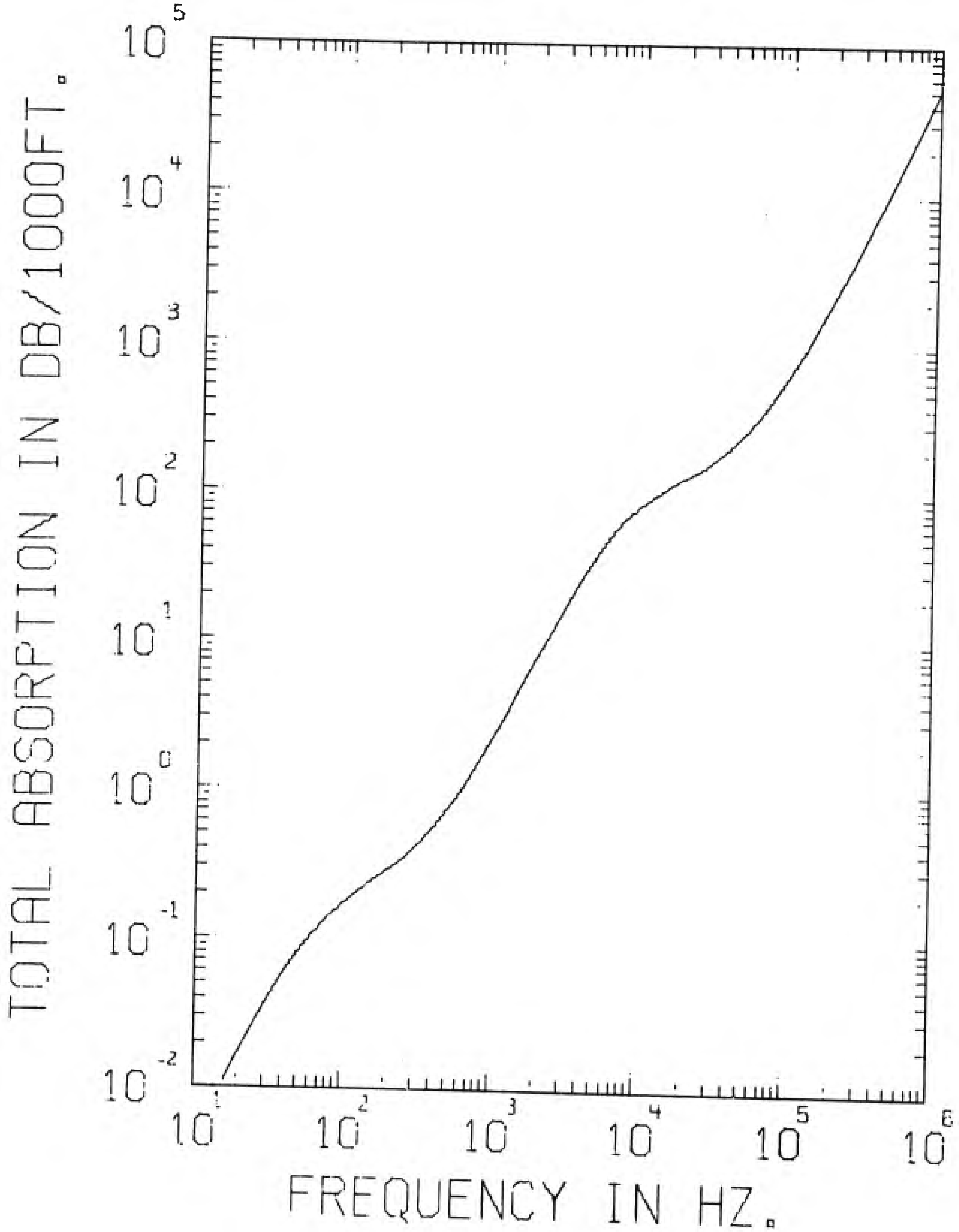


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 12.0% TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.007	0.02	0.008	1.127241
16.	0.012	0.04	0.014	1.127244
20.	0.019	0.06	0.021	1.127246
25.	0.028	0.09	0.032	1.127249
31.	0.040	0.13	0.045	1.127254
40.	0.060	0.20	0.067	1.127260
50.	0.081	0.26	0.091	1.127268
63.	0.106	0.35	0.120	1.127275
80.	0.134	0.44	0.151	1.127284
100.	0.162	0.53	0.183	1.127291
125.	0.192	0.63	0.216	1.127296
160.	0.231	0.76	0.260	1.127301
200.	0.277	0.91	0.312	1.127304
250.	0.342	1.12	0.386	1.127307
315.	0.443	1.45	0.500	1.127308
400.	0.606	1.99	0.683	1.127311
500.	0.844	2.77	0.952	1.127312
630.	1.229	4.03	1.385	1.127314
800.	1.857	6.09	2.093	1.127316
1000.	2.770	9.09	3.123	1.127320
1250.	4.161	13.65	4.690	1.127325
1600.	6.522	21.39	7.352	1.127336
2000.	9.714	31.86	10.951	1.127347
2500.	14.251	46.74	16.066	1.127365
3150.	20.674	67.81	23.308	1.127390
4000.	29.276	96.03	33.007	1.127423
5000.	38.859	127.46	43.812	1.127460
6300.	49.694	163.00	56.030	1.127501
8000.	60.972	199.99	68.748	1.127541
10000.	70.992	232.85	80.048	1.127573
12500.	80.485	263.99	90.755	1.127600
16000.	91.091	298.78	102.716	1.127621
20000.	102.069	334.79	115.096	1.127634
25000.	116.261	381.33	131.100	1.127644
31500.	137.214	450.06	154.730	1.127651
40000.	170.237	558.38	191.969	1.127656
50000.	218.040	715.17	245.875	1.127659
63000.	295.068	967.82	332.737	1.127661
80000.	421.212	1381.58	474.985	1.127663
100000.	606.083	1987.95	683.459	1.127666
125000.	891.771	2925.01	1005.621	1.127667
160000.	1392.281	4566.68	1570.032	1.127669
200000.	2106.940	6910.76	2375.936	1.127671
250000.	3214.324	10542.98	3624.710	1.127674
315000.	5011.270	16436.96	5651.082	1.127675
400000.	7974.289	26155.66	8992.422	1.127677
500000.	12354.000	40521.11	13931.320	1.127677
630000.	19496.242	63947.67	21985.480	1.127678
800000.	31310.672	102698.94	35308.383	1.127679
1000000.	48803.070	160074.00	55034.187	1.127679

SOUND ABSORPTION IN STILL AIR FOR 15% RELATIVE HUMIDITY.

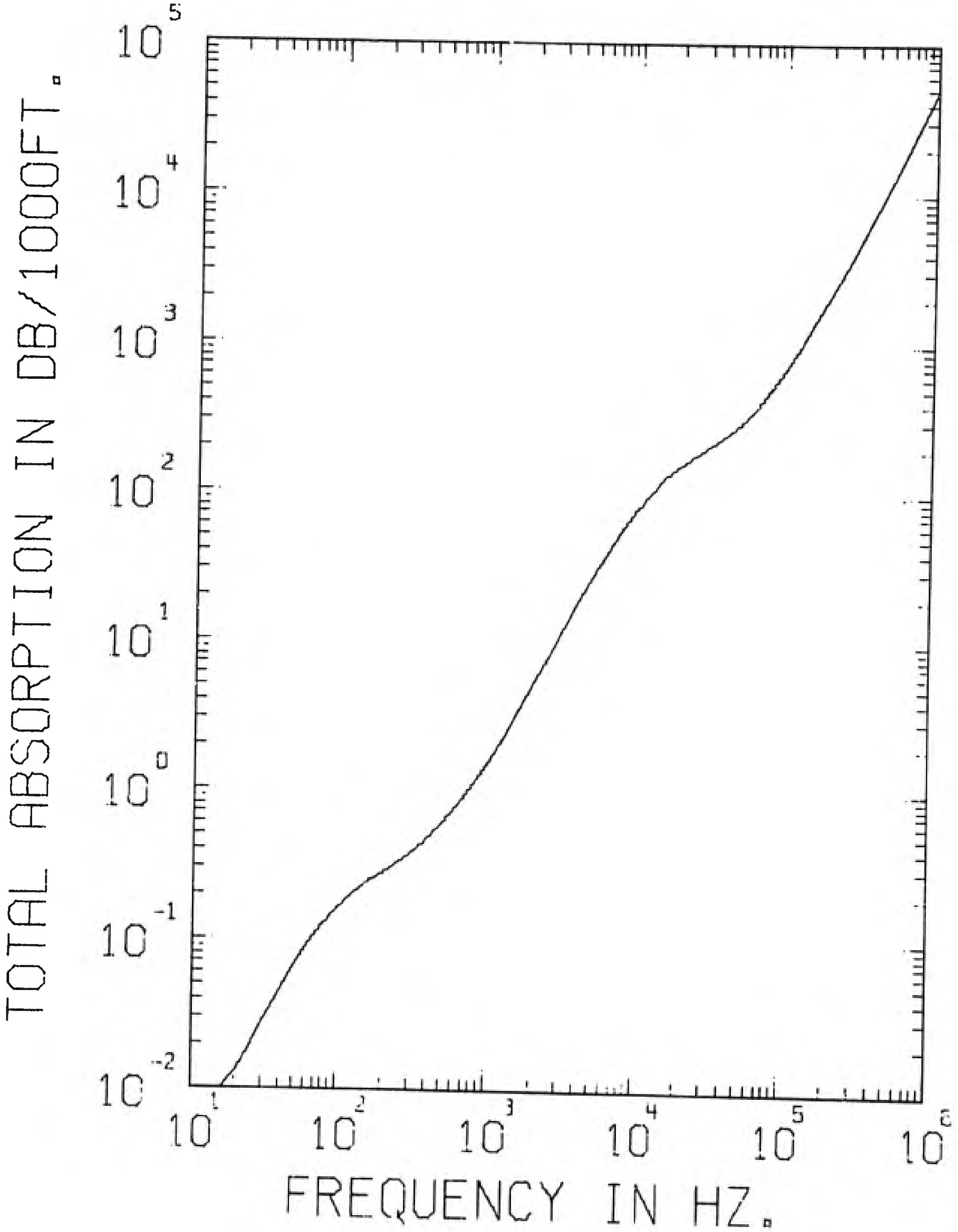


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 15.0%   TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.006	0.02	0.007	1.127363
16.	0.010	0.03	0.012	1.127365
20.	0.016	0.05	0.018	1.127366
25.	0.024	0.08	0.027	1.127369
31.	0.035	0.12	0.040	1.127373
40.	0.054	0.18	0.061	1.127378
50.	0.075	0.25	0.085	1.127383
63.	0.102	0.33	0.115	1.127391
80.	0.133	0.44	0.150	1.127399
100.	0.164	0.54	0.185	1.127407
125.	0.196	0.64	0.221	1.127415
160.	0.234	0.77	0.264	1.127419
200.	0.274	0.90	0.309	1.127424
250.	0.327	1.07	0.369	1.127426
315.	0.404	1.33	0.456	1.127429
400.	0.526	1.72	0.593	1.127431
500.	0.701	2.30	0.791	1.127432
630.	0.985	3.23	1.110	1.127434
800.	1.449	4.75	1.634	1.127435
1000.	2.130	6.99	2.401	1.127437
1250.	3.178	10.42	3.583	1.127440
1600.	4.995	16.38	5.631	1.127445
2000.	7.527	24.69	8.486	1.127453
2500.	11.282	37.00	12.720	1.127463
3150.	16.938	55.56	19.098	1.127479
4000.	25.203	82.67	28.417	1.127502
5000.	35.459	116.31	39.981	1.127530
6300.	48.566	159.30	54.761	1.127567
8000.	64.055	210.10	72.229	1.127608
10000.	79.270	260.00	89.388	1.127646
12500.	94.330	309.40	106.374	1.127681
16000.	110.563	362.65	124.684	1.127713
20000.	125.630	412.07	141.678	1.127736
25000.	142.832	468.49	161.079	1.127752
31500.	165.862	544.03	187.052	1.127763
40000.	200.106	656.35	225.674	1.127771
50000.	248.373	814.66	280.109	1.127777
63000.	325.359	1067.18	366.933	1.127780
80000.	451.116	1479.66	508.760	1.127783
100000.	635.635	2084.88	716.860	1.127786
125000.	921.472	3022.43	1039.224	1.127788
160000.	1423.453	4668.92	1605.355	1.127789
200000.	2141.094	7022.79	2414.707	1.127791
250000.	3252.975	10669.75	3668.686	1.127794
315000.	5055.508	16582.06	5701.582	1.127796
400000.	8024.301	26319.70	9049.789	1.127798
500000.	12408.687	40700.49	13994.504	1.127799
630000.	19554.691	64139.38	22053.797	1.127801
800000.	31371.871	102899.69	35381.254	1.127802
1000000.	48865.840	160279.94	55110.984	1.127802

SOUND ABSORPTION IN STILL AIR FOR 20% RELATIVE HUMIDITY.

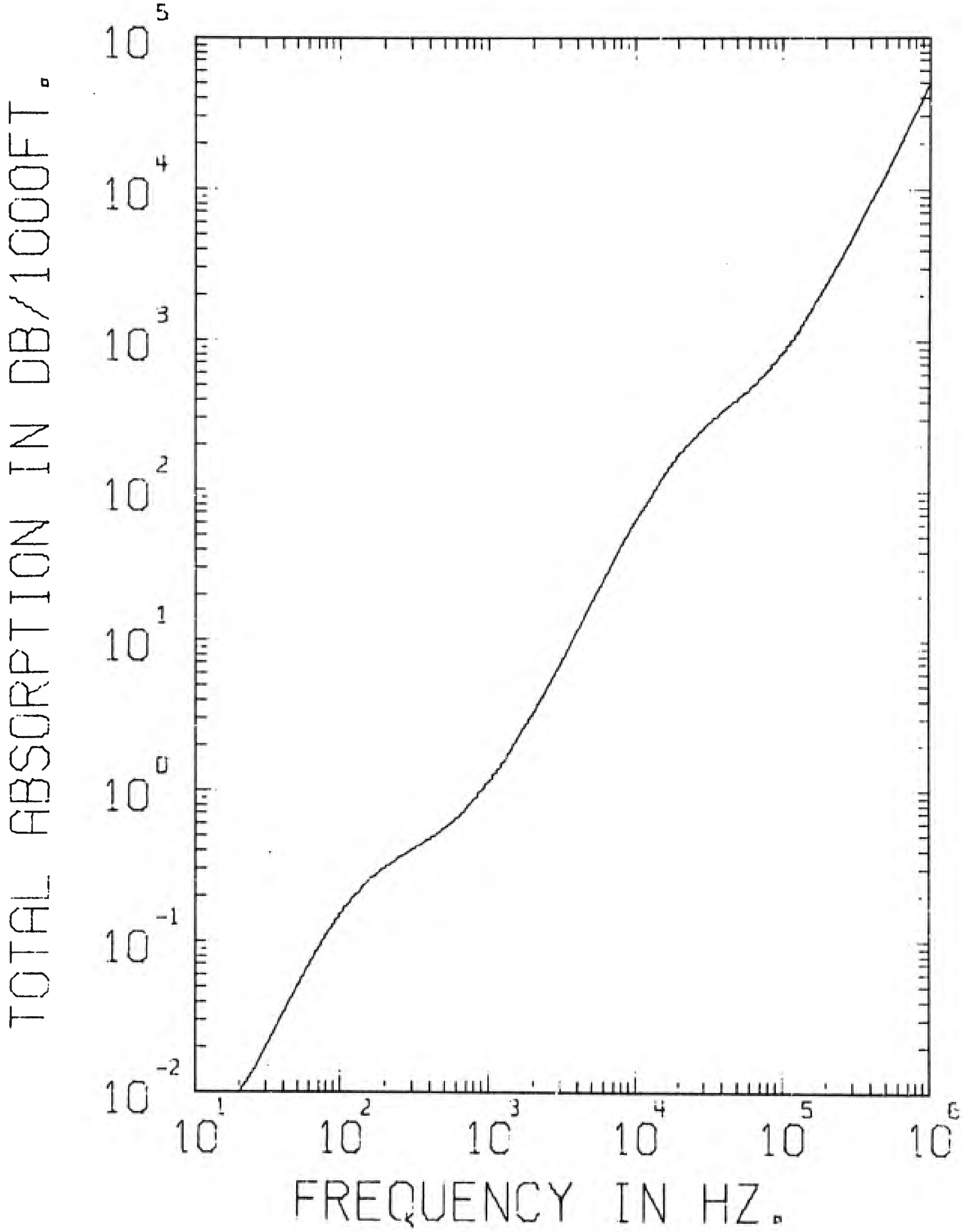


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 20.0%   TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.005	0.02	0.005	1.127567
16.	0.008	0.03	0.009	1.127567
20.	0.013	0.04	0.014	1.127568
25.	0.019	0.06	0.022	1.127570
31.	0.029	0.10	0.033	1.127573
40.	0.045	0.15	0.051	1.127577
50.	0.066	0.22	0.074	1.127582
63.	0.093	0.30	0.105	1.127587
80.	0.127	0.42	0.144	1.127595
100.	0.164	0.54	0.185	1.127603
125.	0.202	0.66	0.228	1.127610
160.	0.245	0.80	0.276	1.127618
200.	0.295	0.93	0.321	1.127624
250.	0.330	1.08	0.373	1.127627
315.	0.390	1.28	0.440	1.127631
400.	0.476	1.56	0.537	1.127633
500.	0.597	1.96	0.674	1.127634
630.	0.789	2.59	0.890	1.127636
800.	1.103	3.62	1.244	1.127637
1000.	1.563	5.13	1.763	1.127639
1250.	2.277	7.47	2.568	1.127640
1600.	3.529	11.58	3.980	1.127643
2000.	5.310	17.42	5.987	1.127645
2500.	8.028	26.33	9.053	1.127650
3150.	12.307	40.37	13.878	1.127659
4000.	18.991	62.29	21.416	1.127670
5000.	28.077	92.09	31.663	1.127687
6300.	41.151	134.98	46.406	1.127710
8000.	59.072	193.76	66.618	1.127742
10000.	79.657	261.28	89.836	1.127778
12500.	103.004	337.85	116.170	1.127817
16000.	130.465	427.93	147.146	1.127859
20000.	155.809	511.05	175.736	1.127893
25000.	182.040	597.09	205.326	1.127921
31500.	212.396	696.66	239.571	1.127944
40000.	251.952	826.40	284.192	1.127960
50000.	303.349	994.98	342.168	1.127970
63000.	382.062	1253.16	430.957	1.127977
80000.	508.369	1667.45	573.431	1.127982
100000.	692.667	2271.95	781.318	1.127986
125000.	978.118	3208.23	1103.306	1.127989
160000.	1480.462	4855.91	1669.948	1.127992
200000.	2200.245	7216.80	2481.864	1.127995
250000.	3316.807	10879.12	3741.346	1.127996
315000.	5126.883	16816.17	5783.113	1.127998
400000.	8105.262	26585.25	9142.742	1.128001
500000.	12498.750	40995.89	14098.629	1.128003
630000.	19653.129	64462.25	22168.809	1.128004
800000.	31477.141	103245.00	35506.371	1.128005
1000000.	48975.668	160640.12	55244.844	1.128006

SOUND ABSORPTION IN STILL AIR FOR 30% RELATIVE HUMIDITY.

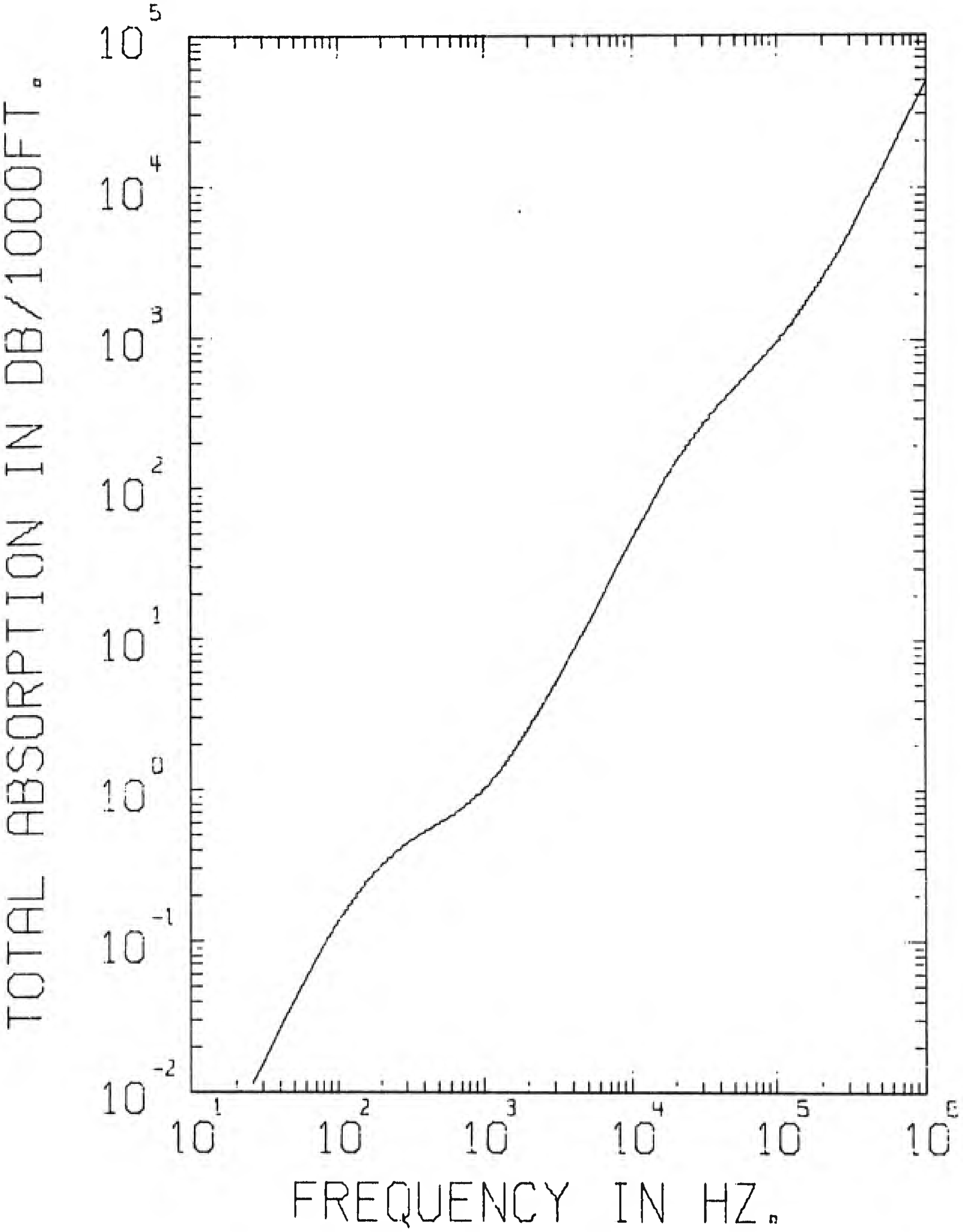


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 30.0%   TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.003	0.01	0.004	1.127975
16.	0.006	0.02	0.007	1.127976
20.	0.009	0.03	0.010	1.127976
25.	0.014	0.05	0.016	1.127977
31.	0.021	0.07	0.024	1.127978
40.	0.034	0.11	0.038	1.127980
50.	0.051	0.17	0.057	1.127984
63.	0.075	0.25	0.085	1.127987
80.	0.110	0.36	0.124	1.127994
100.	0.151	0.50	0.170	1.127999
125.	0.199	0.65	0.224	1.128007
160.	0.256	0.84	0.289	1.128016
200.	0.309	1.01	0.349	1.128023
250.	0.361	1.19	0.408	1.128029
315.	0.417	1.37	0.471	1.128034
400.	0.484	1.59	0.546	1.128037
500.	0.564	1.85	0.637	1.128040
630.	0.682	2.24	0.770	1.128041
800.	0.868	2.85	0.979	1.128044
1000.	1.137	3.73	1.282	1.128045
1250.	1.552	5.09	1.751	1.128045
1600.	2.283	7.49	2.576	1.128046
2000.	3.333	10.93	3.760	1.128047
2500.	4.960	16.27	5.596	1.128049
3150.	7.587	24.89	8.559	1.128053
4000.	11.856	38.89	13.374	1.128056
5000.	18.005	59.06	20.311	1.128062
6300.	27.626	90.61	31.164	1.128072
8000.	42.514	139.44	47.959	1.128086
10000.	62.493	204.98	70.498	1.128105
12500.	89.659	294.08	101.148	1.128131
16000.	128.814	422.51	145.324	1.128166
20000.	171.847	563.66	193.879	1.128204
25000.	220.587	723.53	248.876	1.128243
31500.	275.744	904.44	311.117	1.128283
40000.	338.710	1110.97	382.172	1.128316
50000.	407.767	1337.47	460.100	1.128342
63000.	499.838	1639.47	563.998	1.128361
80000.	635.085	2083.08	716.614	1.128375
100000.	824.065	2702.93	929.861	1.128384
125000.	1111.579	3645.98	1254.295	1.128390
160000.	1614.490	5295.52	1821.781	1.128394
200000.	2334.884	7658.42	2634.680	1.128399
250000.	3454.203	11329.79	3897.725	1.128401
315000.	5271.504	17290.53	5948.387	1.128405
400000.	8263.152	27103.14	9324.191	1.128407
500000.	12673.461	41568.95	14300.852	1.128409
630000.	19847.242	65098.95	22395.871	1.128412
800000.	31690.441	103944.62	35759.910	1.128413
1000000.	49204.289	161390.00	55522.859	1.128415

SOUND ABSORPTION IN STILL AIR FOR 40% RELATIVE HUMIDITY.

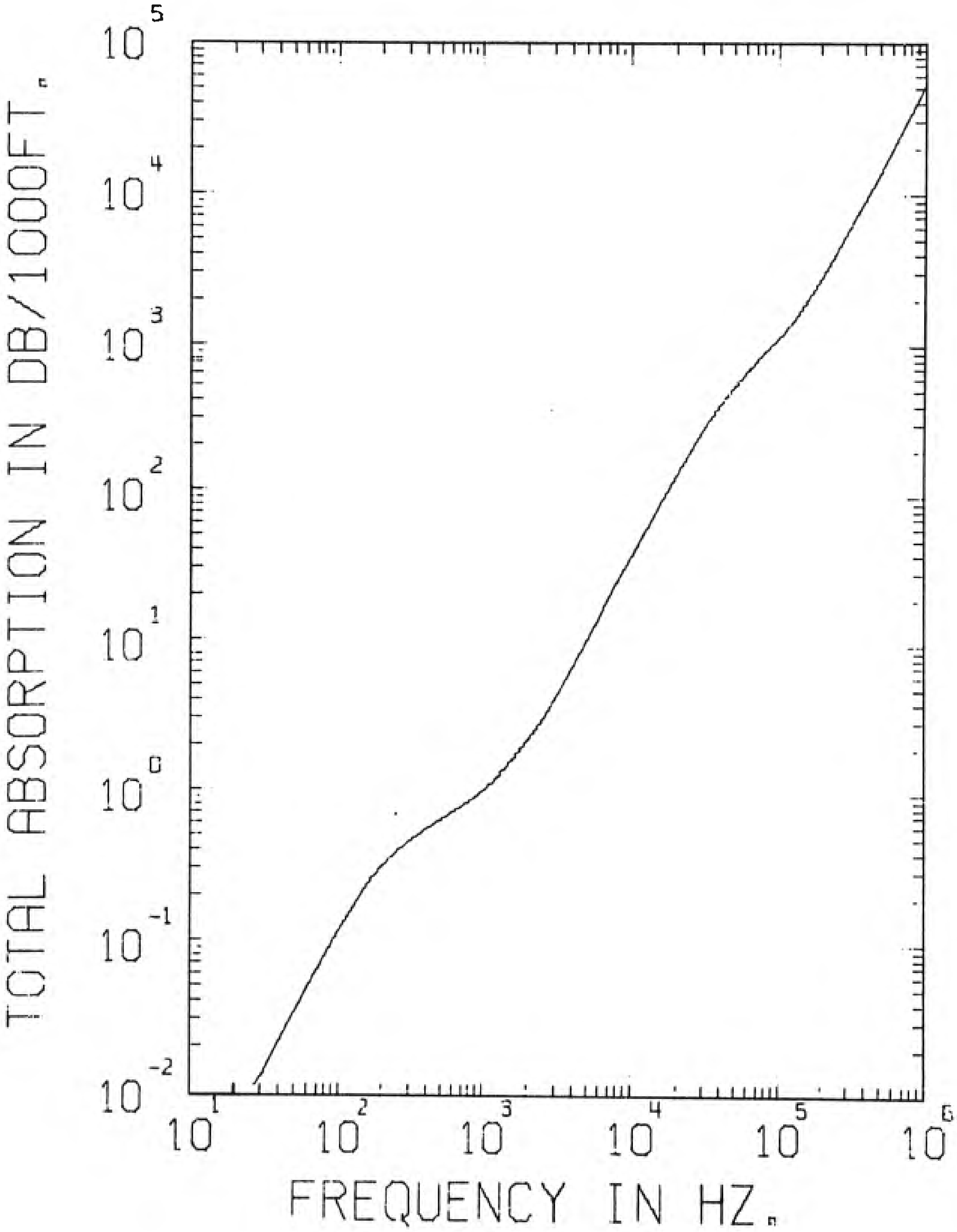


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 40.0% TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.003	0.01	0.003	1.128385
16.	0.004	0.01	0.005	1.128385
20.	0.007	0.02	0.008	1.128386
25.	0.011	0.04	0.012	1.128386
31.	0.016	0.05	0.018	1.128386
40.	0.027	0.09	0.030	1.128388
50.	0.041	0.13	0.046	1.128390
63.	0.062	0.20	0.070	1.128392
80.	0.093	0.31	0.105	1.128397
100.	0.134	0.44	0.151	1.128402
125.	0.185	0.61	0.208	1.128408
160.	0.252	0.83	0.284	1.128416
200.	0.318	1.04	0.359	1.128424
250.	0.385	1.26	0.434	1.128431
315.	0.453	1.49	0.511	1.128437
400.	0.524	1.72	0.592	1.128443
500.	0.597	1.96	0.674	1.128448
630.	0.692	2.27	0.781	1.128449
800.	0.829	2.72	0.935	1.128451
1000.	1.019	3.34	1.150	1.128452
1250.	1.309	4.29	1.477	1.128453
1600.	1.816	5.96	2.050	1.128455
2000.	2.544	8.34	2.870	1.128456
2500.	3.674	12.05	4.146	1.128456
3150.	5.510	18.07	6.218	1.128458
4000.	8.523	27.96	9.618	1.128460
5000.	12.932	42.42	14.593	1.128462
6300.	19.995	65.58	22.564	1.128467
8000.	31.337	102.79	35.363	1.128474
10000.	47.390	155.44	53.478	1.128484
12500.	70.857	232.41	79.962	1.128499
16000.	108.308	355.25	122.228	1.128521
20000.	154.838	507.87	174.742	1.128549
25000.	214.514	703.61	242.097	1.128583
31500.	289.709	950.25	326.972	1.128622
40000.	380.371	1247.62	429.310	1.128663
50000.	477.377	1565.80	538.815	1.128700
63000.	596.091	1955.18	672.827	1.128733
80000.	753.514	2471.53	850.536	1.128758
100000.	957.505	3140.62	1080.808	1.128776
125000.	1254.962	4116.27	1416.584	1.128787
160000.	1764.122	5786.32	1991.335	1.128797
200000.	2487.192	8157.99	2807.548	1.128802
250000.	3607.926	11833.99	4072.648	1.128806
315000.	5427.473	17802.11	6126.590	1.128811
400000.	8424.953	27633.84	9510.199	1.128814
500000.	12845.848	42134.37	14500.605	1.128817
630000.	20035.941	65717.87	22616.957	1.128819
800000.	31899.719	104631.06	36009.082	1.128821
1000000.	49433.414	162141.56	55801.633	1.128824

SOUND ABSORPTION IN STILL AIR
FOR 50% RELATIVE HUMIDITY.

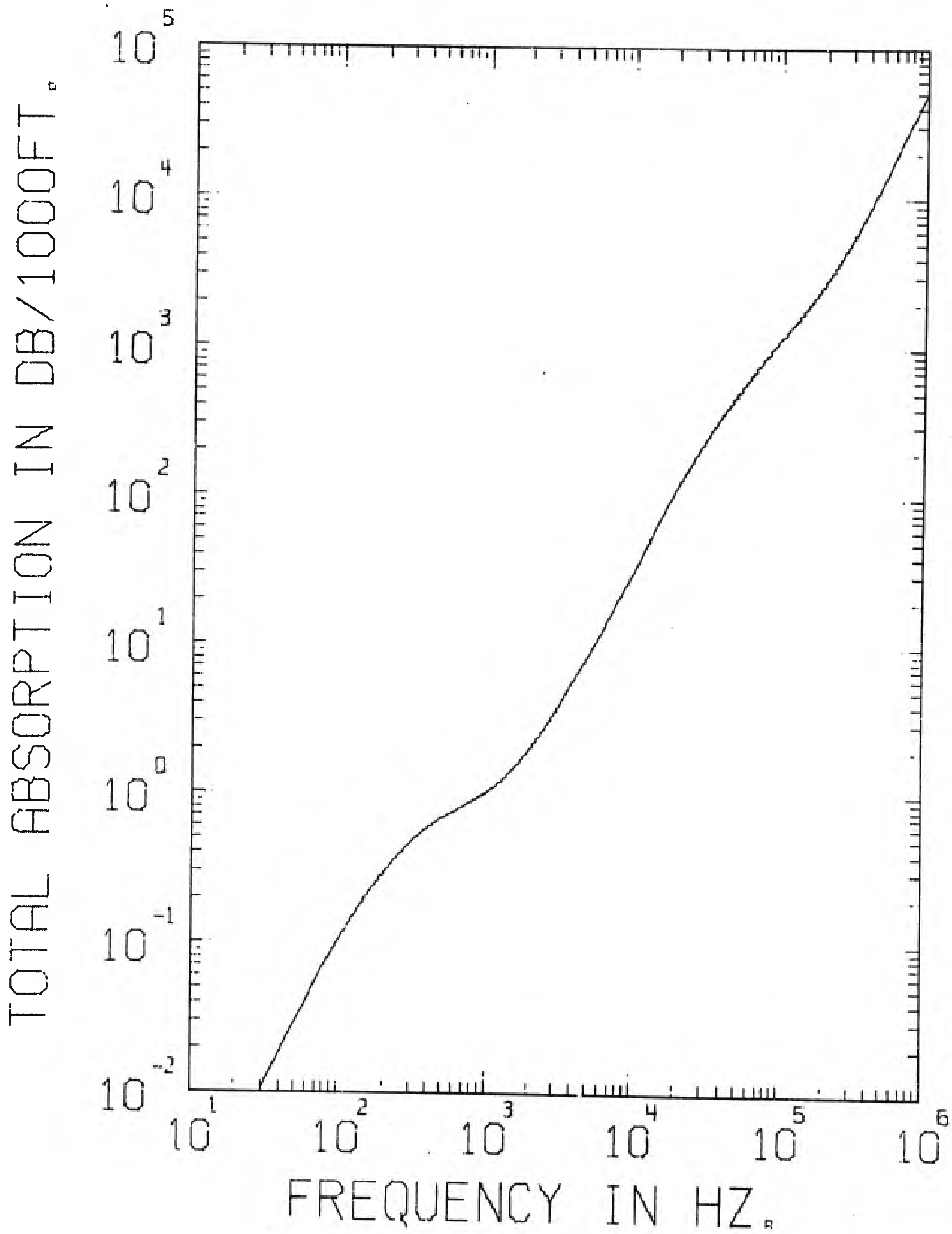


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 50.0% TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.002	0.01	0.002	1.128795
16.	0.004	0.01	0.004	1.128795
20.	0.006	0.02	0.006	1.128795
25.	0.009	0.03	0.010	1.128796
31.	0.013	0.04	0.015	1.128796
40.	0.022	0.07	0.025	1.128797
50.	0.034	0.11	0.038	1.128798
63.	0.052	0.17	0.058	1.128800
80.	0.080	0.26	0.090	1.128802
100.	0.117	0.38	0.132	1.128807
125.	0.167	0.55	0.189	1.128812
160.	0.238	0.78	0.269	1.128819
200.	0.313	1.03	0.353	1.128826
250.	0.394	1.29	0.445	1.128835
315.	0.478	1.57	0.540	1.128842
400.	0.563	1.85	0.636	1.128849
500.	0.643	2.11	0.726	1.128853
630.	0.734	2.41	0.828	1.128858
800.	0.851	2.79	0.961	1.128860
1000.	1.005	3.30	1.134	1.128861
1250.	1.231	4.04	1.390	1.128862
1600.	1.621	5.32	1.830	1.128863
2000.	2.176	7.14	2.457	1.128865
2500.	3.040	9.97	3.431	1.128865
3150.	4.442	14.57	5.015	1.128866
4000.	6.752	22.15	7.622	1.128867
5000.	10.151	33.29	11.459	1.128868
6300.	15.643	51.31	17.659	1.128871
8000.	24.590	80.65	27.758	1.128875
10000.	37.521	123.07	42.357	1.128881
12500.	57.009	186.99	64.357	1.128890
16000.	89.594	293.87	101.143	1.128903
20000.	132.719	435.32	149.830	1.128922
25000.	192.445	631.22	217.260	1.128946
31500.	274.673	900.93	310.101	1.128980
40000.	382.722	1255.33	432.101	1.129020
50000.	504.796	1655.73	569.944	1.129059
63000.	654.606	2147.11	739.115	1.129099
80000.	844.024	2768.40	953.016	1.129133
100000.	1073.683	3521.68	1212.359	1.129160
125000.	1390.927	4562.24	1570.605	1.129179
160000.	1915.079	6281.46	2162.496	1.129194
200000.	2646.428	8680.28	2988.357	1.129204
250000.	3771.796	12371.49	4259.152	1.129211
315000.	5594.066	18348.54	6316.914	1.129217
400000.	8594.629	28190.38	9705.227	1.129220
500000.	13021.227	42709.62	14703.879	1.129224
630000.	20222.340	66329.25	22835.605	1.129227
800000.	32103.441	105299.25	36252.152	1.129230
1000000.	49657.215	162875.62	56074.535	1.129232

SOUND ABSORPTION IN STILL AIR FOR 60% RELATIVE HUMIDITY.

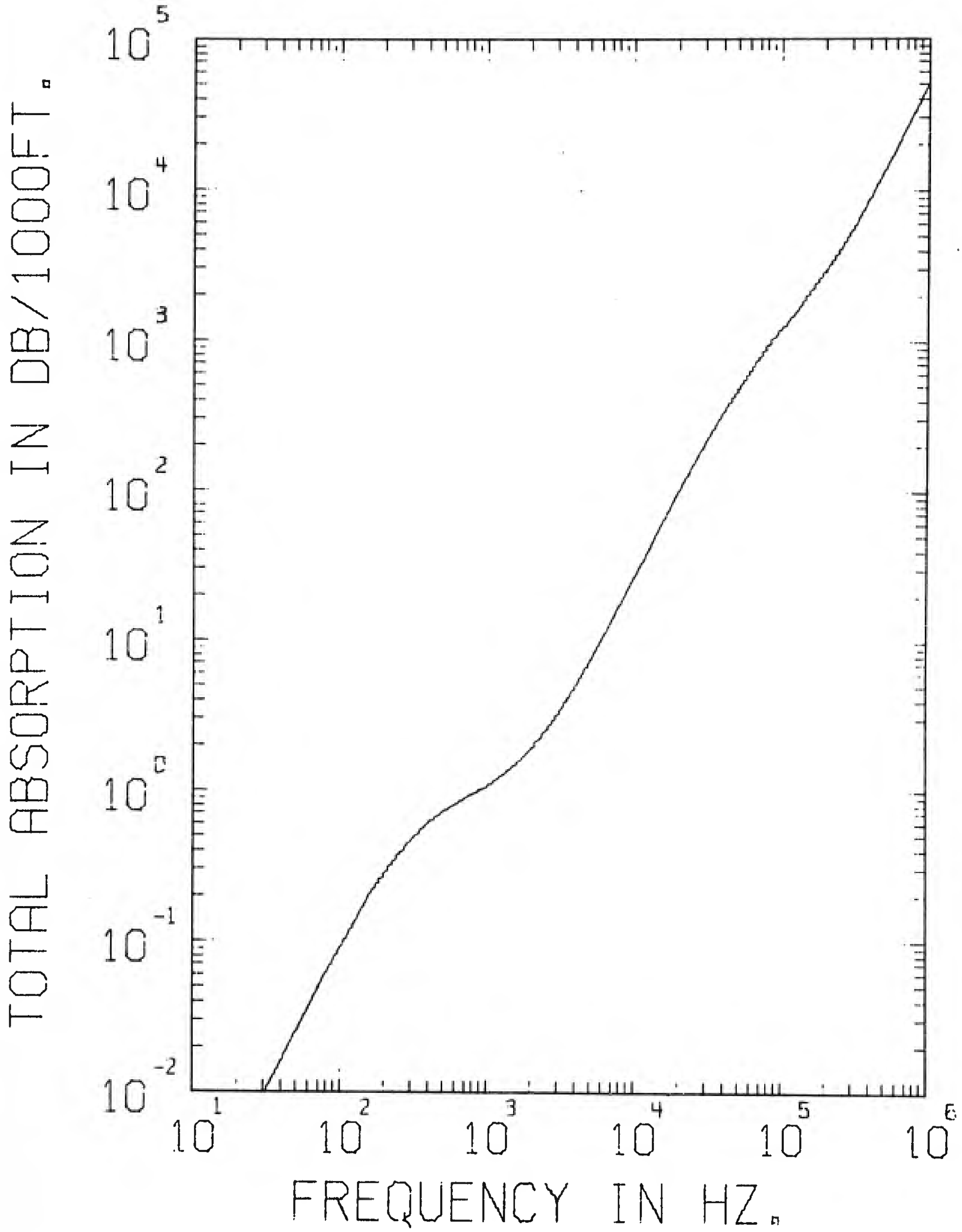


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 60.0%   TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.002	0.01	0.002	1.129207
16.	0.003	0.01	0.003	1.129207
20.	0.005	0.02	0.005	1.129207
25.	0.007	0.02	0.008	1.129207
31.	0.011	0.04	0.013	1.129208
40.	0.018	0.06	0.021	1.129208
50.	0.029	0.09	0.032	1.129209
63.	0.044	0.15	0.050	1.129210
80.	0.069	0.23	0.078	1.129211
100.	0.103	0.34	0.117	1.129215
125.	0.151	0.49	0.170	1.129219
160.	0.221	0.73	0.250	1.129225
200.	0.301	0.99	0.339	1.129232
250.	0.391	1.28	0.442	1.129239
315.	0.491	1.61	0.554	1.129247
400.	0.593	1.94	0.669	1.129254
500.	0.685	2.25	0.774	1.129261
630.	0.782	2.57	0.884	1.129266
800.	0.896	2.94	1.012	1.129269
1000.	1.032	3.39	1.166	1.129271
1250.	1.223	4.01	1.381	1.129273
1600.	1.544	5.07	1.744	1.129274
2000.	1.997	6.55	2.256	1.129275
2500.	2.698	8.85	3.047	1.129275
3150.	3.836	12.58	4.331	1.129276
4000.	5.711	18.73	6.449	1.129277
5000.	8.476	27.80	9.571	1.129278
6300.	12.962	42.51	14.638	1.129279
8000.	20.316	66.64	22.942	1.129282
10000.	31.050	101.84	35.064	1.129286
12500.	47.462	155.67	53.598	1.129292
16000.	75.544	247.78	85.312	1.129300
20000.	113.958	373.78	128.694	1.129313
25000.	169.534	556.07	191.460	1.129331
31500.	250.538	821.76	282.946	1.129355
40000.	364.443	1195.37	411.598	1.129389
50000.	501.573	1645.16	566.489	1.129426
63000.	677.023	2220.64	764.675	1.129467
80000.	899.912	2951.71	1016.458	1.129508
100000.	1161.739	3810.50	1312.232	1.129541
125000.	1507.465	4944.48	1702.784	1.129568
160000.	2056.069	6743.90	2322.516	1.129591
200000.	2802.800	9193.18	3166.055	1.129604
250000.	3938.053	12916.81	4448.484	1.129616
315000.	5766.312	18913.50	6513.758	1.129623
400000.	8770.633	28767.67	9907.551	1.129628
500000.	13201.043	43299.41	14912.320	1.129632
630000.	20409.176	66942.06	23054.934	1.129636
800000.	32303.223	105954.50	36490.969	1.129639
1000000.	49874.566	163588.56	56340.379	1.129642

SOUND ABSORPTION IN STILL AIR
FOR 70% RELATIVE HUMIDITY.

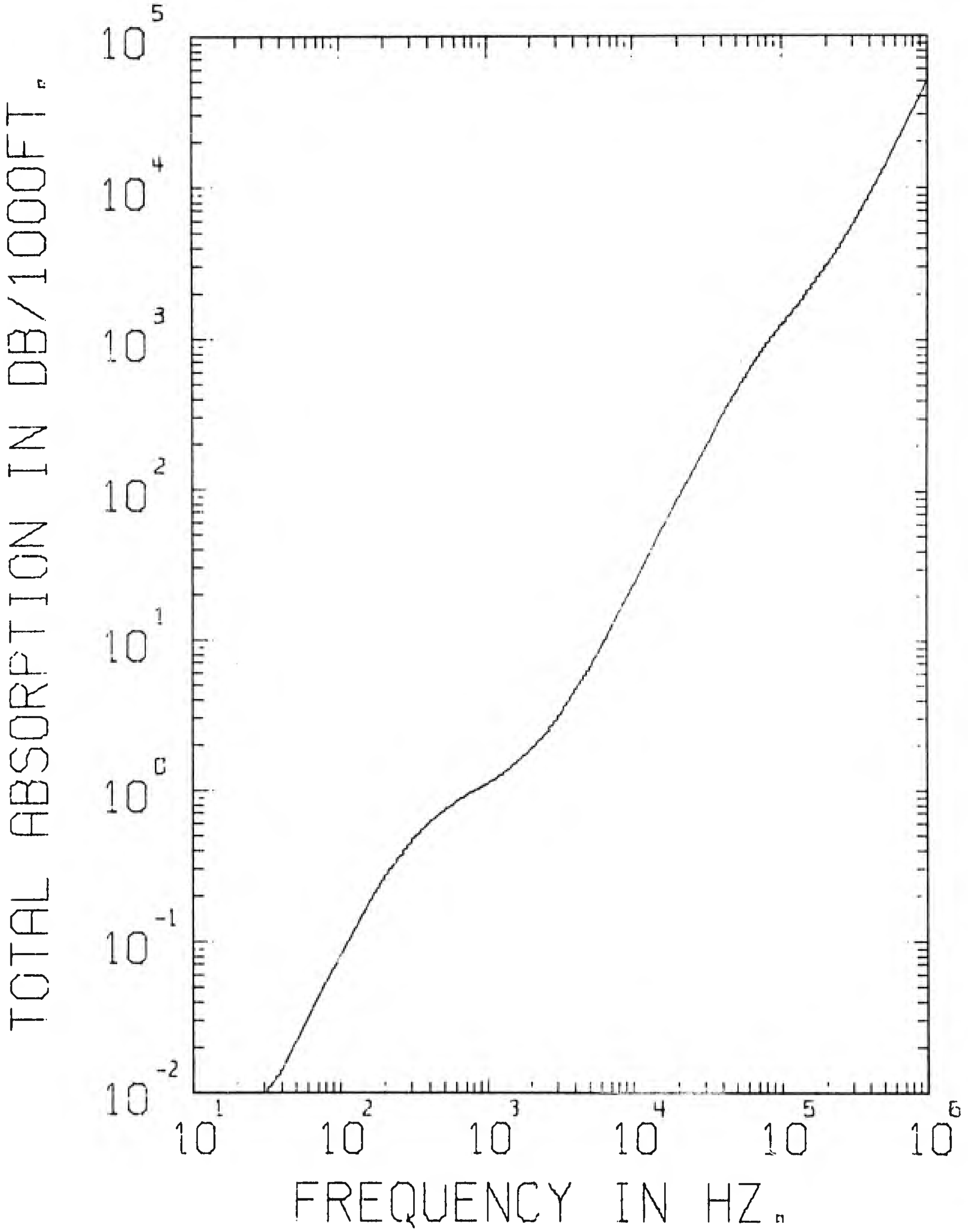


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 70.0%   TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (CB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.001	0.00	0.002	1.129618
16.	0.003	0.01	0.003	1.129618
20.	0.004	0.01	0.005	1.129618
25.	0.006	0.02	0.007	1.129618
31.	0.010	0.03	0.011	1.129618
40.	0.016	0.05	0.018	1.129619
50.	0.025	0.08	0.028	1.129619
63.	0.039	0.13	0.044	1.129620
80.	0.061	0.20	0.069	1.129622
100.	0.092	0.30	0.104	1.129623
125.	0.136	0.45	0.153	1.129627
160.	0.204	0.67	0.230	1.129632
200.	0.284	0.93	0.321	1.129638
250.	0.381	1.25	0.431	1.129645
315.	0.493	1.62	0.557	1.129654
400.	0.611	2.01	0.691	1.129662
500.	0.720	2.36	0.813	1.129668
630.	0.829	2.72	0.937	1.129673
800.	0.947	3.11	1.070	1.129678
1000.	1.078	3.53	1.217	1.129681
1250.	1.250	4.10	1.412	1.129683
1600.	1.528	5.01	1.726	1.129684
2000.	1.915	6.28	2.163	1.129685
2500.	2.509	8.23	2.834	1.129686
3150.	3.471	11.38	3.921	1.129686
4000.	5.056	16.58	5.712	1.129687
5000.	7.395	24.26	8.354	1.129687
6300.	11.197	36.73	12.649	1.129689
8000.	17.450	57.24	19.713	1.129690
10000.	26.624	87.33	30.077	1.129693
12500.	40.758	133.69	46.044	1.129697
16000.	65.246	214.01	73.708	1.129704
20000.	99.365	325.92	112.254	1.129712
25000.	150.000	492.00	169.459	1.129725
31500.	226.468	742.82	255.851	1.129744
40000.	339.153	1112.42	383.165	1.129770
50000.	482.023	1581.04	544.591	1.129803
63000.	673.667	2209.63	761.137	1.129842
80000.	924.481	3032.30	1044.556	1.129884
100000.	1218.987	3998.28	1377.358	1.129921
125000.	1598.232	5242.20	1805.929	1.129954
160000.	2179.337	7148.22	2462.616	1.129984
200000.	2948.748	9671.89	3332.094	1.130003
250000.	4100.031	13448.10	4633.105	1.130017
315000.	5938.926	19479.67	6711.148	1.130028
400000.	8949.742	29355.15	10113.516	1.130034
500000.	13384.277	43900.43	15124.770	1.130040
630000.	20597.547	67559.94	23276.133	1.130044
800000.	32500.840	106602.69	36727.531	1.130049
1000000.	50086.289	164283.00	56600.090	1.130052

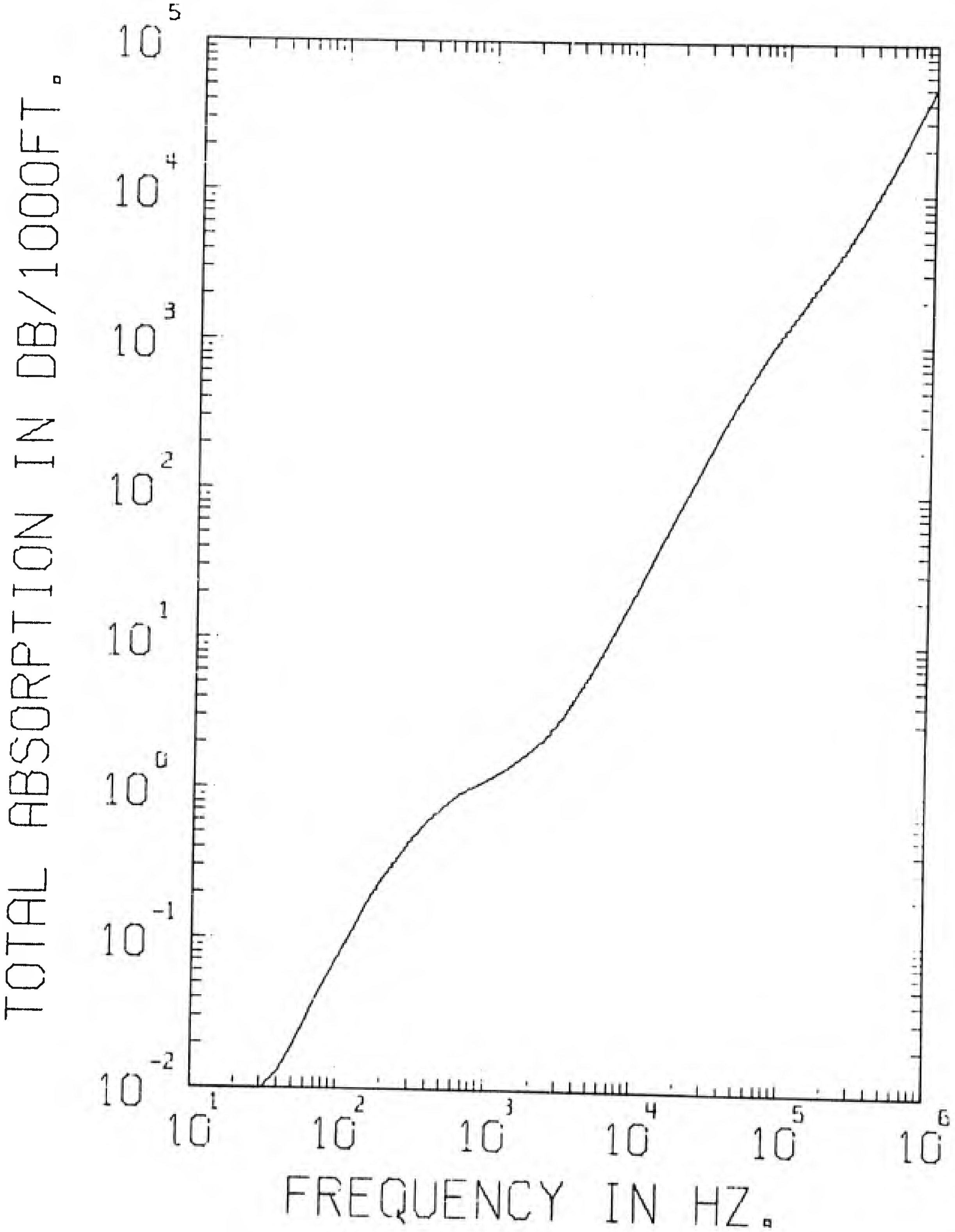
SOUND ABSORPTION IN STILL AIR FOR 80% RELATIVE HUMIDITY.



ABSORPTION AND VELOCITY OF SOUND IN STILL AIR
RELATIVE HUMIDITY = 80.0% TEMPFRATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.001	0.00	0.001	1.130030
16.	0.002	0.01	0.003	1.130030
20.	0.004	0.01	0.004	1.130030
25.	0.006	0.02	0.006	1.130030
31.	0.008	0.03	0.010	1.130030
40.	0.014	0.05	0.016	1.130030
50.	0.022	0.07	0.025	1.130031
63.	0.034	0.11	0.039	1.130032
80.	0.054	0.18	0.061	1.130033
100.	0.082	0.27	0.093	1.130034
125.	0.123	0.40	0.139	1.130036
160.	0.188	0.62	0.212	1.130041
200.	0.267	0.88	0.302	1.130047
250.	0.367	1.20	0.414	1.130053
315.	0.487	1.60	0.550	1.130060
400.	0.620	2.03	0.701	1.130069
500.	0.745	2.44	0.842	1.130076
630.	0.870	2.85	0.983	1.130082
800.	0.998	3.27	1.128	1.130088
1000.	1.130	3.71	1.277	1.130091
1250.	1.293	4.24	1.461	1.130094
1600.	1.545	5.07	1.746	1.130095
2000.	1.887	6.19	2.132	1.130096
2500.	2.407	7.90	2.720	1.130097
3150.	3.246	10.65	3.668	1.130098
4000.	4.626	15.17	5.228	1.130098
5000.	6.663	21.85	7.529	1.130099
6300.	9.976	32.72	11.274	1.130100
8000.	15.435	50.63	17.443	1.130101
10000.	23.466	76.97	26.519	1.130102
12500.	35.896	117.74	40.566	1.130106
16000.	57.588	188.89	65.081	1.130110
20000.	88.144	289.11	99.612	1.130116
25000.	134.198	440.17	151.660	1.130126
31500.	205.333	673.49	232.055	1.130140
40000.	313.525	1028.36	354.334	1.130161
50000.	456.068	1495.90	515.443	1.130189
63000.	655.282	2149.33	740.615	1.130223
80000.	925.566	3035.86	1046.134	1.130264
100000.	1248.492	4095.05	1411.174	1.130303
125000.	1661.857	5450.89	1878.465	1.130341
160000.	2280.556	7480.22	2577.883	1.130375
200000.	3078.994	10099.10	3480.494	1.130400
250000.	4252.531	13948.30	4807.137	1.130418
315000.	6107.367	20032.16	6903.961	1.130432
400000.	9128.473	29941.39	10319.203	1.130442
500000.	13568.906	44506.01	15338.945	1.130448
630000.	20787.070	68181.56	23498.805	1.130453
800000.	32697.352	107247.25	36962.945	1.130457
1000000.	50293.703	164963.31	56855.102	1.130462

SOUND ABSORPTION IN STILL AIR FOR 90% RELATIVE HUMIDITY.

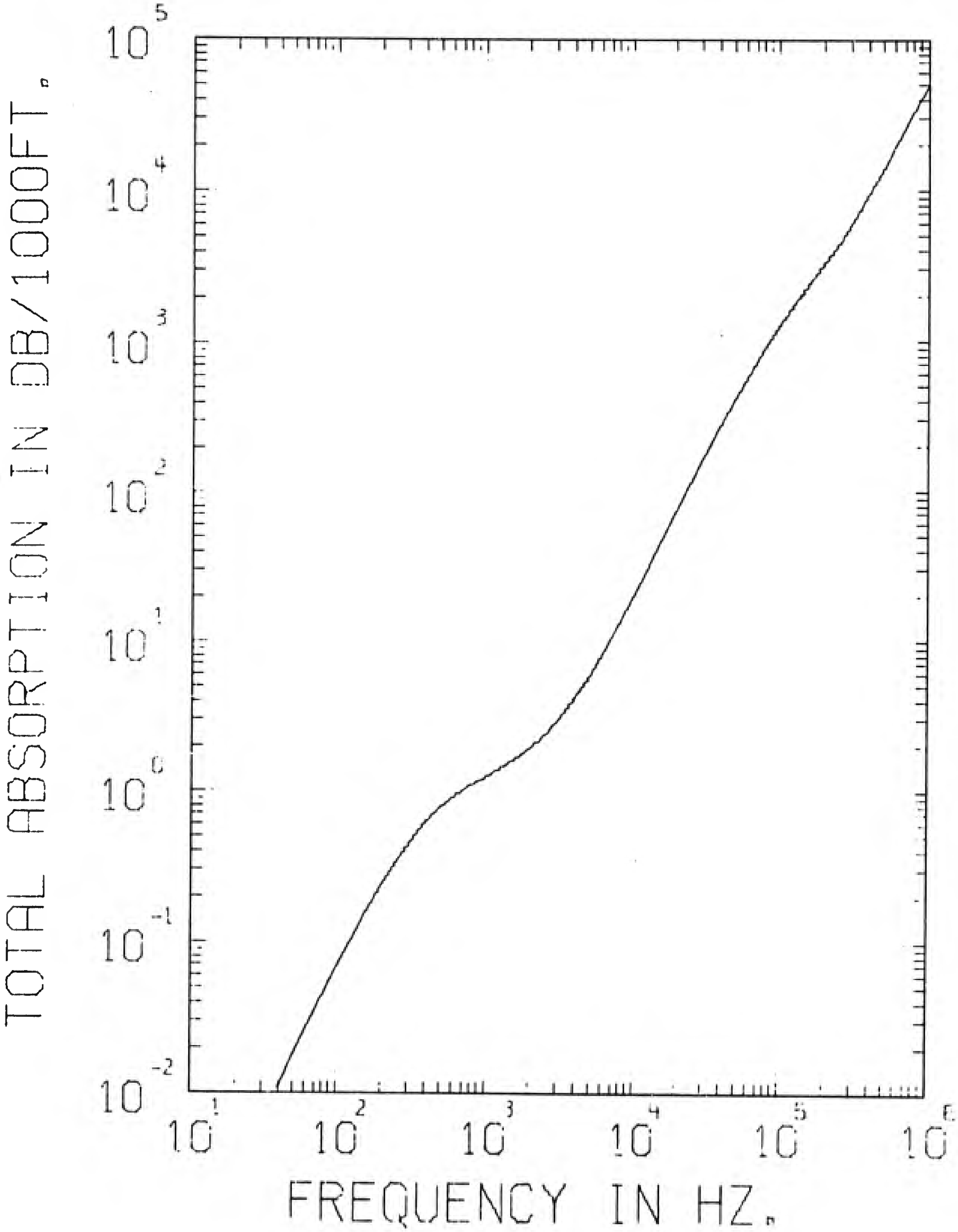


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 90.0% TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.001	0.00	0.001	1.130443
16.	0.002	0.01	0.002	1.130443
20.	0.003	0.01	0.004	1.130443
25.	0.005	0.02	0.006	1.130443
31.	0.008	0.02	0.009	1.130443
40.	0.013	0.04	0.014	1.130443
50.	0.019	0.06	0.022	1.130444
63.	0.031	0.10	0.035	1.130444
80.	0.049	0.16	0.055	1.130445
100.	0.074	0.24	0.084	1.130446
125.	0.112	0.37	0.127	1.130448
160.	0.173	0.57	0.196	1.130452
200.	0.250	0.82	0.283	1.130457
250.	0.350	1.15	0.396	1.130463
315.	0.476	1.56	0.538	1.130470
400.	0.621	2.04	0.702	1.130478
500.	0.761	2.50	0.860	1.130486
630.	0.903	2.96	1.021	1.130493
800.	1.045	3.43	1.182	1.130498
1000.	1.184	3.88	1.338	1.130503
1250.	1.344	4.41	1.520	1.130505
1600.	1.581	5.18	1.787	1.130507
2000.	1.892	6.21	2.139	1.130508
2500.	2.359	7.74	2.667	1.130510
3150.	3.108	10.19	3.513	1.130510
4000.	4.337	14.22	4.903	1.130511
5000.	6.149	20.17	6.952	1.130511
6300.	9.099	29.84	10.286	1.130512
8000.	13.963	45.80	15.785	1.130513
10000.	21.133	69.32	23.891	1.130514
12500.	32.258	105.81	36.468	1.130516
16000.	51.762	169.78	58.518	1.130520
20000.	79.424	260.51	89.791	1.130526
25000.	121.533	398.63	137.397	1.130531
31500.	187.539	615.13	212.021	1.130544
40000.	290.117	951.58	327.995	1.130561
50000.	429.066	1407.34	485.094	1.130582
63000.	629.701	2065.42	711.948	1.130612
80000.	911.286	2989.02	1030.346	1.130651
100000.	1256.028	4119.77	1420.177	1.130690
125000.	1700.482	5577.58	1922.783	1.130729
160000.	2358.361	7735.42	2666.759	1.130768
200000.	3190.381	10464.45	3607.671	1.130796
250000.	4391.773	14405.02	4966.301	1.130819
315000.	6267.992	20559.01	7088.074	1.130836
400000.	9303.785	30516.41	10521.172	1.130849
500000.	13752.715	45108.90	15552.359	1.130857
630000.	20976.715	68803.56	23721.773	1.130862
800000.	32892.934	107888.81	37197.562	1.130868
1000000.	50497.855	165632.94	57106.598	1.130872

SOUND ABSORPTION IN STILL AIR FOR 100% RELATIVE HUMIDITY.

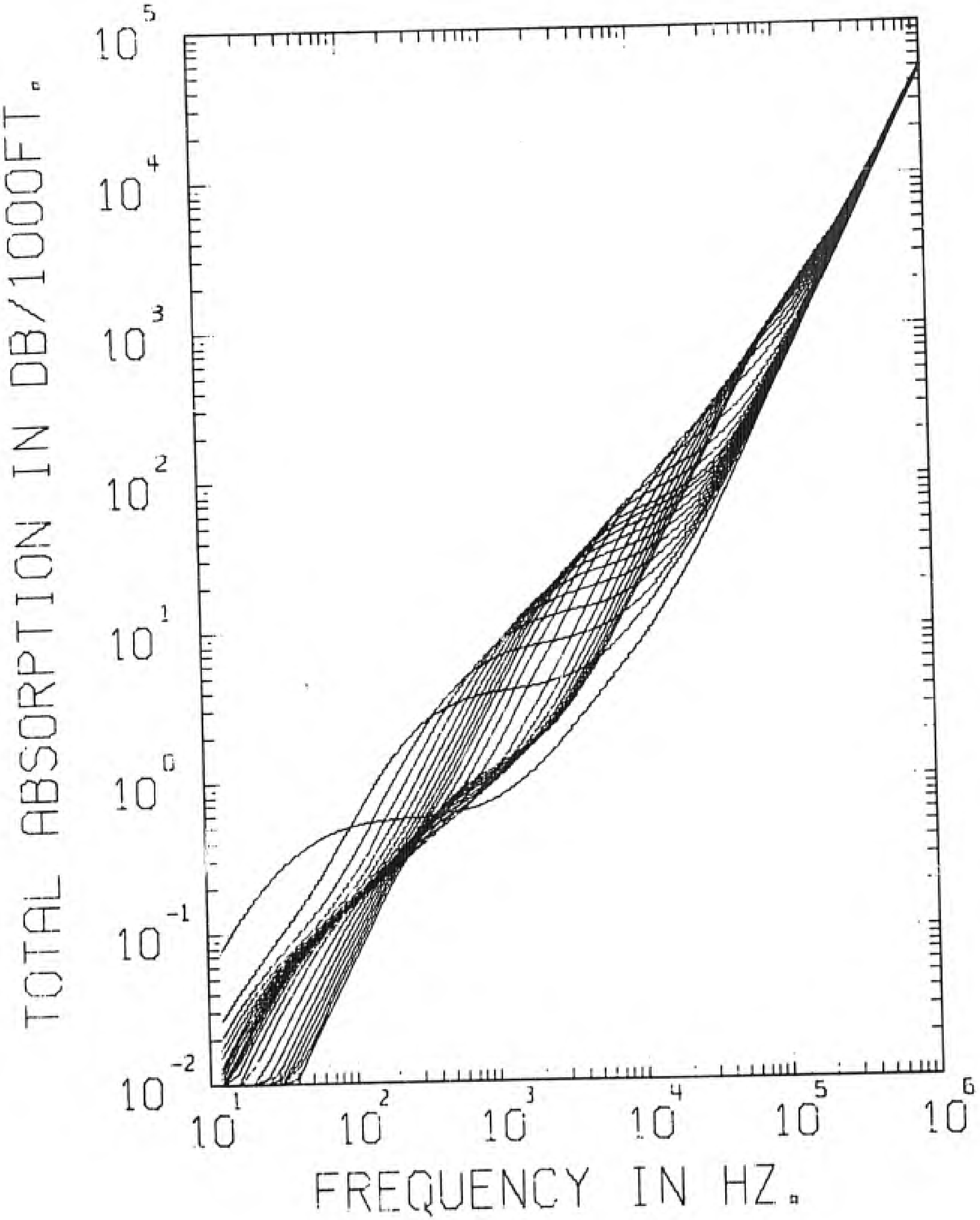


ABSORPTION AND VELOCITY OF SOUND IN STILL AIR

RELATIVE HUMIDITY = 100.0%   TEMPERATURE = 68. DEGREES F

FREQUENCY (HZ)	ABSORPTION (DB/1000FT)	ABSORPTION (DB/KM)	ABSORPTION (DB/SEC)	VELOCITY (1000FT/SEC)
12.	0.001	0.00	0.001	1.130856
16.	0.002	0.01	0.002	1.130856
20.	0.003	0.01	0.003	1.130856
25.	0.004	0.01	0.005	1.130856
31.	0.007	0.02	0.008	1.130856
40.	0.011	0.04	0.013	1.130856
50.	0.018	0.06	0.020	1.130857
63.	0.028	0.09	0.031	1.130857
80.	0.044	0.14	0.050	1.130857
100.	0.068	0.22	0.076	1.130858
125.	0.103	0.34	0.116	1.130860
160.	0.160	0.53	0.181	1.130864
200.	0.234	0.77	0.265	1.130868
250.	0.333	1.09	0.377	1.130873
315.	0.461	1.51	0.522	1.130880
400.	0.616	2.02	0.696	1.130888
500.	0.769	2.52	0.870	1.130896
630.	0.928	3.05	1.050	1.130902
800.	1.087	3.57	1.230	1.130909
1000.	1.236	4.05	1.397	1.130914
1250.	1.399	4.59	1.582	1.130917
1600.	1.627	5.34	1.840	1.130920
2000.	1.917	6.29	2.168	1.130921
2500.	2.346	7.69	2.653	1.130922
3150.	3.027	9.93	3.423	1.130923
4000.	4.140	13.58	4.682	1.130924
5000.	5.781	18.96	6.538	1.130924
6300.	8.451	27.72	9.557	1.130925
8000.	12.856	42.17	14.540	1.130925
10000.	19.357	63.49	21.891	1.130926
12500.	29.461	96.63	33.318	1.130929
16000.	47.227	154.90	53.410	1.130931
20000.	72.538	237.93	82.036	1.130935
25000.	111.323	365.14	125.899	1.130940
31500.	172.729	566.55	195.348	1.130949
40000.	269.598	884.28	304.905	1.130963
50000.	403.475	1323.40	456.322	1.130981
63000.	601.714	1973.62	680.543	1.131007
80000.	888.113	2913.01	1004.492	1.131042
100000.	1247.764	4092.67	1411.319	1.131079
125000.	1718.102	5635.37	1943.378	1.131119
160000.	2413.618	7916.66	2730.190	1.131161
200000.	3281.588	10763.61	3712.110	1.131193
250000.	4515.281	14810.12	5107.773	1.131220
315000.	6417.992	21051.01	7260.285	1.131240
400000.	9473.066	31071.65	10716.453	1.131255
500000.	13933.668	45702.43	15762.664	1.131265
630000.	21165.273	69422.06	23943.687	1.131272
800000.	33087.422	108526.69	37431.102	1.131279
1000000.	50699.195	166293.31	57355.176	1.131284

SOUND ABSORPTION IN STILL AIR



APPENDIX

PREPRINT OF

ATMOSPHERIC ABSORPTION OF SOUND: ANALYTICAL EXPRESSIONS

by

H.E. Bass & H.-J. Bauer * — University of Mississippi
Dept. of Physics & Astronomy
University, Mississippi 38677

L.B. Evans — Wyle Laboratories
7800 Governors Drive, West
Huntsville, Alabama 35807

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ABSTRACT

A set of analytical expression has been developed which will predict the absorption of sound in air at 20° C. The results agree within 3% of previous work in the frequency range of 100 Hz - 1 MHz for all humidities. Below 100 Hz accuracy cannot be judged because of lack of knowledge about the vibration-vibration energy transfer between CO_2 and O_2.

I. LIST OF SYMBOLS

A_i = β_i/β^{∞} = relaxation strength

a_d = $\left[\left(M_{O_2} - M_{N_2}\right)/\left(X_{O_2} M_{O_2} + X_{N_2} M_{N_2}\right)\right]^2 X_{O_2} X_{N_2}$ = Molecular diffusion constant

C_p = Specific heat at constant pressure

C_v = Specific heat at constant volume

C_p^{dyn}, C_v^{dyn} = Frequency dependent complex specific heats

C_p^{∞}, C_v^{∞} = High frequency limits of specific heats (value of the specific heats at frequencies above the vibrational relaxation effects)

C' = Total vibrational specific heat = $\sum C_i'$

C_i' = Vibrational specific heat of the i-th vibrational mode

c = Velocity of sound in 1000 ft/sec

D_{12} = Diffusion coefficient for O_2 and N_2 mixture

f = Sound frequency

H = Percent relative humidity

h = Mole fraction of water vapor

j = $\sqrt{-1}$

k = Wave number

M = Molecular mass

P = Ambient pressure

P_w = Vapor pressure of water

R = Universal gas constant

S = Entropy

T_i = $2\pi \tau_i^{ps}$ = modified relaxation time

V = Frequency dependent sound velocity

V_o = Low frequency limit of sound velocity

V_∞ = High frequency limit of sound velocity

X_i = Concentration of molecular species ($i = O_2, N_2$, etc)

α = Total amplitude sound absorption coefficient

α_{cl} = Amplitude sound absorption coefficient due to classical effects

α_{rot} = Amplitude sound absorption coefficient due to rotation

α_{vib} = Amplitude sound absorption coefficient due to vibration

$\alpha_{relaxation}$ = $\alpha_{rot} + \alpha_{vib}$

β = $(\beta^o - \beta^\infty) = \Sigma\beta_i$ = total adiabatic compressibility of vibrational modes

β^o = Low frequency limit of the adiabatic compressibility

β^∞ = High frequency limit of the adiabatic compressibility

β_i = Adiabatic compressibility of the i-th vibrational process

γ = C_p/C_v

η = Coefficient of shear viscosity

θ = Absolute temperature

κ = Coefficient of heat conductivity

ρ = Density

τ_i^{pt} = Isobaric-isothermal relaxation time of the i-th vibrational process

τ_i^{ps} = Isobaric-isentropic relaxation time of the i-th vibrational process

ω = $2\pi f$

II. INTRODUCTION

In a previous paper[1] a calculation of sound absorption in still air was discussed and results were presented in graphical form over the relative humidity range of 0-100% at 20° C. The calculations were based on fundamental physical principles with as few empirical steps as possible. The method was quite successful and agreement between the predicted values and available experimental data was very good. However, in two oral presentations of those results, desires were expressed for a more usable format than the graphs of absorption in dB/1000 ft as functions of frequency which were presented. To fulfill these needs a set of tables has been produced which cover an expanded frequency range[2], and now in this paper an analytical expression for sound absorption is developed which can be easily programmed for computer computation or solved manually if necessary.

The absorption of sound in air as in all molecular gases is caused by two different mechanisms:

- Classical effects
- Relaxation effects

The classical effects are a result of the transport processes which occur in a gas, i.e., internal friction, heat conduction, and molecular diffusion. Of these mechanisms the internal friction, or viscosity, and heat conduction are the largest contributors to the classical effects. Numerical inspection of the general equation for binary mixtures[3] has shown that the largest of the diffusion terms contributes only 0.5 percent of the total classical absorption, so only that term has been included in the expression for air[1]. For the frequencies of interest, i.e., well below the collision frequency of the molecules, there is no translational dispersion and the transport properties of the gas obey the ordinary equations of continuum hydrodynamics, so

$$\alpha_{cl} = \frac{2\pi^2 f^2}{\gamma P V_0} \left[\frac{4}{3}\eta + \frac{\gamma - 1}{C_p}\kappa + \gamma a_d D_{12} \rho \right] \qquad (1)$$

and

$$V^2 = \frac{P}{\rho}\frac{C_p}{C_v} = \frac{\gamma R \theta}{M} = \frac{1}{\rho\beta} \qquad (2)$$

The relaxation effects are a result of an additional loss mechanism inherent in molecular gases. As a sound wave progresses in a molecular gas part of the compressional energy is stored in the internal degrees of freedom of the molecules. Since this storage involves excitation and de-excitation of internal energy states which occur during collisions, it requires time, and a phase lag between the internal and translational energy modes of the gas results. This relaxation effect can be taken into account by introducing into Eq. (2) either frequency-dependent and complex dynamic heat capacities C_p^{dyn} and C_v^{dyn} or adiabatic compressibility β. If the transport processes are neglected and only one internal storage mode for the energy with a single relaxation time is considered then

$$C_p^{dyn} = C_p^{\infty} + \frac{C'}{1 + j\omega\tau^{pt}} \qquad (3)$$

and the well known bell shaped absorption curve for $\alpha\lambda$ versus f would be obtained along with the S-shaped dispersion curve for the speed of sound[4].

In the presence of internal relaxation, the classical absorption is altered in several ways[3]

- the heat capacities appearing in Eq. (1) must be considered as frequency dependent and complex

- the diffusion of excited molecules supplies an additional and frequency dependent mechanism for the heat conduction, so that $\kappa = \kappa(\omega)$.
- for infrared active modes the emission and re-absorption of radiation must be considered along with the diffusion outlined above. (However, it can be shown that there is no influence in the full frequency range in air owing to radiation effects. For high frequencies there is only small coupling into the internal modes due to the inefficient collision processes occuring in air, and for low frequencies the chance that the infrared photons are re-absorbed in essentially the same portion of the acoustic wavelength is very high.)
- if both the transport and relaxation parts of the absorption become very large, then after the above mentioned alterations have been applied the sound absorption is no longer a simple sum of separate absorption processes.

Fortunately, numerical estimates show that all these complicated interdependances become negligible for the special case of air below a frequency of 1 MHz. This means that the dispersion can be calculated as if the transport processes are absent, i.e.,

$$V^2 = \frac{P}{\rho} \operatorname{Re} \frac{C_p^{dyn}}{C_v^{dyn}} \tag{4}$$

Also the absorption can be obtained by simple addition of the transport and relaxation contributions

$$\alpha = \alpha_{\text{classical}} + \alpha_{\text{relaxation}} \tag{5}$$

where Eq. (1) for the classical absorption can be expressed as[1]

$$\alpha_{cl} = \frac{2\ {}^{2} f^{2}}{\gamma P V_{0}} \quad (1.9) \quad \eta \tag{6}$$

III. THEORETICAL METHOD

The fact that in air there is more than one storage mode for the internal energy must be taken into account. These modes are sub-divided into

- rotational degrees of freedom
- vibrational degrees of freedom

The frequency range important for absorption in air is well below the rotational relaxation frequency and the contributions owing to rotation give a term which is linear in frequency for frequencies less than 1 MHz. There is also negligible velocity dispersion in this region as a result of rotation. To calculate the absorption due to rotation the rate constant for dry air can be taken from Greenspan[5], assuming that it is not humidity dependent. Unfortunately, there is no experimental verification of that assumption. In fact, very little is known about rotational relaxation in a mixture of rotators; however, it is thought that the error introduced by this assumption is small. When these assumptions are made the absorption due to relaxation effects is

$$\alpha_{\text{relaxation}} = \alpha_{\text{rotation}} + \alpha_{\text{vibration}} \tag{7}$$

where

$$\alpha_{rot} = \frac{2\pi^2 f^2}{\gamma P V_0} \ (0.6)\ \eta$$

at 20° C and the rotational relaxation rate has been taken from Greenspan.

For the vibrational relaxation processes a simple extension of the addition technique applied above would lead to

$$C_{vib}^{dyn} = \sum \frac{C_i'}{1 + j\omega\tau_i^{pt}} \tag{8}$$

as a representation of the vibrational dynamic heat capacity where the C_i' are the vibrational heat capacities of O_2, N_2, CO_2 and H_2O, and the τ_i^{pt} are closely connected to the lifetimes of the corresponding vibrational quantas. However, this interpretation of Eq. (8) is correct only if the vibrational energy is converted totally into translational energy (V-T process). If instead there is a vibration to vibration exchange of energy between the molecules (V-V process), then the heat capacities of these modes are coupled via that process. As a result of this coupling, each C_i' contains part of the heat capacities of all the vibrational degrees of freedom which are present in air and each τ_i^{pt} contains lifetimes of all quanta which depend upon the transition probabilities of all V-T and V-V processes. Furthermore, depending upon the number of excited levels involved, there can even be more than four vibrational relaxation times present in Eq. (8). Since at least three close resonances between vibrational states exist in air, namely those between N_2 and CO_2; O_2 and CO_2; and O_2 and H_2O, these V-V processes certainly must be considered. These processes totally dominate the sound absorption in the audible region, and there are no other means to predict the acoustic behavior except to investigate their influence and to determine their rates.

The method of calculation of the C_i' and τ_i^{pt} proceeds in a standard way. The coupled equations for the V-V processes owing to the excited vibrational levels are decoupled by means of a main axis transformation[6]. Each of the decoupled equations furnishes one term in Eq. (8). The significance of these terms is that they form the simplest mathematical representation of the dynamic heat capacities. Now, the dispersion and absorption can be given by

$$\frac{1}{V^2} = \frac{\rho}{P} \operatorname{Re}\left[\frac{C_v^{\infty} + C_{vib}^{dyn}}{C_p^{\infty} + C_{vib}^{dyn}}\right]$$

and (9)

$$\alpha = \alpha_{class} + \alpha_{rot} + \frac{\omega}{2}\left(\frac{V}{V_{\infty}^2}\right) \operatorname{Im}\left[\frac{C_v^{\infty} + C_{vib}^{dyn}}{C_p^{\infty} + C_{vib}^{dyn}}\right]$$

where each contains a complex rational function of high order in $(j\omega)$. The separation into real and imaginary parts would yield an even more complicated fraction; however, for the convenience of the user, we have expressed $\left(C_v^{\infty} + C_{vib}\right) \Big/ \left(C_p^{\infty} + C_{vib}\right)$ in partial fractions by using a second main axis transformation. This yields

$$\left(\frac{k}{\omega}\right)^2 = \frac{\rho}{P} \frac{C_v^{\infty}}{C_p^{\infty}} \left(1 + \sum \frac{A_i}{1 + j\omega\tau_i^{ps}}\right) + \text{classical effects} + \text{rotational effects} \qquad (10)$$

where the τ_i^{ps} differ slightly from the τ_i^{pt}, $A_i = \beta_i/\beta^{\infty}$, $\beta^{\infty} = \dfrac{C_v^{\infty}}{PC_p^{\infty}}$ and

$\sum A_i = (\beta^0 - \beta^{\infty})/\beta^{\infty} = \sum \beta_i/\beta^{\infty} = \beta/\beta^{\infty}$ is closely related to the so-called relaxation strength of a single relaxation process $(\beta^0 - \beta^{\infty})/\beta^0 = \beta/\beta^0$. The A_i could be interpreted as telling which part of the vibrationally relaxing adiabatic compressibility, β , is connected to the particular τ_i^{ps} (called isobaric-adiabatic or isobaric-isentropic relaxation time in Ref. 6). Using this notation, the separation of the imaginary and real parts of the propagation constant k can be accomplished to obtain

$$\frac{V_\infty^2}{V^2} = 1 + \sum \frac{A_i}{1 + (\omega\tau_i^{ps})^2} \tag{11}$$

and

$$\alpha = \alpha_{class} + \alpha_{rot} + \frac{\omega}{4} \left(\frac{V}{V_\infty^2}\right) \sum \frac{A_i\, \omega\tau_i^{ps}}{1 + (\omega\tau_i^{ps})^2} \quad . \tag{12}$$

IV. RESULTS

The 24 binary energy transfer rates defined in Ref. 1 were used to obtain relaxation times and strengths which were in turn inserted into Eqs. (11) and (12) of this paper to obtain the absorption and dispersion of sound in still air. To facilitate these calculations the rate MOP_1^1 (5,2,0) was changed to 7×10^5 sec^{-1} atm^{-1}. After this change the absorption results were within 3% of those published in Ref. 2 for all frequencies above 100 Hz. Below 100 Hz the two differ by as much as 15% for some humidities; however, this is not considered serious since below 100 Hz the values in Ref. 2 may be in error by as much as 50%. The difference in the MOP_1^1 (5,2,0) rate will be discussed in a subsequence publication. The eigenvalue analysis using the 24 rates yielded several relaxation times; however, only three of these had an associated relaxation heat or strength large enough to influence the absorption. As a result, instead of requiring 24 rates to describe the vibrational relaxation absorption as in Ref. 1, only three relaxation times and strengths are needed at each humidity. In addition, the strengths are very nearly independent of humidity. For 20°C, the relaxation times and strengths are presented in Figs. 1 and 2. It is not possible to associate a relaxation time to a specific component of the atmosphere; however, examination of the contributions to the adiabatic compressibility shows that τ_1^{ps} is closely related to the relaxation of N_2 and τ_2^{ps} to O_2. These relaxation times should be considered only as useful computational parameters, and no attempt should be made to ascribe fundamental physical significance to them. The fundamental quantities are the binary rate constants.

Using Eq. (12), adding the various absorption terms, and combining constants gives the results in dB/1000 ft

$$\alpha = 27.26 \left\{ \sum_{i=1}^{4} \frac{f\, T_i\, A_i}{1 + f^2 T_i^2} + 1.525 \times 10^{-9} f \right\} \frac{f}{c} \tag{13}$$

The values of (T_1, T_2, T_3) and (A_1, A_2, A_3) can be taken from Figs. 1 and 2 respectively or calculated using

$$\log_e (T_i \text{ or } A_i) = b_0 + b_1 (\log_e H) + b_2 (\log_e H)^2 + b_3 (\log_e H)^3 \tag{14}$$

where the regression coefficients are given in Table I. A_4 is defined to be unity, $T_4 = 6.5 \times 10^{-10}$ sec and c is calculated by

$$c = \frac{1}{30480} \left[\left(\frac{3.5 + 5h}{2.5 + 5h} \right) \frac{8.3166 \times 10^7\, \theta}{28.966 - 10.95h} \right]^{1/2} \tag{15}$$

where $h = P_w H/100$.

For computational convenience c may be set equal to 1.13 if an empirically derived $T_4 = 5 \times 10^{-10}$ sec is used. This will also reproduce the tables of Ref. 2 within 3%. During any of these calculations it must be remembered, that the frequency divided by the pressure, not the actual acoustic frequency is the important variable. Hence, a decrease in pressure is equivalent to an increase in frequency. For calculations at pressures other than one standard atmosphere, f/p should be inserted at all places f presently appears except outside the brackets in Eq. (13).

V. SUMMARY

A set of equations has been developed which will accurately predict the absorption of sound in still air at 20°C over the frequency range of 12 Hz - 1 MHz and over all humidities. The method of calculation presented was devised primarily as a computational convenience. The accuracy of the calculations is still limited, as was noted in Ref. 1 by limited knowledge of the binary energy transfer rates, but not by the computational method. Specifically, this lack of knowledge limits the accuracy of low frequency (12 Hz to 60 Hz) calculations which might be off as much as a factor of 2 due to the lack of knowledge about CO_2/O_2 V-V energy transfer. The ability to apply this formalism at other temperatures is also severely limited by lack of knowledge about the temperature dependence of the CO_2/O_2 rates and those rates involving H_2O as a collision partner. Nevertheless, the problem of sound absorption in still air has been simplified while maintaining a correct physical formalism. The temperature dependence and low frequency problems will be solved as soon as binary rate data is available.

VI. ACKNOWLEDGMENTS

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* NSF Senior Foreign Scientist on leave from Universität Stuttgart, Germany

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TABLE I. Regression Coefficients for Eq. 14.

	b_0	b_1	b_2	b_3
T_1	- 2.357009	-0.5423307	-0.05253065	-0.0006430596
T_2	- 5.388992	-1.231140	-0.04769421	0.004000068
T_3	- 9.780594	-0.8459473	-0.03399849	0.002532959
A_1	- 8.974335	-0.003204346	-0.0004720688	-0.0001525879
A_2	- 7.397324	0.006179810	0.0001125336	-0.00001049042
A_3	-10.40355	0.01698303	-0.002468109	-0.0002794266

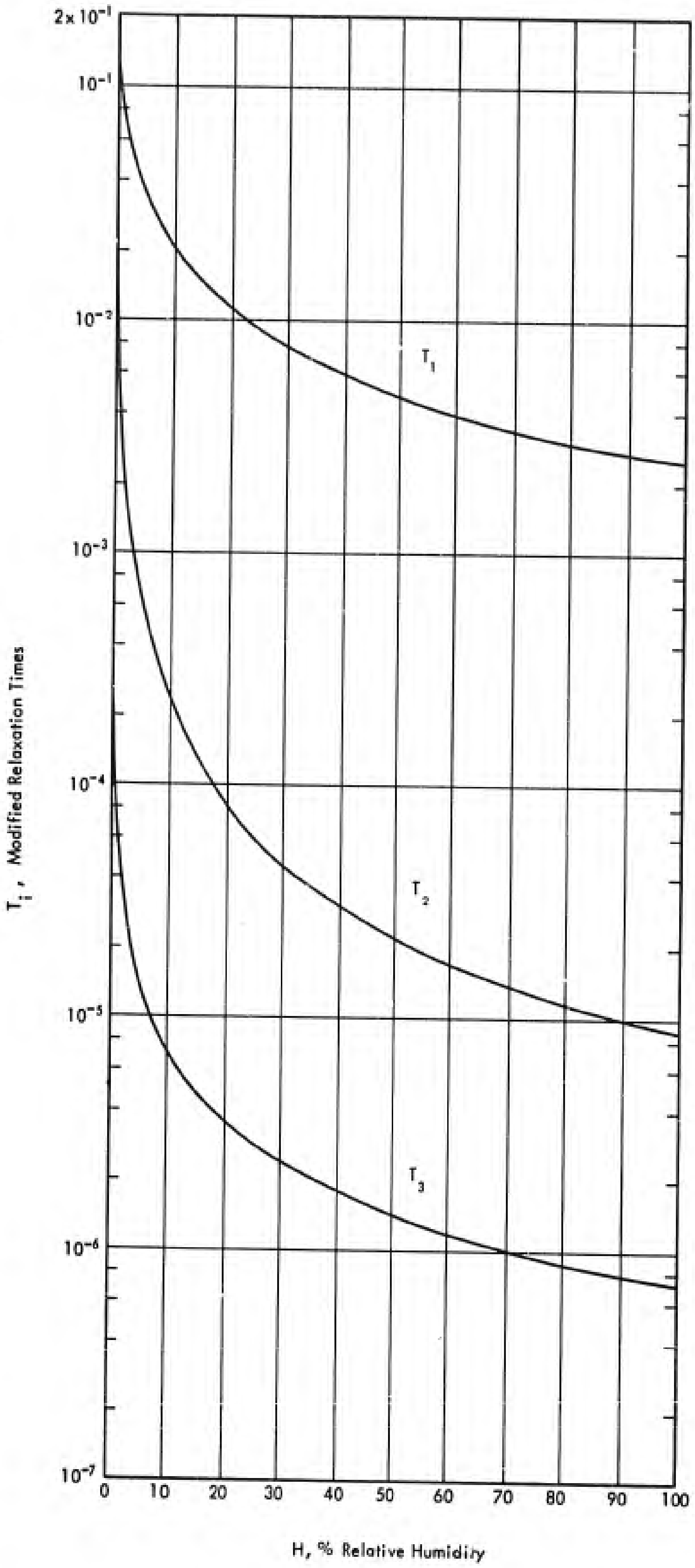

Figure 1. Modified Relaxation Times T_1, T_2 and T_3 as a Function of Percent Relative Humidity.

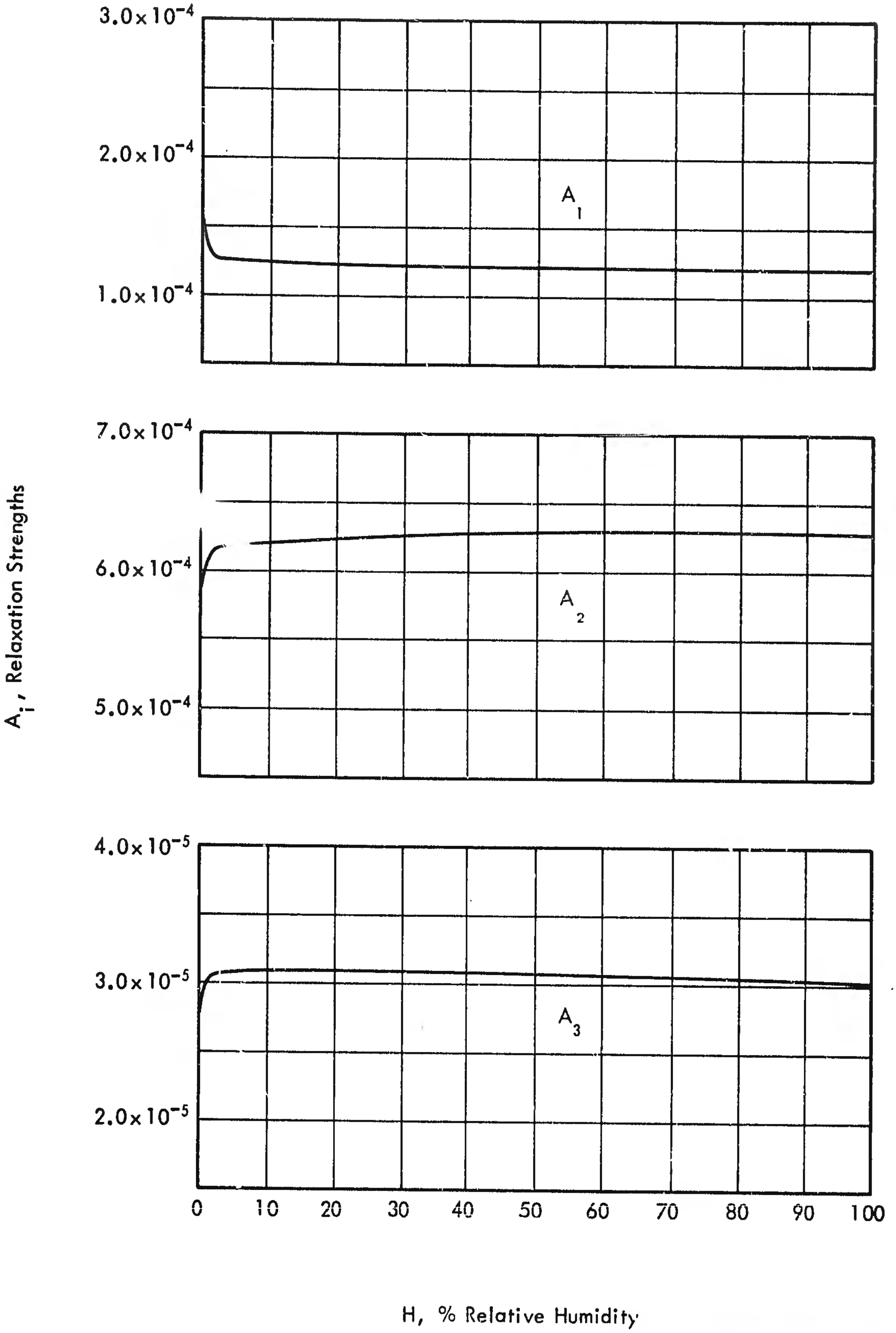

Figure 2. Derived Relaxation Strengths A_1, A_2 and A_3 as a Function of Percent Relative Humidity.