Absorption of Sound in Air versus Humidity and Temperature

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Measurements have been made of the absorption of sound in air at $\frac{1}{3}$-octave frequency intervals from 2000 to 12 500 Hz, as a function of humidity, at six temperatures in the range from $-0.5°$ to $25.1°C$ at normal atmospheric pressure. The results of the new study are presented and compared with those of past investigations. Then a "best fit" is obtained to existing data. The resulting information is presented in both tabular and graphical form, useful for the solutions to problems of the calculation of attenuation of sound propagated in the atmosphere and the computation of the effects of air absorption in problems of room acoustics. These results have been extrapolated downward in frequency to 125 Hz and extrapolated to cover the temperature range from $-10°$ to $30°C$ at normal atmospheric pressure.

INTRODUCTION

IN a paper by the author[1] in 1963, measured values of the absorption of sound in air were given as a function of humidity in the frequency range between 2000 and 12 500 Hz (cps), at normal atmospheric pressure and at a temperature of 20°C. The data presented here greatly extend the previous work over a wide temperature range and provide measured values having greater accuracy through improved methods of data reduction. A total of 2800 measurements were made at $\frac{1}{3}$-octave frequency intervals from 2000 to 12 500 Hz at each of six temperatures in the range from $-0.5°$ to 25.1°C at normal atmospheric pressure. The new data are compared with those of past investigations. Then a "best fit" is obtained to existing data. These results make it possible to evaluate the effects of air absorption over a range of environmental conditions encountered in practical problems in acoustical engineering, for example: (1) the calculation of the attenuation of sound in air owing to air absorption; (2) the calculation of the contribution of air absorption to the total absorption in a large room; (3) the correction for air absorption in reverberation-time measurements in large auditoriums; and (4) the correction for air absorption in the measurement of the sound-absorption coefficients of materials tested in a reverberation chamber. These results have been extrapolated downward in frequency to 125 Hz and extrapolated to cover the temperature range from $-10°$ to 30°C.

The experimental setup and measurement techniques used here are the same as those employed in the earlier

[1] C. M. Harris, J. Acoust. Soc. Am. **35**, 11–17 (1963).

study and are described in detail in that paper.[1] Therefore, they are outlined only briefly here. Suffice it to say that the attenuation coefficient of sound in air was evaluated from measurements of the decay rate of diffuse sound in a spherical chamber 1.68 m in diameter. During measurements, the temperature of the chamber was held constant to within 0.1°C. Precautions were taken to rid the chamber of contamination by evacuating it by means of vacuum pumps; then the spherical chamber was filled with dry air having a carbon dioxide content of 300 parts per million, which is a usual value. Random noise from a source in the chamber was picked up by a microphone, amplified, and fed through $\frac{1}{3}$-oct filter to a high-speed level recorder. When the random noise source was turned off, a curve of the decay of sound in the chamber was obtained. The slope of the curve determined the decay rate in decibels per second at the frequency of the center of the band to which the $\frac{1}{3}$-oct analyzer is set. For a single test condition, three decay curves were superposed; then the average slope of three such sets of superposed curves was obtained to determine the decay rate for this condition. This decay rate, when corrected for losses at the boundaries of the chamber, is a measure of the total absorption of sound in the chamber.

In determining the magnitude of the absorption of sound in air from measurements of the rate of decay of sound in a chamber, it is necessary to evaluate the contribution to decay rate that may be attributed to losses in acoustic energy at the boundaries of the chamber. The technique used here is to evaluate these wall losses directly, by means of decay-rate data obtained when

the chamber is filled with prepurified dry nitrogen (which exhibits no anomalous absorption in the frequency range of measurement). The difference between the measured value of the rate of decay of sound in the nitrogen-filled chamber and the value computed from absorption data on nitrogen (the nitrogen data of Parbrook and Tempest[2] are used in this calculation) represents the contribution to the decay rate due to wall losses. This can be shown as follows. The decay rate of sound in the chamber that one measures, $R_{measured(N_2)}$, when it is filled with nitrogen is given by

$$R_{measured(N_2)} = R_{N_2} + R_{wall} \text{ dB/sec}, \qquad (1)$$

where R_{wall} is the decay rate due to absorption at the boundaries of the chamber, and where R_{N_2} is the decay rate due only to the nitrogen gas. Similarly, when the chamber is filled with air, the measured decay rate is

$$R_{measured(air)} = R_{air} + R_{wall} \text{ dB/sec}, \qquad (2)$$

where R_{wall} is the decay rate contributed by the wall losses and R_{air} is the calculated decay rate due only to air absorption. The wall-loss term in these equations is approximately the same because both gases are closely similar in molecular weight and characteristic acoustic impedance. By combining Eqs. 1 and 2, the rate of decay of sound in the chamber owing only to the absorption of sound in air is given by

$$R_{air} = R_{measured(air)} - [R_{measured(N_2)} - R_{N_2}] \text{ dB/sec}, \qquad (3)$$

where the quantity within the brackets represents the contribution to the rate of decay of sound in a chamber that is due to wall losses. Consideration has been given to possible variation in the boundary losses with changes in the humidity within the sphere. As pointed out by Evans and Bazley[3] in discussing this possibility, the work of Knudsen, Wilson, and Anderson[4] indicates that such an effect is not significant; their data show that there is no appreciable change in wall absorption even when moisture condenses on the wall surface.

The value of R_{air} in decibels per second given by Eq. 3, which represents the contribution to the rate of decay of sound in a chamber or room caused by air absorption, may be converted to the attenuation coefficient m per meter as expressed in the equation $I = I_0 e^{-mx}$ by the relation

$$m = R_{air}/(4.343c) \text{ meters}^{-1}, \qquad (4)$$

where c is the velocity of sound in meters per second.

The methods of data reduction that were employed to determine the values of m for various conditions in this study are described in detail in the next Section. A comparison of the new data for air with earlier studies is given in Sec. II. Then a best fit is obtained. The new results are presented in Sec. III. Then they are applied

[2] H. D. Parbrook and W. Tempest, Acustica 8, 345–350 (1958).

[3] E. J. Evans and E. N. Bazley, Acustica 6, 238–245 (1956).

[4] V. O. Knudsen, V. Wilson, and N. S. Anderson, J. Acoust. Soc. Am. 20, 849–857 (1948).
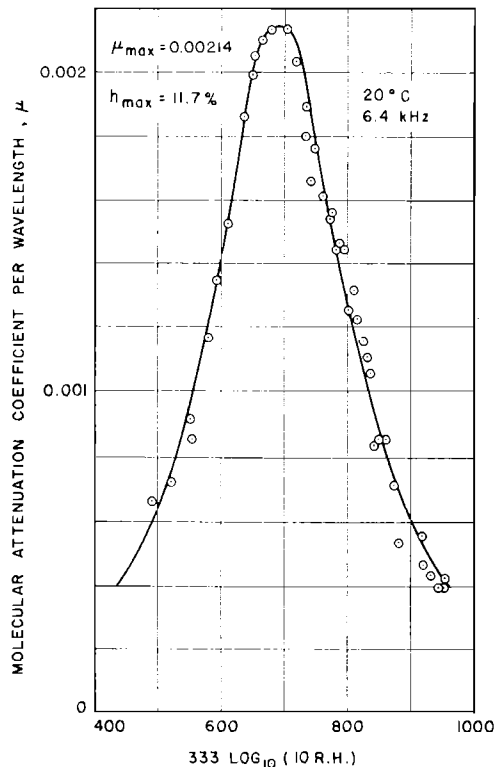
FIG. 1. Example of a plot of experimental data of the molecular attenuation coefficient per wavelength in air as a function of humidity. These data are for a temperature of 20°C and a frequency of 6400 Hz.

to problems in the propagation of sound in air and room acoustics in Sec. IV.

I. DATA REDUCTION

For a given condition of temperature and humidity, the decay rate of sound in air was measured for the various frequencies. The result of each decay-rate measurement was punched on an IBM card along with the following information: (1) temperature; (2) frequency; (3) value of classical absorption m_c for these conditions; (4) humidity; (5) wavelength λ of sound for these conditions, computed from sound-velocity data given in Tables compiled by the National Bureau of Standards[5]; and (6) the value of wall losses for these conditions.

From the above input data, a computer program provided for the printout of the following results: (1) total attenuation coefficient $m = m_m + m_c$ (i.e., the sum of the attenuation coefficients due to molecular and classical attenuation) corrected for wall losses; (2) molecular attenuation coefficient, m_m; and (3) molecular attenuation coefficient per wavelength $\mu = m_m \lambda$. The results provided by this computer program were analyzed as indicated in this Section. Then a computational procedure was developed for evaluating the total at-

[5] J. Hillsenrath et al., "Table of Thermal Properties of Gases," Natl. Bur. Std. (U. S.) Circ. No. 564 (1 Nov. 1955).
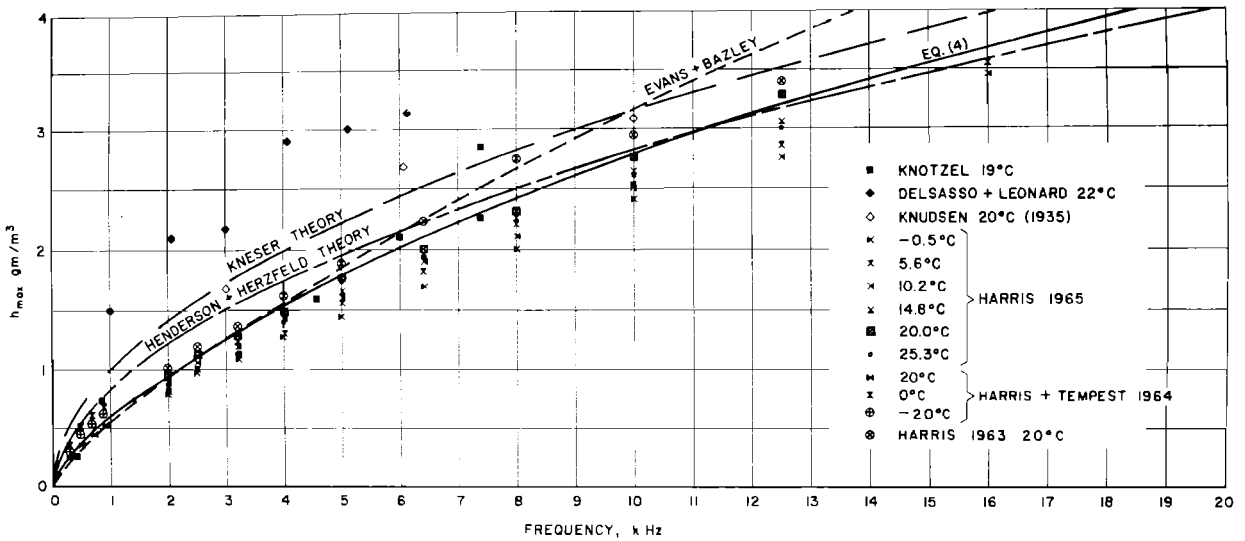
FIG. 2. Relaxation frequency as a function of the concentration of water vapor in air expressed in gm/m³. The relationship used in the results presented in this paper is shown as the solid curve.

tenuation coefficient for any temperature, frequency, or humidity within the range over which the experimental data may be extrapolated with confidence.

A. Values of h_{max}

For a given temperature and frequency, the molecular absorption m_m varies with the moisture content of the air. For a given frequency, the value of humidity at which the molecular absorption is maximum is defined as h_{max}. The measured value of h_{max} may be determined from plots of the molecular attenuation per wavelength versus the logarithm of the relative humidity, such as the one shown in Fig. 1. [Here, because an automatic plotting device was employed, it was convenient to plot μ against $333 \log(10 \text{ R.H.})$ rather than against $\log(\text{R.H.})$ directly.] For example, the original data points for sound having a frequency of 6400 Hz in air having a temperature of 20°C are plotted in Fig. 1. Here the resulting value of h_{max} is 11.7%. A total of 54 such plots was made, i.e., one for each of six different values of temperature ($-0.5°$, $5.6°$, $10.2°$, $14.8°$, $20.0°$, and $25.1°C$) at nine different frequencies (2.0, 2.5, 3.2, 4.0, 5.0, 6.4, 8.0, 10.0, and 12.5 kHz). From these plots, an experimentally determined value of h_{max} for each frequency, and at each temperature, was obtained. These data are shown in Fig. 2, where the values of h_{max} are expressed in grams per cubic meter, along with similar data from other studies. The solid curve represents a best fit to the data at 20°C from this and previous data obtained with the same experimental setup,[1,6] as well as data obtained by other experimenters as weighted by the author. This solid curve, in the frequency range between 125 and 12 500 Hz, may be expressed by the equation

$$f_{max} = 0.79h^2 + 1.47h - 0.15, \qquad (5)$$

where f_{max} is the frequency in kilohertz corresponding to absorption peak at h (expressed in grams per cubic centimeter). The values of h given by this solid curve were used in calculating the absorption curves presented in Sec. III. There is a marked disagreement between this curve and the theoretical relationship of Kneser,[7] which predicts that f_{max} varies as h^2, as indicated by the dashed curve. In contrast, there is reasonably good agreement with the more recent theoretical relationship given by Henderson and Herzfeld[8] for a temperature of 20°C.

In considering the relationship between f_{max} and h, the water-vapor content h is usually expressed either in terms of mol fractions (or percent molar concentration) of water or in terms of the weight of the water in grams per cubic meter (as in Fig. 2). The temperature dependency of the relationship between f_{max} and h depends on the units in which h is expressed. According to the experimental data of Knotzel,[9] the relationship between f_{max} and h is relatively independent of temperature if the water vapor is expressed in grams per cubic meter. If we make this assumption and now obtain an equivalent relationship in which the water vapor is expressed in mol fractions, then f_{max} *increases* as the temperature decreases! Such an "inverse" relationship has been observed experimentally for other gases containing water vapor.[10] According to data of Ref. 9, the relationship, where h is expressed in grams per cubic meter, is not actually constant; instead, at high concentrations of water vapor, as the temperature decreases the value of f_{max} increases, thereby accentuating the

[6] C. M. Harris and W. Tempest, J. Acoust. Soc. Am. 36, 2390–2394 (1964).

[7] H. O. Kneser, J. Acoust. Soc. Am. 5, 122–126 (1933); also, Akust. Z. 5, 256–257 (1940); Ergeb. Exakt. Naturwiss. 22, 121–185 (1949).

[8] M. C. Henderson and K. F. Herzfeld, J. Acoust. Soc. Am. 37, 986–988 (1965).

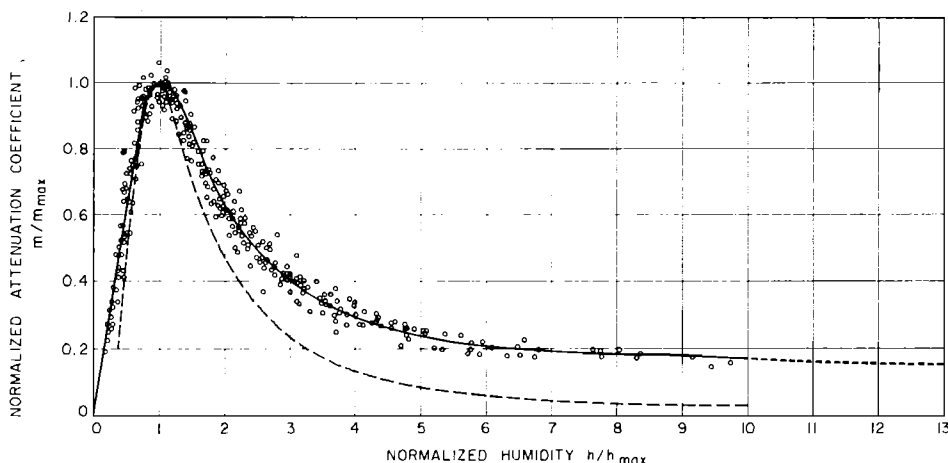[9] H. Knotzel, Akust. Z. 5, 245–256 (1940).

FIG. 3. Plot of experimental data of the molecular attenuation coefficient in air versus humidity. These data are presented in the normalized form, m/m_{max} vs h/h_{max} for comparison with the theoretical relationship of Kneser shown by the dashed line.

"inversion" effect. The data obtained in this study at different temperatures show an even more pronounced trend in this direction, which would accentuate the inversion effect. However, it should be noted that the accuracy of determination of f_{max} is greatest at 20°C and that it is progressively less at lower temperatures. This point bears further investigation and may result in a modification of the above Eq. 5 at lower temperatures.

B. Maximum Value of Molecular Absorption versus Frequency

For a given temperature and frequency, the maximum value of molecular attenuation coefficient m_m is represented by m_{max}. According to theory, the maximum values of molecular absorption increase linearly with frequency.[7,10] Since $m_{max} = \mu_{max}/\lambda$, we may obtain values of both μ_{max} and m_{max} from plots of μ versus humidity, such as the one shown in Fig. 1. For example, in this illustration, $\mu_{max} = 0.00214$; dividing by the wavelength for a frequency of 6400 Hz at 20°C, we obtain the maximum value of molecular absorption at this frequency and temperature, i.e., 0.0399 m^{-1}. The values of μ_{max} measured at the various frequencies were averaged, obtaining the following values of μ_{max} at the temperatures indicated: -0.5°C, 0.00152; 5.6°C, 0.00170; 10.2°C, 0.00187; 14.8°C, 0.00205; 20.0C, 0.00214; 25.1°C, 0.00247. These values, which are higher than similar data obtained in past studies with this experimental setup, were averaged with the earlier data.[1,6] A smooth curve drawn through the resulting values of μ_{max} yields values that are close to those predicted by theory.

The following values of μ_{max} were employed, at the temperatures indicated, in the computer program for determining the values of m_{max}: -10°C, 0.00114; -5°C, 0.00128; 0°C, 0.00143; 5°C, 0.00159; 10°C, 0.00176; 15°C, 0.00194; 20°C, 0.00214; 21°C, 0.00218; 22°C, 0.00223; 23°C, 0.00227; 24°C, 0.00231; 25°C, 0.00235; 30°C, 0.00258. Thus, at a given temperature T, the maximum value of the molecular absorption m_m

for a frequency f was obtained by dividing the value of μ_{max} for the temperature by the wavelength corresponding to that frequency at temperature T. For example, for a temperature of 30°C, the maximum absorption at 10 000 Hz was determined by dividing the value of μ_{max} for 30°C (0.00258) by λ for this frequency and temperature, obtaining a value of m_{max} equal to 0.0740 m^{-1}. The corresponding value at 1000 Hz is equal to 0.0074 m^{-1}, etc.

C. Normalized Curves of Molecular Absorption versus Humidity

The data points for each curve of molecular absorption versus humidity at constant frequency were normalized in the following way. At a given temperature, the value of the molecular coefficient (m_m) for each data point was divided by the maximum value of the molecular attenuation coefficient for that temperature; this ratio is defined here as m/m_{max}. Similarly, the corresponding value of relative humidity h for the data point was divided by h_{max}. According to the theory of Kneser, absorption-versus-humidity data for various frequencies that are so normalized should all fall along a single curve, which is shown by dashed lines in Fig. 3. This study shows that such a normalization procedure results in a single curve. For example, the data points for 20°C are shown in Fig. 3 and the best fit through these data, obtained at different frequencies, is represented by the solid curve. This solid curve indicates that theory does not fit the measured values of absorption below and above the maximum value of absorption—a result that has been observed in the past when the data of earlier investigators were presented in normalized form.[11] This is because the above theory assumed that the angular relaxation frequency varies with h^2, as indicated by the dashed curve of Fig. 2, whereas the experimental data

[10] K. F. Herzfeld and T. A. Litovitz, *Absorption and Dispersion of Ultrasonic Waves* (Academic Press Inc., New York, 1959).

[11] W. L. Nyborg and D. Mintzer, Wright Air Development Center, Wright–Patterson AFB, WADC Tech. Rept. No. 54-602 (May 1955), Sec. 1.2.4.

show that the relationship is more complex. The present study indicates that the value of $m/m_{\max}$ is slightly below 0.2 at high values of humidity. Knudsen's data[12] show much greater discrepancies between measured and theoretical values of $m/m_{\max}$ at high values of humidity. In contrast, the study of Delsasso and Leonard[13] shows much closer agreement with the present data shown in Fig. 2.

Although the above theory does not fit the experimental data, it is important to note that a single curve is obtained by rationalizing absorption data at all frequencies and temperatures as indicated above, and that this solid curve represents a best fit through the experimental data, and that the data collapse to a single curve within the limits of experimental measurement. Thus one may conclude that it is possible to measure the value of $h_{\max}$ and $m_{\max}$ for various frequencies and for various conditions of temperature. Then one can use the solid curve shown in Fig. 3, in combination with these measured values, to compute curves of molecular absorption versus humidity for various frequencies and temperatures. This procedure was followed, employing a high-speed digital computer that had been programmed to calculate the curves of molecular absorption versus humidity, using the data from experimental measurements as input information. In the computer, the classical absorption was added to the molecular absorption to yield the total value of the attenuation coefficient. The advantage of this evaluation procedure is that it provides a convenient means of determining sound absorption at frequencies and temperatures other than the exact values at which the measurements were made, by interpolation or extrapolation. This procedure was followed to obtain the results presented in Sec. III.

II. DISCUSSION AND COMPARISON WITH OTHER STUDIES

In this Section, a comparison is made between the present results and those obtained in other investigations. In most of these studies, the reverberation-chamber method has been employed, in which the rate of decay of sound in air has been measured for various humidity conditions at a constant value of frequency. Laboratory measurements of the absorption of sound in air are subject to several major sources of error (systematic or random) resulting from (1) an inability to evaluate with precision losses in acoustic energy introduced by the walls of the test chamber; (2) the lack of adequate control of the test-chamber environment, including temperature and gas composition; and (3) the lack of precision in humidity measurement, either as a result of instrumentation error or as a result of absorption of moisture by the walls of the test chamber. These sources of error are considered below in comparing the results of the various studies.

[12] V. O. Knudsen, J. Acoust. Soc. Am. **5**, 112–121 (1933).
[13] L. P. Delsasso and R. W. Leonard, "The Attenuation of Sound in the Atmosphere," Univ. Calif., Los Angeles, Rept. USAF contract W-28-099-AC-228 (25 Feb. 1953).

A. Evaluation of Wall Losses

In order to achieve higher accuracy in the measurement of the absorption of sound in air by the reverberation method (or the "intensity" method), it is necessary to evaluate wall losses with precision. The greater the wall losses, the more important is this source of error. Because the decay rate that is measured depends upon the sum of the absorptions by the walls and the air, the wall losses should be small compared with the air losses. Therefore, the losses of acoustic energy at the walls of the test chamber should be reduced to a bare minimum.

For the above reasons, a spherical chamber was employed in this study, because it presents the smallest wall surface area for a given volume and because its shape makes it possible to achieve a very high value of acoustical impedance at the boundaries. By using very heavy walls in the present experimental setup, it was possible to achieve a reverberation time in dry air of 43 sec at 1000 Hz. This is very many times longer than the comparable values in earlier studies, and the associated boundary losses are significantly lower. In determining the attenuation coefficients for air, the effects of wall losses were subtracted out, as indicated by Eq. 3.

In the "two-chamber" method employed by Knudsen,[12] it was assumed that the absorption coefficients of both chambers were the same. Although his chamber walls were of steel and were reinforced with spot-welded angle irons, it is unlikely that the boundary conditions in the chambers were identical because the walls were only 4.8 mm thick. Intercomparisons between three or more similarly fabricated model chambers have shown that it is difficult to achieve identical boundary conditions in chambers of different sizes. In contrast, the steel walls of the sphere used in the present study were 16 mm thick, and the boundary losses were evaluated in the same chamber in which the measurements were carried out.

In the study by Evans and Bazley, a single chamber was employed, but because of physical limitations it was impractical to seal the chamber and fill it with a gas, such as nitrogen, for the purpose of calibrating wall losses. Hence, they used the following indirect evaluation procedure, which afforded greater opportunity for error. They computed their wall losses and curves of absorption versus humidity from the following equation and only a *single* set of experimental measurements (i.e., measurements of the reverberation time of an empty reverberation chamber for various humidity conditions):

$$A = \underbrace{\frac{137.2f \times 10^{-4}}{(k/2\pi f)+(2\pi f/k)}}_{\text{molecular}} + \underbrace{4.6(f)^{\frac{1}{2}} \times 10^{-2}}_{\text{ideal surface}}$$
$$+ \underbrace{4.1f^2 \times 10^{-8}}_{\text{classical}} + \delta, \quad (6)$$

where A is the total absorption of sound in the chamber in square meters, f is the frequency in Hertz, k is the angular relaxation frequency $(2\pi f_{max})$, δ represents the difference between the actual wall losses and the values predicted by theory, and the numerical constants are dependent on the physical characteristics of the room. The first term had a maximum value of $68.6 f \times 10^{-4}$. The single set of data, obtained over a period of two years, was corrected to a temperature of 20°C and the above equation was used to (1) evaluate their wall losses; (2) determine the angular relaxation frequency k; (3) determine the magnitude of the molecular absorption; (4) compute the total absorption, i.e., molecular plus classical absorption; and (5) check their results. Since physical limitations of the measurement setup made it impossible to provide any independent means of measuring the above parameters, including the effects of wall losses, the check was one of self-consistency. Since present theory is not adequate for predicting the value of molecular absorption accurately for various temperatures and humidities, the first term in Eq. 6, which includes the term "k" $(k = 2\pi f_{max})$, is open to question. Further, it has not been established that the room absorption, in a nonideal situation such as their reverberation chamber, can be represented by the second term plus a constant in the form shown in Eq. 6.

B. Control of Environment of Test Chamber

In the present study, the test chamber was completely surrounded by 1–2 ft of fiberglass to provide thermal insulation. A refrigeration system maintained the temperature of the chamber to within 0.1°C. In contrast to this and the controls employed in other studies, no temperature control was employed in the chamber used by Evans and Bazley. As a result, the standard deviation of the room temperature at which measurements were made was 2.1°C. It was necessary for them to rely on theory to correct their results to 20°C and an adequate theoretical treatment of how absorption varies with temperature has yet to be established.

The measurements described in this paper were made using a closed air circulation system, shown in Fig. 4 and described in Ref. 1. To lower the humidity, moisture was taken from the test chamber and deposited in the "saturator"; to raise the humidity, the process was reversed. Thus all measurements were made on the same air, of known chemical content. This system avoids the possibility of contamination of the air under test, either by smog or by chemical drying agents such as those employed by Evans and Bazley to reduce the value of humidity in their test chamber. Furthermore, it avoids the addition of acoustic absorption into the measurement system, which such a drying technique introduces.

C. Humidity Measurements; f_{max} versus h_{max}

Using the present experimental setup, the author tried several different methods of humidity measure-
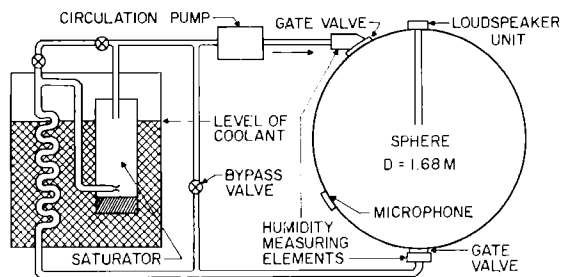

FIG. 4. Simplified schematic diagram of the air-circulation system. Air is recirculated continuously through the spherical chamber. The saturator either takes away moisture from the air or adds moisture to it, depending on the relative temperatures of the spherical chamber and the saturator.

ment that had been employed by earlier investigators. One method was to weight the amount of water that was evaporated in the test chamber prior to the establishment of a given humidity condition. It was demonstrated that this technique can lead to serious error since a significant fraction of the water that enters the chamber may be absorbed by the walls of the chamber. Similarly, if the humidity of the air that enters or leaves the test chamber is measured (which is another technique that has been employed by some investigators in the past), the measurement value does not represent the humidity within the chamber because of absorption or emission of moisture by the walls of the test chamber—unless a steady-state humidity condition is achieved. To avoid these errors, the humidity control and measurement system shown in Fig. 4 was constructed. Air was recirculated until a steady-state condition of humidity was achieved; often, this required as much as $\frac{1}{2}$ hour of recirculation. Then the humidity was determined by electric hygrometer sensing elements as described in Ref. 1.

A determination of the relationship between relaxation frequency and humidity requires highly accurate measurement of humidity, particularly at low concentrations of water vapor where the accuracy of measurement is relatively poor. Although a humidity measurement error may have a small effect on the peak value of the absorption curve, a small error in measuring humidity can have a significant effect in shifting the position of the peak along the humidity scale and, hence, in determining the value of h_{max}. For this reason, there has been considerable discrepancy between such data measured by various investigators. Comparisons are shown in Fig. 2 of the results of several air-absorption studies in terms of the relaxation frequency f_{max} versus concentration of water vapor (h, expressed in grams per cubic centimeter) at which the maximum absorption is achieved for the frequency.

Knudsen's data, represented by the three experimental points at 20°C, do not provide sufficient data for an explicit relationship between the relaxation frequency and concentration of water vapor. Evans and Bazley reported that the relaxation frequency varies as

TABLE I. Values of the product $4m$ at a frequency of 2000 Hz for various temperatures and values of relative humidity. The attenuation coefficient m is expressed in ft⁻¹.

R.H. (%)	TEMPERATURE			
	15°C (59.0°F)	20°C (68.0°F)	25°C (77.0°F)	30°C (86.0°F)
30	0.00436	0.00362	0.00346	0.00339
40	0.00338	0.00316	0.00313	0.00305
45	0.00317	0.00303	0.00300	0.00291
46	0.00312	0.00301	0.00298	0.00288
47	0.00308	0.00299	0.00296	0.00286
48	0.00305	0.00297	0.00294	0.00285
49	0.00302	0.00294	0.00291	0.00283
50	0.00300	0.00292	0.00289	0.00281
51	0.00298	0.00290	0.00287	0.00279
52	0.00296	0.00289	0.00285	0.00277
53	0.00294	0.00287	0.00283	0.00275
54	0.00292	0.00285	0.00281	0.00274
55	0.00291	0.00283	0.00279	0.00272
60	0.00282	0.00274	0.00269	0.00264
70	0.00267	0.00259	0.00255	0.00250
80	0.00255	0.00246	0.00244	0.00239

TABLE IV. Values of the product $4m$ at a frequency of 4000 Hz for various temperatures and values of relative humidity. The attenuation coefficient m is expressed in meters⁻¹.

R.H. (%)	TEMPERATURE			
	15°C (59.0°F)	20°C (68.0°F)	25°C (77.0°F)	30°C (86.0°F)
30	0.04861	0.03794	0.03130	0.02814
40	0.03577	0.02870	0.02570	0.02506
45	0.03178	0.02603	0.02435	0.02413
46	0.03107	0.02564	0.02417	0.02395
47	0.03040	0.02527	0.02401	0.02377
48	0.02974	0.02499	0.02385	0.02362
49	0.02914	0.02472	0.02369	0.02347
50	0.02861	0.02444	0.02353	0.02332
51	0.02809	0.02419	0.02337	0.02317
52	0.02759	0.02397	0.02321	0.02301
53	0.02714	0.02371	0.02306	0.02286
54	0.02670	0.02343	0.02293	0.02271
55	0.02632	0.02321	0.02280	0.02257
60	0.02444	0.02243	0.02216	0.02192
70	0.02227	0.02131	0.02107	0.02072
80	0.02086	0.02042	0.02014	0.01979

TABLE II. Values of the product $4m$ at a frequency of 2000 Hz for various temperatures and values of relative humidity. The attenuation coefficient m is expressed in meters⁻¹.

R.H. (%)	TEMPERATURE			
	15°C (59.0°F)	20°C (68.0°F)	25°C (77.0°F)	30°C (86.0°F)
30	0.01432	0.01187	0.01136	0.01113
40	0.01110	0.01037	0.01029	0.01002
45	0.01040	0.00996	0.00986	0.00955
46	0.01026	0.00989	0.00979	0.00947
47	0.01013	0.00982	0.00972	0.00941
48	0.01003	0.00974	0.00964	0.00935
49	0.00993	0.00967	0.00957	0.00928
50	0.00986	0.00960	0.00950	0.00922
51	0.00979	0.00954	0.00943	0.00916
52	0.00972	0.00948	0.00936	0.00910
53	0.00966	0.00942	0.00929	0.00904
54	0.00960	0.00936	0.00922	0.00899
55	0.00954	0.00930	0.00916	0.00893
60	0.00925	0.00901	0.00884	0.00868
70	0.00878	0.00851	0.00839	0.00823
80	0.00838	0.00807	0.00803	0.00784

TABLE V. Values of the product $4m$ at a frequency of 6300 Hz for various temperatures and values of relative humidity. The attenuation coefficient m is expressed in ft⁻¹.

R.H. (%)	TEMPERATURE			
	15°C (59.0°F)	20°C (68.0°F)	25°C (77.0°F)	30°C (86.0°F)
30	0.03217	0.02559	0.02088	0.01718
40	0.02412	0.01901	0.01589	0.01416
45	0.02131	0.01695	0.01444	0.01340
46	0.02078	0.01659	0.01421	0.01330
47	0.02033	0.01623	0.01401	0.01322
48	0.01991	0.01591	0.01382	0.01313
49	0.01948	0.01561	0.01368	0.01305
50	0.01908	0.01534	0.01354	0.01297
51	0.01871	0.01507	0.01340	0.01289
52	0.01836	0.01483	0.01327	0.01280
53	0.01802	0.01459	0.01316	0.01272
54	0.01770	0.01438	0.01302	0.01265
55	0.01739	0.01419	0.01288	0.01258
60	0.01599	0.01322	0.01242	0.01225
70	0.01384	0.01215	0.01183	0.01168
80	0.01242	0.01145	0.01136	0.01119

TABLE III. Values of the product $4m$ at a frequency of 4000 Hz for various temperatures and values of relative humidity. The attenuation coefficient m is expressed in ft⁻¹.

R.H. (%)	TEMPERATURE			
	15°C (59.0°F)	20°C (68.0°F)	25°C (77.0°F)	30°C (86.0°F)
30	0.01481	0.01156	0.00954	0.00857
40	0.01090	0.00874	0.00783	0.00763
45	0.00968	0.00793	0.00742	0.00735
46	0.00947	0.00781	0.00736	0.00730
47	0.00926	0.00770	0.00732	0.00724
48	0.00906	0.00761	0.00727	0.00720
49	0.00888	0.00753	0.00722	0.00715
50	0.00872	0.00745	0.00717	0.00710
51	0.00856	0.00737	0.00712	0.00706
52	0.00841	0.00730	0.00707	0.00701
53	0.00827	0.00722	0.00703	0.00696
54	0.00813	0.00714	0.00699	0.00692
55	0.00802	0.00707	0.00695	0.00687
60	0.00744	0.00683	0.00675	0.00668
70	0.00678	0.00649	0.00642	0.00631
80	0.00635	0.00622	0.00613	0.00603

TABLE VI. Values of the product $4m$ at a frequency of 6300 Hz for various temperatures and values of relative humidity. The attenuation coefficient m is expressed in meters⁻¹.

| R.H. (%)	TEMPERATURE			
	15°C (59.0°F)	20°C (68.0°F)	25°C (77.0°F)	30°C (86.0°F)
30	0.10556	0.08398	0.06852	0.05637
40	0.07914	0.06238	0.05215	0.04648
45	0.06993	0.05561	0.04738	0.04397
46	0.06819	0.05444	0.04664	0.04366
47	0.06672	0.05327	0.04599	0.04337
48	0.06532	0.05220	0.04537	0.04310
49	0.06392	0.05124	0.04490	0.04283
50	0.06261	0.05033	0.04443	0.04256
51	0.06139	0.04945	0.04397	0.04229
52	0.06024	0.04867	0.04355	0.04202
53	0.05912	0.04789	0.04317	0.04175
54	0.05807	0.04721	0.04274	0.04150
55	0.05707	0.04656	0.04228	0.04129
60	0.05247	0.04340	0.04075	0.04021
70	0.04542	0.03988	0.03883	0.03833
80	0.04075	0.03757	0.03729	0.03672
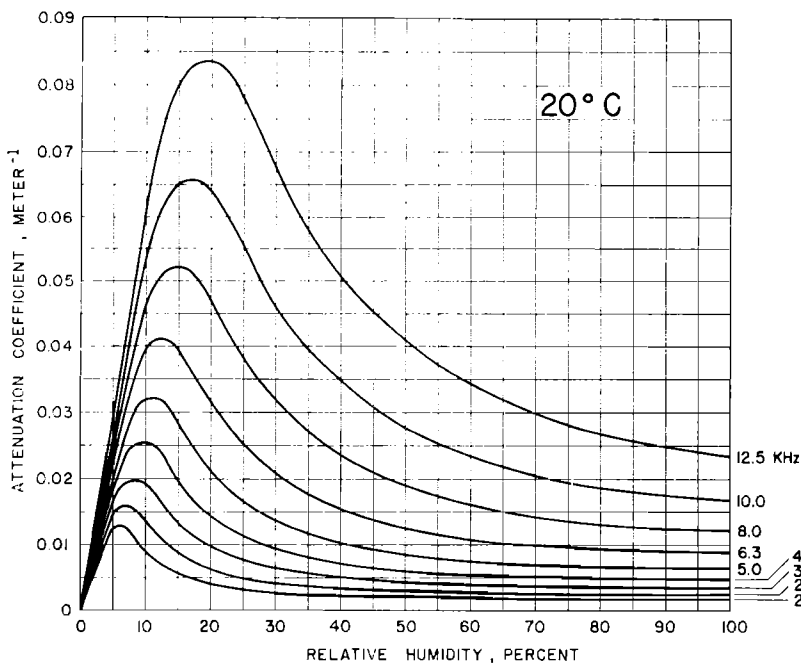
FIG. 5. Values of the total attenuation coefficient m versus percent R.H. for air at 20°C and normal atmospheric pressure for frequencies between 2.0 and 12.5 kHz at $\frac{1}{3}$-oct intervals.

$h^{1.3}$. This is shown as a dashed curve in Fig. 2. The 20°C data of the present study are within the measurement accuracy of the earlier data of Refs. 1 and 6. Likewise, the data of Knotzel also could be represented by the solid curve of Eq. 5.

D. Comparison of Data for Oxygen Containing Water Vapor

One means of providing an independent check on the over-all measurement system for the absorption of sound in air is to use the system to measure the absorption of sound in oxygen and then to compare these data with results obtained by a different measurement technique that is not subject to the same types of errors. Such an independent check has been made at 20°C. The experimental setup used for sound-absorption data presented here was used to measure the absorption of sound in oxygen as a function of water-vapor content.[14] The results so obtained agree very closely with recent data for oxygen obtained by Henderson,[15,16] who employed a resonant pressure-chamber measurement system,[17] using a measurement technique that avoids the use of a hygrometer, which may introduce one of the principle sources of error. Also, these results are in close agreement with the oxygen data of Knotzel and Knotzel,[18] as

indicated by the comparison shown in Fig. 2 of Ref. 14 (also see Fig. 3 of Ref. 16). In contrast, the results of Knudsen and Obert[19] for oxygen are in substantial disagreement with these more recent data. A comparison of this type could not be made by Evans and Bazley[3] since their experimental setup did not permit them to make sound-absorption measurements in gases other than air.

III. RESULTS

Employing the above data-reduction procedures, the attenuation coefficients of sound in air at normal pressure have been evaluated for the following conditions: (1) at the temperatures of $-10°$, $-5°$, $0°$, $5°$, $10°$, $15°$, $20°$, $21°$, $22°$, $23°$, $24°$, $25°$, and $30°C$; (2) at relative humidities of 5%–100% in increments of 5% R.H. [except in the range from 45% to 55% R.H., where the increments are 1%]; and (3) for frequencies of 125, 250, 500, 1000, 2000, 2500, 3200, 4000, 5000, 5940, 6300, 8000, 10 000, and 12 500 Hz. Values in the frequency range from 125 to 1000 Hz were determined by extrapolation from the data at higher frequencies by the procedure indicated in Sec. I. Data for the full temperature and humidity ranges listed above are tabulated, in both the metric and English systems of units, in a National Aeronautics and Space Administration report[20] now in publication. Excerpts of some of these data, over restricted temperature and humidity ranges, are given in Tables I and II for 2000 Hz, Tables III and IV for

[14] C. M. Harris and W. Tempest, J. Acoust. Soc. Am. 36, 2416–2417 (1964).

[15] M. C. Henderson, J. Acoust. Soc. Am. 34, 349–350 (1962).

[16] M. C. Henderson, A. V. Clark, and P. R. Lintz, J. Acoust. Soc. Am. 37, 456–463 (1965).

[17] M. C. Henderson and J. G. Donnelly, J. Acoust. Soc. Am. 34, 779–784 (1962).

[18] H. Knotzel and L. Knotzel, Ann. Phys. 2, 393–403 (1948).

[19] V. O. Knudsen and L. Obert, J. Acoust. Soc. Am. 7, 249–253 (1936).

[20] C. M. Harris, "Absorption of Sound in Air versus Humidity and Temperature," NASA Contractor Rept. (to be published).

4000 Hz, and Tables V and VI for 6300 Hz. Figure 5 shows the results of this study of total attenuation coefficient versus humidity for sound in air at one of the above temperatures (20°C). This information is presented in another form for other values of temperature and humidity in Fig. 6.

The effect of temperature on curves of sound absorption versus humidity at constant frequency is illustrated in Fig. 7, which presents absorption data for a frequency of 4000 Hz. Here the total attenuation coefficient m is plotted as a function of humidity for different values of temperature. Note that (1) the maximum value of absorption increases with increasing temperature, and (2) the peak in the curves shifts to a lower

value of relative humidity as the temperature increases. Figure 8 shows curves of absorption versus temperature for constant values of frequency—all for a relative humidity of 50%.

IV. APPLICATION OF RESULTS TO ROOM ACOUSTICS AND PROPAGATION PROBLEMS

A. Propagation of Sound in Air

For problems concerned with the propagation of sound in air, it is convenient to express attenuation of sound in terms of decibels per unit distance. Values of
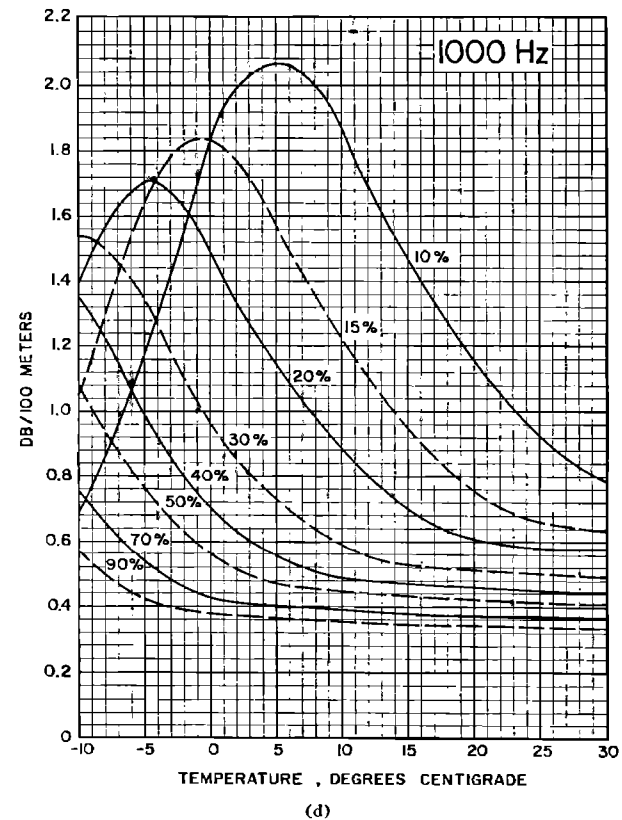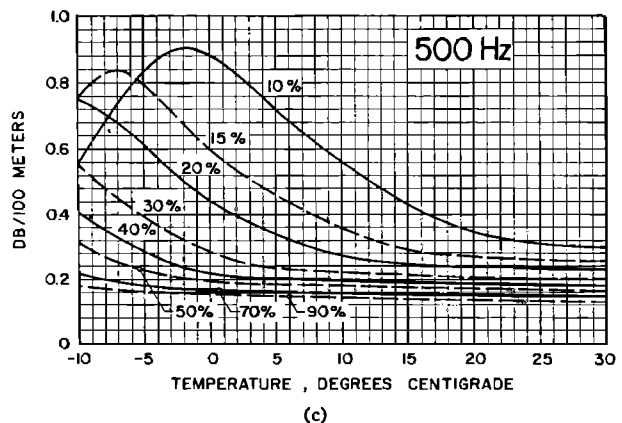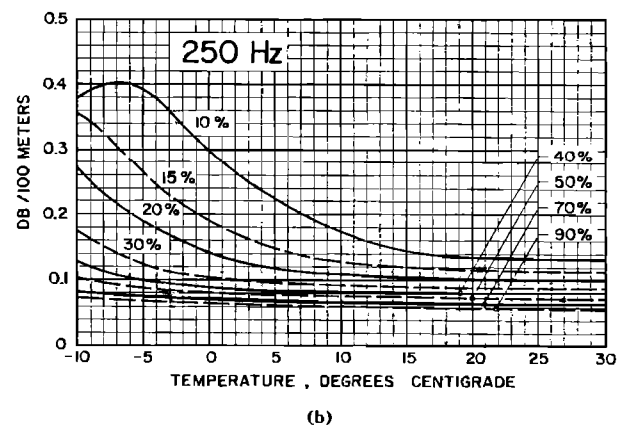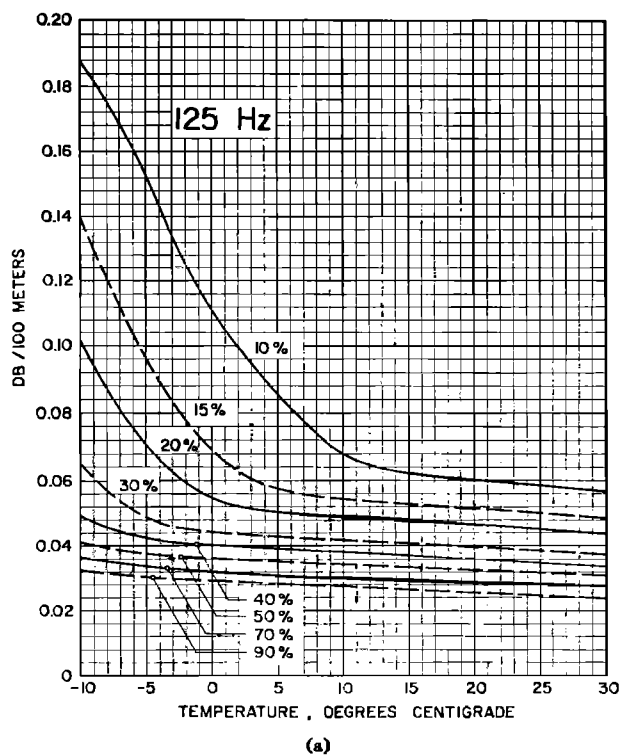

FIG. 6. Attenuation of sound in air versus temperature for various values of relative humidity. The attenuation is given in dB/100 meters.

attenuation in decibels per meter are obtained by multiplying the total attenuation coefficient by 4.343. This information has been tabulated in full in Ref. 20, both in the metric and English systems of units. Some of these data are plotted in Fig. 6, which gives the attenuation in decibels per 100 meters as a function of temperature for various values of relative humidity. This represents the attenuation of a plane wave in a homogeneous medium owing only to air absorption. This is the attenuation in excess of the loss due to spherical divergence, which is 6 dB for each doubling of the distance from

the source, so that it is sometimes referred to as "excess attenuation." It does not include losses due to other factors such as scattering.

B. Calculation of Reverberation Time

In calculating the reverberation time of a room, the total absorption in the room is required. This total is the sum of the absorptions due to the losses at the boundaries, to the furnishings in the room, and to air absorption. The absorption due to losses in air usually is important only in large rooms and/or at high frequencies, and is given by $4mV$. This term represents the area of a perfectly absorptive surface that is equivalent to the absorption of sound in air in a room of volume V. The product $4m$ is given in Tables I through VI in the metric and English systems of units for 2000, 4000, and 6300 Hz. These values need only be multiplied by the volume of the room to determine the values of air absorption.

Example. Suppose that a room has a volume of 1 000 000 ft³ (28 320 m³) and is at a temperature of 20°C and a relative humidity of 47%. Find the absorption in the room owing to air at a frequency of 4000 Hz. From Table III, the product $4m$ for these conditions equals 0.0077 ft⁻¹. Multiplying by the volume 1 000 000 ft³, we obtain a total absorption of 7700 sabins. An equivalent result is obtained in the metric system from Table IV if we use a value of $4m$ equal to 0.0253 m⁻¹ and multiply by a volume of 28 320 m^3 to obtain the total absorption in metric sabins.

C. Corrections to Reverberation-Time Measurements

As indicated by the data of Tables I–VI, the contribution to the rate of decay of sound in a large room owing to air absorption is significant at higher frequencies and it varies with humidity and temperature. One source of discrepancy in the measured values of reverberation time of the same auditorium by different investigators may be attributed to differences, during the measurements, of temperature and humidity conditions. The following procedure is suggested to correct this possible source of discrepancy, and to provide an improved basis for the comparison of reverberation-time data for various large halls at higher frequencies. *In presenting reverberation-time data for large auditoriums, irrespective of the humidity and temperature at which measurements are made, correct the reverberation time so that it represents the reverberation time that would have been obtained if the measurements had been made at a relative humidity of 50% and a temperature of 20°C, i.e., standard conditions.* This correction may be made as follows. Subtract the decay rate due to air absorption for the actual measurement conditions from the rate of decay at 20°C and 50% R.H. This difference is to be added to the measured value of the rate of decay of sound in the
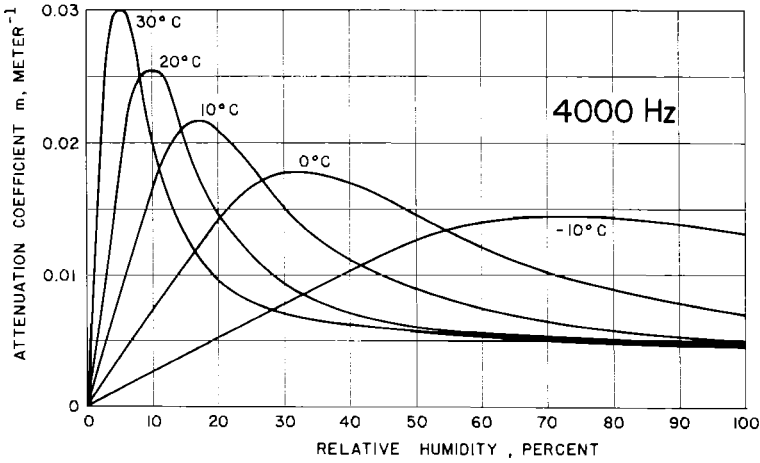
(e)

(f)
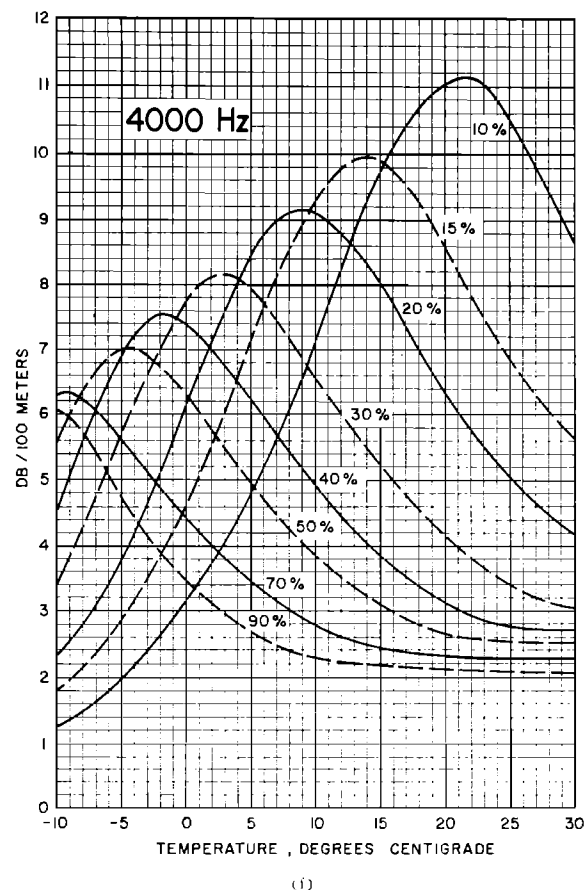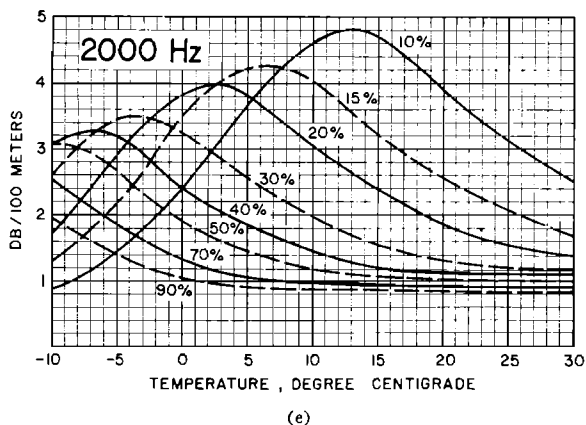
FIG. 7. Values of total attenuation coefficient *m* verus humidity for a frequency of 4000 Hz at temperatures of −10°, 0°, 10°, 20°, and 30°C.

room. From this corrected decay rate, compute the corrected reverberation time.

Example. Suppose that reverberation-time measurements are made in an auditorium at a temperature of 25°C and a relative humidity of 80%. At 4000 Hz, the measured value of the reverberation time is 2.10 sec. What would the reverberation time be under "standard condition" (20°C, 50% R.H.)?

Step 1: Calculate the measured decay rate:

$$R_{\text{measured}} = 60 \text{ dB}/2.10 \text{ sec} = 28.57 \text{ dB/sec}. \quad (7)$$

Step 2: Subtract the decay rate due to air absorption at a relative humdity of 50% and a temperature of 20°C (obtained from Tables VII, VIII, and IX) from the decay rate due to air absorption under measurement conditions. For a frequency of 4000 Hz, the rate of decay due to air absorption at 25°C and 80% R.H. is 7.57 dB/sec; at "standard conditions" of 20°C, 50% R.H., the corresponding value is 9.11 dB/sec. Subtracting, the difference R_D is −1.54 dB/sec.

Step 3: Add the value of R_D obtained in Step 2 to the measured rate of decay. This represents the decay rate corrected to normal conditions.

$$R_{\text{corrected}} = R_{\text{measured}} + R_D = 28.57 \text{ dB/sec} - 1.54 \text{ dB/sec}$$
$$= 27.03 \text{ dB/sec} \quad (8)$$

Therefore, the reverberation time under standard conditions is

$$t_{60} = 60 \text{ dB}/27.03 \text{ dB/sec} \simeq 2.2 \text{ sec}. \quad (9)$$

D. Corrections to Measurements of Sound-Absorption Coefficients

According to Eq. 2, the rate of decay of sound in a test chamber (or a room) may be represented as the sum of two terms: (1) the rate of decay of sound owing to air absorption, and (2) the rate of decay of sound resulting from absorption at the boundaries. Thus, if measurements of the absorption coefficients of an acoustical material are made in a reverberation chamber, at higher
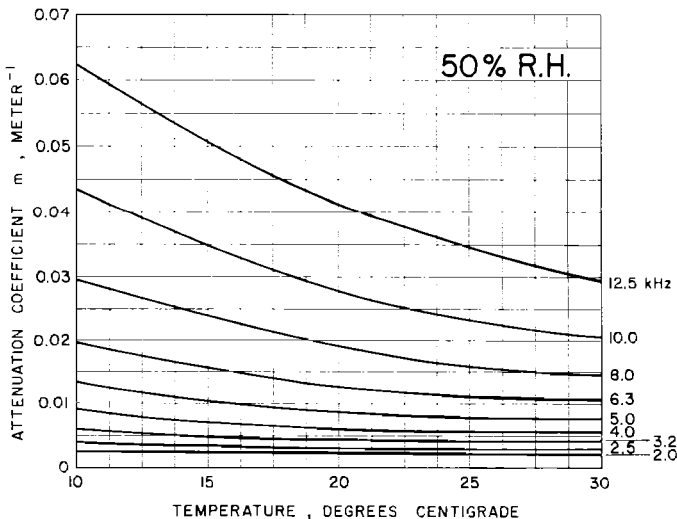

FIG. 8. Values of total attenuation coefficient *m* versus temperature for constant values of frequency. All data are for a relative humidity of 50%.

Table VII. Values of the decay rate of sound in a room owing to the contribution of air absorption, at various values of temperature and relative humidity. These data, expressed in dB/sec, are for a frequency of 2000 Hz.

R.H.	TEMPERATURE			
(%)	15°C (59.0°F)	20°C (68.0°F)	25°C (77.0°F)	30°C (86.0°F)
30	5.29	4.43	4.27	4.22
40	4.10	3.87	3.87	3.80
45	3.85	3.71	3.71	3.62
46	3.79	3.69	3.68	3.59
47	3.75	3.66	3.65	3.57
48	3.71	3.63	3.63	3.54
49	3.67	3.61	3.60	3.52
50	3.64	3.58	3.57	3.50
51	3.62	3.56	3.55	3.47
52	3.59	3.53	3.52	3.45
53	3.57	3.51	3.49	3.43
54	3.55	3.49	3.47	3.41
55	3.53	3.47	3.44	3.39
60	3.42	3.36	3.33	3.29
70	3.25	3.17	3.16	3.12
80	3.10	3.01	3.02	2.97

Table IX. Values of the decay rate of sound in a room owing to the contribution of air absorption, at various values of temperature and relative humidity. These data, expressed in dB/sec, are for a frequency of 6300 Hz.

R.H.	TEMPERATURE			
(%)	15°C (59.0°F)	20°C (68.0°F)	25°C (77.0°F)	30°C (86.0°F)
30	39.01	31.30	25.76	21.37
40	29.24	23.25	19.60	17.62
45	25.84	20.73	17.81	16.67
46	25.20	20.29	17.53	16.55
47	24.65	19.85	17.29	16.44
48	24.14	19.46	17.05	16.34
49	23.62	19.10	16.88	16.23
50	23.14	18.76	16.70	16.13
51	22.68	18.43	16.53	16.03
52	22.26	18.14	16.37	15.93
53	21.85	17.85	16.23	15.82
54	21.46	17.59	16.07	15.73
55	21.09	17.35	15.89	15.65
60	19.39	16.18	15.32	15.24
70	16.78	14.87	14.60	14.53
80	15.06	14.00	14.02	13.92

frequencies—where air absorption is significant—an error in evaluating the absorption coefficients will result unless the contribution to the total decay caused by air absorption is subtracted out. If this correction is made, then one should obtain the same value of absorption coefficient for the material under test even if

Table VIII. Values of the decay rate of sound in a room owing to the contribution of air absorption, at various values of temperature and relative humidity. These data, expressed in dB/sec, are for a frequency of 4000 Hz.

R.H.	TEMPERATURE			
(%)	15°C (59.0°F)	20°C (68.0°F)	25°C (77.0°F)	30°C (86.0°F)
30	17.96	14.14	11.77	10.67
40	13.22	10.70	9.66	9.50
45	11.74	9.70	9.15	9.15
46	11.48	9.56	9.07	9.08
47	11.24	9.42	9.03	9.01
48	10.99	9.32	8.97	8.95
49	10.77	9.21	8.91	8.90
50	10.57	9.11	8.85	8.84
51	10.38	9.02	8.79	8.78
52	10.20	8.94	8.73	8.72
53	10.03	8.84	8.67	8.67
54	9.87	8.73	8.62	8.61
55	9.73	8.65	8.57	8.55
60	9.03	8.36	8.33	8.31
70	8.23	7.94	7.92	7.85
80	7.71	7.61	7.57	7.50

measured under different conditions of humidity and temperature. Such a correction can be made conveniently by the use of Tables VII–IX. For example, suppose that measurements at 4000 Hz are made in a reverberation chamber at a temperature of 25°C and a relative humidity of 80%. According to Table VIII, the rate of decay due to sound absorption in air R_{air} is 7.57 dB/sec. According to Eq. 2, the measured decay rate is equal to the sum of the decay rate due to absorption at the boundaries of the room and due to air absorption. Thus, if the measured value of the rate of decay is 22.10 dB/sec, the actual decay rate corrected for air absorption is $(22.10-7.57) \approx 13.5$ dB/sec. Thus it is possible to correct for air absorption in measuring the absorption coefficient of a material in a reverberation chamber. Such a procedure has been proposed in Committee C-20 of the American Society for Testing Materials.[21]

ACKNOWLEDGMENT

[21] R. Huntley, personal communication.