HANDBOOK OF THE SPEED OF SOUND IN REAL GASES

Volume 3

Allan J. Zuckerwar

Handbook of the Speed of Sound in Real Gases

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VOLUME III Speed of Sound in Air

Allan J. Zuckerwar

with a chapter on Air Sound Speed Measurement and Computation: A Historical Review *by George S. K. Wong, National Research Council of Canada*

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CONTENTS

PREFACE

Volume III is dedicated to the speed of sound in air, a gas mixture that will serve as a model for predicting the speed of sound in other gas mixtures. The underlying principles for predicting the sound speed of individual gases generally apply to gas mixtures, but the property data for individual gases are adequate to determine only some properties of the mixture, like specific heat ratio and molar mass, but inadequate to determine others, like compressibility and relaxation. In the latter cases interaction terms are needed, which generally are of limited availability and then over only a limited range. Further, relaxation in air is based on an *ad hoc* theory that has not been applied, to the author's knowledge, to other gas mixtures; in most cases the treatment of Chapter 5 will serve as an alternative. This volume contains theory, measurements, and sound speed tables for air over wide ranges of temperature, pressure, humidity, and frequency. It can be read as a ''stand-alone'' volume, for the reader will find the necessary formulas and gas data without having to refer to the previous volumes. The closing chapter is a historical survey of the speed of sound in air by George S. K. Wong.

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Allan J. Zuckerwar

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CHAPTER 16

Speed of Sound in Air

16.1 INTRODUCTION

Volume III is dedicated in its entirety to the speed of sound in air, a gas mixture of obvious biological, meteorological, and industrial importance. As a gas mixture, it will serve as a model for predicting the speed of sound in other gas mixtures.

Human interest in the speed of sound in air can be traced back to antiquity [1] and remains vibrant to this day. A historical overview of acoustical measurements in air will be presented by G. S. K. Wong in Chapter 17.

The various designations of air are defined in Section 16.2. The composition of air and its variability are discussed in Section 16.3, with emphasis on the variability of carbon dioxide and water vapor content.

A generalized treatment of the physical properties of a mixture in terms of the properties of its individual constituents is presented in Section 16.4. In particular, the mixing rules for determining the mass of air and the supporting parameters of the speed of sound in air — specific heat, virial *B*- and *C*-coefficients, relaxation time, and relaxation strength — follow. Section 16.5 provides an analytical expression for the speed of sound in air that will prove valid over wide ranges of

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humidity, pressure, temperature, and acoustic frequency, and will conclude with an estimate of the uncertainty.

Section 16.6 is a series of reviews of measurements taken from selected literature sources. Each of these provides experimental values that are utilized to determine the speed of sound under standard conditions—273.15 K, 1 atm, zero humidity, and zero frequency.

The chapter concludes with a set of tables listing the speed of sound in air for selected values of humidity (0–100% relative humidity), pressure (0.5–100 atm), temperature (233–603 K), and acoustic frequency (0–100 kHz), together with estimated uncertainties (Section 16.7).

16.2 DESIGNATIONS OF AIR

Acoustical considerations require that one distinguish among several designations of air, namely, *standard air*, *CO_2-free air*, and *atmospheric air*. Standard air "is assumed to represent the relative concentrations of the several gas species comprising dry air at sea level" [2, 3]. The composition will be detailed in Section 16.3.1. CO_2-free air is standard air with the carbon dioxide removed, as the name implies. The reasons for including this composition will be given in Section 16.3.2. Atmospheric (real) air is standard air with the addition of water vapor, discussed in Section 16.3.3.

16.3 COMPOSITION OF AIR

16.3.1 MOLE FRACTIONS OF CONSTITUENTS IN A VARIABLE MIXTURE

A listing of the leading constituents of standard air, their molar masses, and mole fractions appears in Table 16.1; however, the composition of atmospheric air varies with geography, time, and altitude above Earth's surface. The constituents that reveal the greatest variability are carbon dioxide and water vapor.

Let x_i be the mole fraction of the ith constituent of a multiconstituent mixture, defined by

$$x_i = \frac{n_i}{n}(i = 1, 2, \ldots) \tag{16.1}$$

where n_i and n are the molar densities (per unit volume) of the ith constituent and total composition, respectively. Then it must be true that

$$\sum x_i = 1. \tag{16.2}$$

If an additional constituent having a molar density n_a and mole fraction x_a is added to the mixture, then the original constituents will assume new mole fractions x_i'.

TABLE 16.1 Constituents of Standard Air: Molar Mass, Mole Fraction, and Mass Contribution[a]

Constituent	Molar mass (g/mol)	Mole fraction	Mass contribution (g/mol)
Nitrogen	28.01348	0.78084	21.874046
Oxygen	31.9988	0.209476	6.7029806
Argon	39.948	0.00934	0.3731143
Carbon dioxide	44.0095	0.000314	0.013819
Neon	20.1797	1.818×10^{-5}	0.0003669
Helium	4.002602	5.24×10^{-6}	2.097×10^{-5}
Krypton	83.8	1.14×10^{-6}	9.553×10^{-5}
Methane	16.04246	2×10^{-6}	3.208×10^{-5}
Hydrogen	2.01588	5×10^{-7}	1.008×10^{-6}
Xenon	131.29	8.7×10^{-8}	1.142×10^{-5}
Nitrous oxide	44.01288	2.7×10^{-7}	1.188×10^{-5}
Carbon monoxide	28.011	1.9×10^{-7}	5.322×10^{-6}
Total			28.9645

[a]Ref. 2.

It follows that

$$x_i' = \frac{n_i}{n + n_a} \tag{16.3}$$

$$x_a = \frac{n_a}{n + n_a}. \tag{16.4}$$

Upon substituting Eqs. (16.1) and (16.4) into (16.3) one can express the new mole fraction in terms of the original:

$$\begin{aligned} x_i' &= \frac{n_i}{n + n_a} = \frac{x_i n}{n + n_a} = x_i \frac{n + n_a - n_a}{n + n_a} \\ &= x_i(1 - x_a). \end{aligned} \tag{16.5}$$

If, on the other hand, a constituent having a mole fraction x_a is removed from the mixture, the roles of x_i and x_i' are reversed. It follows that

$$x_i' = \frac{x_i}{1 - x_a} \tag{16.6}$$

where now x_i' represents the mole fraction after the constituent is removed.

16.3.2 Variability of Carbon Dioxide Content

This section will consider *CO_2-free air* and the *long-term variability* of carbon dioxide in Earth's atmosphere. CO_2-free air is of interest for two reasons. First, it serves as a convenient baseline for updating the composition of air with ever-increasing carbon dioxide content. Second, many sound speed measurements in

TABLE 16.2 Mole Fraction of Constituents in Dry CO_2-Free Air and Dry 1999 Air

Constituent	Mole fraction in CO_2-free air	Mole fraction in 1999 air
Nitrogen	0.78109	0.78080
Oxygen	0.20954	0.20946
Argon	0.009343	0.009339
Carbon dioxide	0	0.000368
Neon	1.819×10^{-5}	1.818×10^{-5}
Helium	5.242×10^{-6}	5.240×10^{-6}
Krypton	1.140×10^{-6}	1.140×10^{-6}
Methane	2.001×10^{-6}	2.000×10^{-6}
Hydrogen	5.002×10^{-7}	5.000×10^{-7}
Xenon	8.703×10^{-8}	8.700×10^{-8}
Nitrous oxide	2.701×10^{-7}	2.700×10^{-7}
Carbon monoxide	1.901×10^{-7}	1.900×10^{-7}

the past were conducted in air with the carbon dioxide removed. The composition of CO_2-free air, based on Eq. (16.6) and the original mole fractions listed in Table 16.1, appears in Table 16.2.

The long-term increase in carbon dioxide content, spanning an interval of over 40 years, is shown in Fig. 16.1 [4]. In 1958 the carbon dioxide mean mole fraction was 314 ppm; in 1999 it increased to 368 ppm. The average increase amounts to 13 ppm per decade, with no abatement in sight. The Standard Air value of

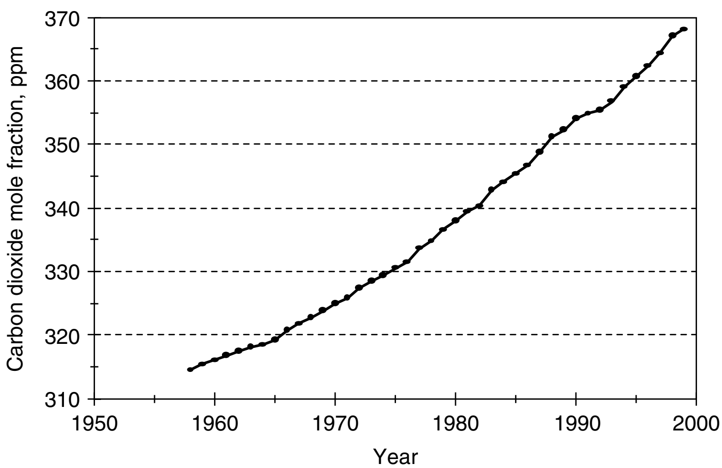

FIGURE 16.1 Mean annual mole fraction of carbon dioxide in dry air from 1958 to 1999.

314 ppm is based on the 1958 listing. The composition of 1999 air, based on Eq. (16.5), is given in Table 16.2. Here the mole fractions of CO_2-free air, listed in the second column, serve as the original mole fractions. The impact upon the speed of sound will be discussed in Section 16.5.7.

16.3.3 VARIABILITY OF WATER VAPOR CONTENT

Unlike carbon dioxide, water vapor exhibits familiar short-term variability in Earth's atmosphere and must be monitored continually during the course of an experiment. (This is also good practice during a laboratory experiment.) Water can exist as a liquid from the triple point (273.16 K, 0.006 atm) to the critical point (647.1 K, 217.6 atm). Supercooled water can exist at temperatures considerably below the triple point but then is not in thermodynamic equilibrium; however, vapor pressure tables used in acoustics commonly list saturation pressures over water rather than over ice at temperatures below the triple point.

Key terms related to water vapor content are defined as follows:

The *mole fraction* x_h of water vapor in a gas mixture is the ratio of the number of moles of water vapor to the total number of moles in the mixture.

The *relative humidity* h_r is the ratio of the mole fraction of water vapor to the mole fraction x_{sat} of water vapor at saturation:

$$h_r = \frac{x_h}{x_{sat}}. \tag{16.7}$$

The *vapor pressure* $P_{sat}(T)$ is the pressure of water vapor on the saturation line. It is the maximum pressure of water vapor that can exist in equilibrium at a given temperature.

The *dew point* T_d is the temperature of water vapor on the saturation line. It is the minimum temperature at which a given molar content of water can exist in equilibrium as a vapor without condensation.

The *enhancement factor* $f_e(P, T)$ is a correction to the mole fraction of water vapor in air due to the nonideality of the latter.

The goal of this section is to determine the mole fraction of water vapor, the quantity appearing in acoustical equations of interest, from knowledge of the temperature, pressure, and humidity.

The humidity can be determined by measurement of either the relative humidity or dew point. The relative humidity is measured with a wet bulb–dry bulb hygrometer or by any of various absorption hygrometers. In this case the mole fraction is determined by

$$x_h = h_r f_e(P, T)\frac{P_{sat}(T)}{P}. \tag{16.8}$$

The dew point T_d is measured with a dew point hygrometer. In terms of the dew point the mole fraction is found to be

$$x_h = f_e(P, T_d)\frac{P_{sat}(T_d)}{P}. \tag{16.9}$$

The remaining issues are to determine the vapor pressure and the enhancement factor.

The vapor pressure can be found from any of several available tables or from an equation describing the saturation line. It will be expressed here in atmospheres. Selected examples are presented in Table 16.3.

Haar, Gallagher, and Kell list values of water vapor pressure versus temperature in tabular form [5] in steps of 1 K with an uncertainty specification of 120 ppm (0.012%). Their values will serve as the basis for comparison with the analytical values derived from the equations to follow.

The four-constant version of Wexler's equation [6] is

$$\begin{aligned} P_{sat} = [&\exp(1.2811805 \times 10^{-5}T^2 - 1.9509874 \times 10^{-2}T \\ &+ 34.04926034 - 6353.6311/T)]/101325 \end{aligned} \tag{16.10}$$

which is limited to the temperature range 273.15–373.15 K. The uncertainty varies with temperature, having a maximum of 43 ppm at 298.15 K. The uncertainty limits overlap those of Ref. 5 over the specified temperature range. Giacomo [7] and Cramer [8] refer to this equation in studies of density and sound absorption in humid air.

The International Standard ISO 9613-1 specifies an equation based on calculations by the World Meteorological Association [9]. Because of the use of tiered exponentials it is written here in the following form:

$$\log_{10}(P_{sat}) = -6.8346 \times (273.16/T)^{1.261} + 4.6151 \tag{16.11}$$

where P_{sat} is expressed in atmospheres. The values computed from this equation differ from those listed in Ref. 5 by 0.7% at 373.15 K. The difference reaches a maximum of 2.55% at 493.15 K and then declines steadily over the remaining temperatures in the table.

The American National Standard ANSI S1.26-1995 utilizes another equation attributed to the World Meteorological Association [10], written in a similar form:

$$\begin{aligned} \log_{10}(P_{sat}) = {} & 10.79586[1 - (273.16/T)] \\ & - 5.02808 \log_{10}(T/273.16) \\ & + 1.50474 \times 10^{-4}\left\{1 - 10^{-8.29692[(T/273.16)-1]}\right\} \\ & + 4.2873 \times 10^{-4}\left\{-1 + 10^{4.76955[1-(273.16/T)]}\right\} \\ & - 2.2195983. \end{aligned} \tag{16.12a}$$

TABLE 16.3 Vapor Pressure of Water According to Selected Sources

Temperature (K)	Vapor pressure (atm)		
	Wexler[a] 1976	ISO 9613-1[b] 1993	ANSI S1.26[c] 1995
273.15	0.006032	0.006028	0.006027
283.15	0.01212	0.01211	0.01211
293.15	0.02308	0.02306	0.02306
303.15	0.04190	0.04186	0.04187
313.15	0.07285	0.07280	0.07281
323.15	0.12183	0.12182	0.12177
333.15	0.19672	0.19687	0.19665
343.15	0.30770	0.30830	0.30760
353.15	0.46756	0.46917	0.46746
363.15	0.69203	0.69562	0.69196
373.15	0.99997	1.00715	1.00000
383.15	1.41364	1.42679	1.41388
393.15	1.95877	1.98133	1.95944
403.15	2.66472	2.70136	2.66621
413.15	3.56457	3.62130	3.56747
423.15	4.69509	4.77932	4.70040
433.15	6.09687	6.21724	6.10611
443.15	7.81426	7.98027	7.82973
453.15	9.89549	10.1168	9.92058
463.15	12.3927	12.6781	12.4323
473.15	15.3621	15.7179	15.4229
483.15	18.8640	19.2921	18.9554
493.15	22.9633	23.4583	23.0979
503.15	27.7298	28.2752	27.9240
513.15	33.2381	33.8026	33.5135
523.15	39.5688	40.1008	39.9527
533.15	46.8087	47.2297	47.3356
543.15	55.0517	55.2494	55.7643
553.15	64.3994	64.2188	65.3503
563.15	74.9626	74.1959	76.2152
573.15	86.8618	85.2371	88.4922
583.15	100.229	97.3974	102.328
593.15	115.209	110.729	117.882
603.15	131.962	125.284	135.332

[a]Ref. 6.
[b]Ref. 9.
[c]Refs. 10, 11.

This equation is said to have an uncertainty of 0.04% for $233 < T < 273$ and of 0.06% for $T > 273$ [11]; however, the equation yields a value that differs from that in the table of Ref. 5 by 0.08% at 283.15 K. The difference remains less than 0.1% up to a temperature of 423.15 K and then gradually increases to 6% at 603.15 K.

For purposes of this handbook, Eq. (16.12a) will be used to compute the vapor pressure. It is enjoying widespread use in computations of the relaxation frequencies in humid air as specified by the same standard, and it is the only source having an uncertainty specification at temperatures below 273.15 K. The saturation curve based on Eq. (16.12a) is shown in Fig. 16.2.

The uncertainty in the saturation pressure contains contributions from the uncertainty in the original values (120 ppm) and the uncertainty due to the misfit between ANSI and Haar et al. The former contribution is small and will be neglected. A simple but conservative formulation that accounts for the uncertainty trend just described is the following:

$$\begin{aligned}\frac{\delta P_{sat}}{P_{sat}} &= 0.1\%, \quad T \leq 470\ \text{K} \\ &= [-0.74 + 0.042(T - 450)]\%, \quad T > 470\ \text{K}. \qquad (16.12\text{b})\end{aligned}$$

The vapor pressure relationships presented here apply to water as an individual substance and must be modified for mixtures of water vapor and air. At a given temperature and pressure, the nonideality of air influences the mole fraction of water vapor. The subject is treated in detail by Hyland [12]. Starting with an expression for the Gibbs free energy in terms of the virial coefficients, including the cross terms, he derives a transcendental equation and solves it for the mole fraction of dry air and hence the enhancement factor. The resulting tables cover the pressure range 0.25 to 100 bar and the temperature range 193.15 to 363.15 K (−80 to 90 °C), although only data at 233.15 K (−40 °C) and above will be utilized here.

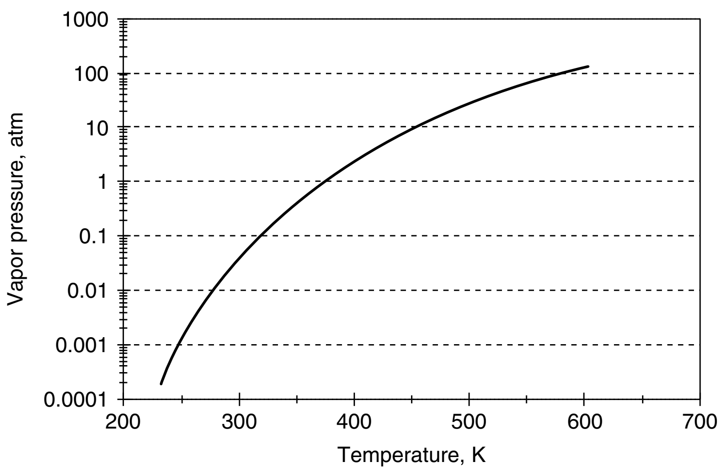

FIGURE 16.2 The saturation curve of water vapor according to ANSI S1.26-1995 [10].

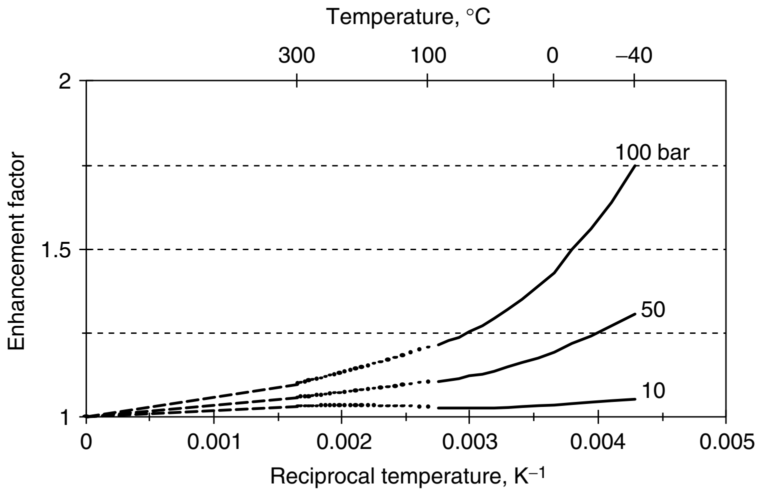

FIGURE 16.3 Enhancement factor versus reciprocal temperature along the 100-, 50-, and 10-bar isobars. Solid lines: data taken from Ref. 12, 233.15 to 363.15 K (−40 to 90 °C). Dotted lines: Lagrange three-point interpolation using (0,1) as an end point, 363.15 to 603.15 K (90 to 330 °C). Dashed lines: region beyond the range considered in this handbook.

In Fig. 16.3 the enhancement factor is plotted against reciprocal temperature along three different isobars (100, 50, 10 bar). The solid lines are plots of the data listed in Hyland's tables, which are limited to a maximum temperature of 363.15 K (90 °C). For handbook purposes it is desirable to have values conforming to the temperature range of the predicted sound speed, somewhat beyond 600 K. The key to extending the temperature range is based on the physical fact that in the limit of infinite temperature the enhancement factor must approach unity (as the gases approach ideality). The dotted lines in the figure are obtained from a sliding Lagrange three-point interpolation, where one end point is always kept at the high-temperature limit ($f_e = 1$ at $1/T = 0$). The dashed lines fall within a range of temperatures not considered in this handbook.

For convenience, the pressures listed in Hyland's tables are revised to designate atmospheres, and the enhancement factors are accordingly adjusted by an interpolation procedure. Along each isobar the temperature dependence of the enhancement factor is fitted to a polynomial of the form

$$\ln(f_e) = a_e(0) + \frac{a_e(1)}{T} + \frac{a_e(2)}{T^2}. \tag{16.13a}$$

Values of the coefficients in Eq. (16.13) are listed in Table 16.4 for selected isobars. A comparison of the best fit of the tabular and interpolated data to Eq. (16.13) along the 100-atm isobar is shown in Fig. 16.4.

TABLE 16.4 Coefficients of Eq. (16.13a) for the Natural Logarithm of the Enhancement Factor Along Selected Isobars

Pressure (atm)	Coefficient		
	$a_e(0)$	$a_e(1)$	$a_e(2)$
0.5	−0.00102	0.3503	136.34
1	−0.00201	0.8446	231.06
2	0.01272	−1.92212	217.09
5	0.05685	−25.6409	4177.29
10	0.07699	−37.9880	7372.09
20	0.09474	−51.2165	12330.9
50	0.11944	−78.1289	26101.4
100	0.22372	−163.3002	55803.2

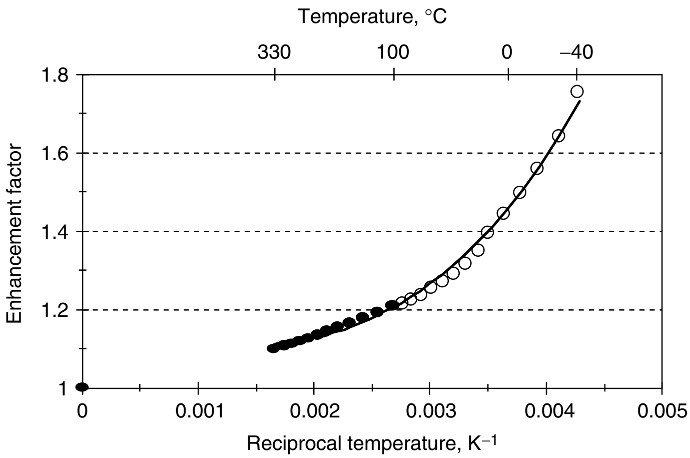

FIGURE 16.4 Enhancement factor versus reciprocal temperature along the 100-atm isobar. Open circles: data of Ref. 12. Filled circles: interpolated data using (0, 1) as an end point. Solid line: best fit to Eq. (16.13a).

As may be inferred from Fig. 16.3, the enhancement factor becomes significant only at high pressures. At a pressure of 1 atm, the enhancement factor changes the mole fraction of water vapor by less than 1% over the entire temperature range.

It is readily verified that the enhancement factor has a nearly exponential dependence upon the pressure. Therefore, for interpolation between pressures P_1 and P_2 along an isotherm the following interpolation formula is recommended for finding f_e at an intermediate pressure P:

$$\ln[f_e(P)] = \frac{(P - P_2)}{(P_1 - P_2)} \ln[f_e(P_1)] + \frac{(P - P_1)}{(P_2 - P_1)} \ln[f_e(P_2)]. \qquad (16.13b)$$

As pointed out by Hyland [12], the enhancement factor loses meaning under saturation equilibrium conditions, for according to Eq. (16.8) such would lead to the absurd requirement that $P_{sat} > P$ (or $x_h > 1$) since $f_e > 1$. Therefore, there is a constraint on the maximum saturation pressure for which Eq. (6.8) is valid:

$$\frac{P_{sat}}{P} < \frac{1}{f_e}. \tag{16.13c}$$

The uncertainty in f_e, comprising contributions from the original data and from an imperfect fit, depends strongly on both temperature and pressure. At low pressures the uncertainty is dominated by the imperfect fit, in which case one must refer directly to Hyland's tables [12] to improve the accuracy. Because at temperatures above 363.15 K the enhancement factor itself lies close to unity, a small uncertainty will have little impact upon the sound speed and can be neglected. Then, the uncertainty in f_e can be conveniently represented as

$$\begin{aligned}\frac{\delta f_e}{f_e} &= \frac{P}{100}\,[1.04 - 0.043(T - 363.15)]\,\%, \quad T \le 363.15\ \text{K}\\ &= 0, \quad T > 363.15\ \text{K}\end{aligned} \tag{16.14}$$

where P is in atm. As an example consider air at 363.15 K (90 °C) and 50% relative humidity. Find the mole fraction of water vapor at 50, 60, and 100 atm.

From Eq. (16.12) the saturation vapor pressure for water as an individual gas is found to be

$$P_{sat} = 0.6920\ \text{atm}. \tag{16.15a}$$

From Eq. (16.13a) and Table 16.4 one finds the enhancement factor at the tabulated pressures:

$$\begin{aligned}P = 50\ \text{atm}, \ln(f_e) &= 0.11944 - 78.1289/363.15 + 26101.4/(363.15)^2\\ &= 0.1022\\ f_e &= \exp(0.1022) = 1.1076.\end{aligned} \tag{16.15b}$$

$$\begin{aligned}P = 100\ \text{atm}, \ln(f_e) &= 0.22372 - 163.3002/363.15 + 55803.2/(363.15)^2\\ &= 0.1972\\ f_e &= \exp(0.1972) = 1.2180.\end{aligned} \tag{16.15c}$$

The value of f_e at 60 atm must be interpolated. From Eq. (16.13b) one finds

$$\begin{aligned}P = 60\ \text{atm}, \ln(f_e) &= \frac{60-100}{50-100} \times 0.1022 + \frac{60-50}{100-50} \times 0.1972 = 0.1212\\ f_e &= \exp(0.1212) = 1.1289\end{aligned} \tag{16.15d}$$

which agrees well with Hyland's tabulated value of 1.128.

One obtains the mole fraction from Eq. (16.8):

$$P = 50\ \text{atm}, x_h = 0.5 \times 1.1076 \times 0.6920/50 = 0.00766$$
$$P = 100\ \text{atm}, x_h = 0.5 \times 1.2180 \times 0.6920/100 = 0.00421$$
$$P = 60\ \text{atm}, x_h = 0.5 \times 1.1289 \times 0.6920/60 = 0.00651. \quad (16.15e)$$

The uncertainty in mole fraction is due to uncertainties in saturation pressure and enhancement factor. The uncertainty in the saturation pressure is obtained from Eq. (16.12b). Because the temperature is less than 450 K, the uncertainty is simply 0.1%. The uncertainty in the enhancement factor is obtained from Eq. (16.14). The resulting uncertainties are 0.52% at 50 atm, 1.04% at 100 atm, and 0.62% at 60 atm. The uncertainty of the enhancement factor is clearly the dominant contribution in this example.

16.4 THE MIXING RULES

The purpose of this section is to determine a property Y of a mixture from known values of the property Y_i of its individual constituents.

16.4.1 General

Many properties of a mixture can be represented as

$$Y = \sum_i Y_i x_i \quad (i = 1, 2, \ldots) \quad (16.16)$$

where the summation is taken over the number of constituents in the mixture. The mole fractions x_i are subject to the constraint (16.2). Because the properties of dry air have been studied extensively and enjoy numerous tabulations, the approach taken here is to consider air as a binary mixture of standard air and water vapor. Then, for a binary mixture ($i = 1, 2$) Eq. (16.16) becomes

$$Y = Y_1 x_1 + Y_2 x_2 \quad (16.17)$$

which represents properties like the molar mass and specific heat; however, some properties mix according to higher powers of the mole fraction, for example,

$$Y = Y_{11} x_1^2 + Y_{12} x_1 x_2 + Y_{22} x_2^2 \quad (16.18)$$

if Y represents the virial B-coefficient, and

$$Y = Y_{111} x_1^3 + Y_{112} x_1^2 x_2 + Y_{122} x_1 x_2^2 + Y_{222} x_2^3 \quad (16.19)$$

if Y represents the virial-C coefficient. However, representations in polynomial form are not exclusive, as will be seen in the case of the relaxation times.

Standard air can be considered a binary mixture of CO_2-free air and CO_2. In this case the properties of the mixture are known, and the properties of a constituent can be determined. For example, Eq. (16.17) can be rearranged to yield

$$Y_1 = \frac{Y - Y_2 x_2}{x_1} = \frac{Y - Y_2 x_2}{1 - x_2} \tag{16.20}$$

where in this case Y_1 would represent a property of CO_2-free air and Y_2 the same property of CO_2.

In the remaining subsections the following subscripts to a property will be used: d for dry air, c for carbon dioxide, cf for CO_2-free air, h for water vapor, and no subscript for atmospheric air.

16.4.2 Molar Mass

The mass of dry air in terms of the masses of its constituents is obtained from Eq. (16.16):

$$M_d = \sum M_i x_i \tag{16.21}$$

in which the masses, mole fractions, and mass contributions are found in Table 16.1. The mass of CO_2-free air is found from Eqs. (16.20) and (16.21):

$$M_{cf} = \frac{M_d - M_c x_c}{1 - x_c} \tag{16.22}$$

where x_c is the mole fraction of CO_2 in standard air. The mass M'_d of 1999 air is found from Eqs. (16.17) and (16.22):

$$M'_d = M_{cf}(1 - x'_c) + M_c x'_c \tag{16.23}$$

where x'_c is the mole fraction of CO_2 in 1999 air. The mass of atmospheric air containing a mole fraction x_h of water vapor is found from Eq. (16.17):

$$M = M_d(1 - x_h) + M_h x_h. \tag{16.24}$$

The mass of air for each of the designations corresponding to Eqs. (16.21)–(16.24) is shown in Table 16.5. The listed standard air mass of 28.9645 g/mol (314) is somewhat smaller than the oft-cited value of Hilsenrath et al. [13] — 28.966 g/mol (300) — but greater than that of Giacomo [7] — 28.9635 g/mol (400), where the number in parentheses is the mole fraction of carbon dioxide in ppm. The smaller value of Giacomo is attributed to adjustments in the contents of nitrogen, oxygen, and argon that supersede those listed in Ref. 2.

TABLE 16.5 Molar Mass of Several Designations of Air

Designation	Symbol	Molar mass (g/mol)
Standard	M_d	28.9645
CO_2-free	M_{cf}	28.9598
1999	M_d'	28.9653
Atmospheric, saturated[a] at 273.15 K	M	28.8985
Atmospheric, saturated[b] at 293.15 K	M	28.7120

[a] Mole fraction of water vapor = 0.006027.
[b] Mole fraction of water vapor = 0.023064.

16.4.3 Specific Heat

As was explained in Chapter 3, the ideal specific heat of an individual gas, normalized to the universal gas constant, can be accurately represented by a polynomial of the following form [14]:

$$C_P^o/R = a_0 + a_1T + a_2T^2 + a_3T^3. \quad (16.25)$$

Values of the coefficients for dry air and water vapor are given in Table 16.6. The uncertainty specification is stated to be 0.5% for dry air and 1% for water vapor over the full range of temperatures. The ideal specific heat may be used here, instead of the real-gas specific heat, because real gas effects are lumped with the virial correction, which is to be discussed in the following subsection. Equation (16.25), together with the coefficients listed in Table 16.6, yields a value of 3.4960 for the normalized specific heat of dry air at 273.15 K.

If the specific heats of dry air and water vapor are found from Eq. (16.25) at a given temperature, then the specific heat of the mixture (i.e., humid air) can be

TABLE 16.6 Values of the Coefficients in Eq. (16.25) to Determine the Specific Heat C_P^o/R of Dry Air and Water Vapor [14]

	Dry air		Water vapor	
	Temperature range		Temperature range	
Coefficient	250–600 K	600–1500 K	270–800 K	800–1500 K
a_0	3.5623	3.0440	4.0996	3.4293
a_1	−0.0006128	0.001124	−0.001171	0.001391
a_2	1.401×10^{-6}	-1.249×10^{-7}	3.780×10^{-6}	3.006×10^{-7}
a_3	-1.696×10^{-10}	-6.935×10^{-11}	-1.817×10^{-9}	-1.618×10^{-10}

found from the mixing rule (16.17):

$$C_p^o = C_{pd}^o x_d + C_{ph}^o x_h \tag{16.26}$$

where the subscripts d and h designate dry air and water vapor, respectively. The simple specific heat ratio, ideal specific heat ratio, and specific heat correction become

$$\gamma_s = 1 + \left[\left(\frac{7}{2}\right)x_d + \left(\frac{8}{2}\right)x_h - 1\right]^{-1} \tag{16.27a}$$

$$\gamma_o = 1 + (C_p^o/R - 1)^{-1} = 1 + [(C_{pd}^o x_d + C_{ph}^o x_h)/R - 1]^{-1} \tag{16.27b}$$

and

$$K_c = (\gamma_o/\gamma_s) - 1 = \gamma_s^{-1}\{1 + [(C_{pd}^o x_d + C_{ph}^o x_h)/R - 1]^{-1}\} - 1. \tag{16.28}$$

For dry air the simple specific heat ratio is taken to be that of a diatomic gas, $\gamma_s = \frac{7}{5} = 1.4$.

It is of interest to compare the normalized specific heat computed from the polynomial formula (16.25) with that computed from the mixing rule (16.16):

$$C_{pd}^o/R = \sum_i \left(C_{pi}^o/R\right) x_i \tag{16.29}$$

in which the specific heats, mole fractions, and specific heat contributions are found in Table 16.7. The value 3.4949 obtained from Eq. (16.29) agrees with that obtained from (16.25) to within 0.03%.

TABLE 16.7 Constituents of Standard Air: Normalized Ideal Specific Heat, Mole Fraction, and Specific Heat Contribution at 273.15 K

Constituent	Normalized ideal specific heat C_{pi}^o/R	Mole fraction x_i	Ideal specific heat contribution$(C_{pi}^o/R)x_i$
Nitrogen	3.4986	0.78084	2.7318
Oxygen	3.5246	0.209476	0.73831
Argon	2.5	0.00934	0.02335
Carbon dioxide	4.3233	0.000314	0.0013575
Neon	2.5	1.818×10^{-5}	4.545×10^{-5}
Helium	2.5	5.24×10^{-6}	1.31×10^{-5}
Krypton	2.5	1.14×10^{-6}	2.85×10^{-6}
Methane	4.2114	2×10^{-6}	8.423×10^{-6}
Hydrogen	3.4172	5×10^{-7}	1.709×10^{-6}
Xenon	2.5	8.7×10^{-8}	2.175×10^{-7}
Nitrous oxide	4.5038	2.7×10^{-7}	1.216×10^{-6}
Carbon monoxide	3.5028	1.9×10^{-7}	6.655×10^{-7}
Total			3.4949

16.4.4 Virial

As mentioned in Section 16.4.3, the virial B-coefficient obeys the mixing rule (16.18), written here for the case of humid air:

$$B = B_{dd}(1 - x_h)^2 + 2B_{dh}(1 - x_h)x_h + B_{hh}x_h^2 \tag{16.30}$$

where B_{dd} and B_{hh} are the second virial coefficients of dry air and water vapor, and B_{dh} the ''interaction'' coefficient. The first two can be represented by the ''square-well'' function [Eq. (4.18), Vol. I]:

$$B_{dd} = a_d - b_d \exp(c_d/T) \tag{16.31a}$$

$$B_{hh} = a_h - b_h \exp(c_h/T). \tag{16.31b}$$

First, consider water vapor, which was first discussed in Chapter 4 of Vol. I. Values for the square-well constants for water vapor are found in Table 4.1:

$$a_h = 31.5\ \text{cm}^3/\text{mol}, b_h = 13.6\ \text{cm}^3/\text{mol}, c_h = 1375.3\ \text{K}.$$

These values are valid over the temperature range 423–1173 K. The function (16.31b) is plotted in Fig. 4.19a. For temperatures below 423 K values must be obtained by extrapolation.

For the second virial coefficient of dry air there is good agreement among various sources of data compilation [13, 15, 16, 17]. Hilsenrath et al. [13] and Levelt Sengers et al. [16] compile averaged data in tabular form, whereas Sychev et al. [15] and Davis [17] both provide a formula for the compressibility from which the virial coefficients can be extracted. The results are plotted in Fig. 16.5. The best fit to Eq. (16.31a), shown as a solid line, corresponds to the following constants in the equation:

$$a_d = 152.2\ \text{cm}^3/\text{mol}, b_d = 111.3\ \text{cm}^3/\text{mol}, c_d = 108.1\ \text{K}.$$

These constants are valid over the temperature range 230–650 K. The formula of Davis yields values (not shown) that agree with the others up to a temperature of about 340 K.

Data for the interaction coefficient B_{dh} are provided by Hyland [12] over a limited temperature range (223–343 K). Because of the electrostatic nature of the interaction energy between a water molecule and an oxygen or nitrogen molecule, it is reasonable to assume a square-well interaction energy, as in the case of homomolecular interactions. Then, the virial interaction coefficient can be written:

$$B_{dh} = a_{dh} - b_{dh} \exp(c_{dh}/T). \tag{16.32}$$

A fit to Hyland's data yields the following values of the parameters:

$$a_{dh} = 224.0\ \text{cm}^3/\text{mol}, b_{dh} = 184.6\ \text{cm}^3/\text{mol}, c_{dh} = 94.6\ \text{K}.$$

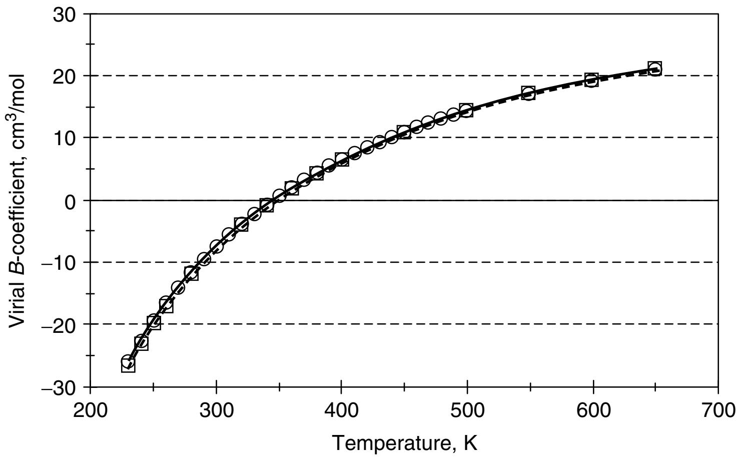

FIGURE 16.5 Virial B-coefficient of dry air. Circles: Ref. 13. Squares: Ref. 16. Dashed line: Ref. 15. Solid line: best fit, Eq. (16.31a).

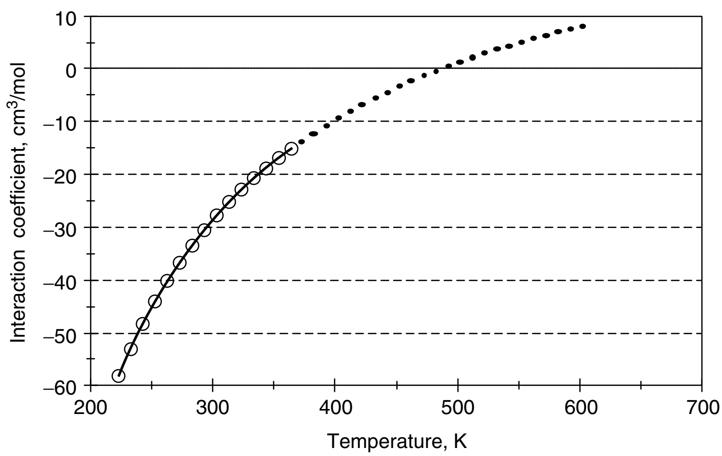

FIGURE 16.6 Second virial interaction coefficient B_{dh} of dry air and water vapor. Circles: Ref. 12. Solid line: best fit, Eq. (16.32). Dotted line: Extrapolation beyond range of data of Ref. 12.

A plot showing Hyland's data together with Eq. (16.32), using the preceding parameters, appears in Fig. 16.6. An extrapolation of Eq. (16.32) beyond the range of Hyland's data is shown as a dotted line.

The contributions to the total second virial coefficient of a dry air–water vapor mixture are shown in Fig. 16.7 at temperatures above the normal boiling point of

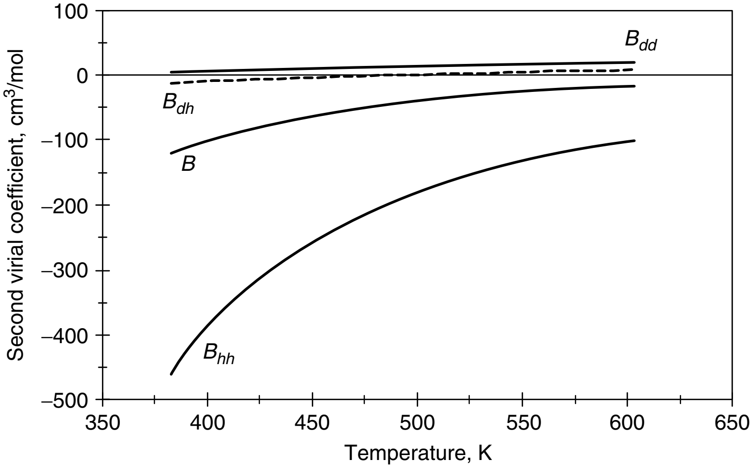

FIGURE 16.7 Second virial coefficients of dry air and water vapor: B_{dd} dry air, B_{hh} water vapor, B_{dh} interaction (dashed), and B of the dry air–water vapor mixture, Eq. (16.30), assuming a mole fraction $x_h = 0.5$ of water vapor.

water. The virial coefficient B_{hh} of water vapor is clearly much greater in magnitude than that of both dry air and the interaction coefficient. At a sufficiently large molar content of water vapor B_{hh} will play a dominant role in the virial coefficient of the mixture, but at a small molar content B_{hh} will yield to B_{dd}. The plot of B for the mixture is for a mole fraction $x_h = 0.5$.

The role of water vapor in the second virial coefficient of the mixture depends upon whether the temperature is below or above the critical temperature. Below the critical temperature the pressure of water vapor is limited by the saturation vapor pressure; above the critical temperature, no such limitation exists.

Figure 16.8 shows the second virial coefficient of the mixture at a pressure of 1 atm and at constant relative humidities of 10%, 25%, 50%, and 90%. The mole fraction of water vapor increases with temperature because the saturation vapor pressure increases. The drop at higher temperatures indicates a shift in dominance of B_{dd} to B_{hh} as the mole fraction of water vapor grows larger. Figure 16.9 shows the same coefficient at constant mole fraction. Here the contributions of B_{dd} and B_{hh} retain their proportions, in which case the mixture coefficient shows the traditional monotonic increase with temperature.

At low mole fractions of water vapor the contribution of the interaction coefficient B_{dh} is small because x_h is small. As the content of water vapor increases, its contribution still remains small because it is overwhelmed by the magnitude of B_{hh}. Figure 16.10 shows the second virial coefficient of two mixtures, having relative humidities of 10% and 90%, respectively, with and without the interaction

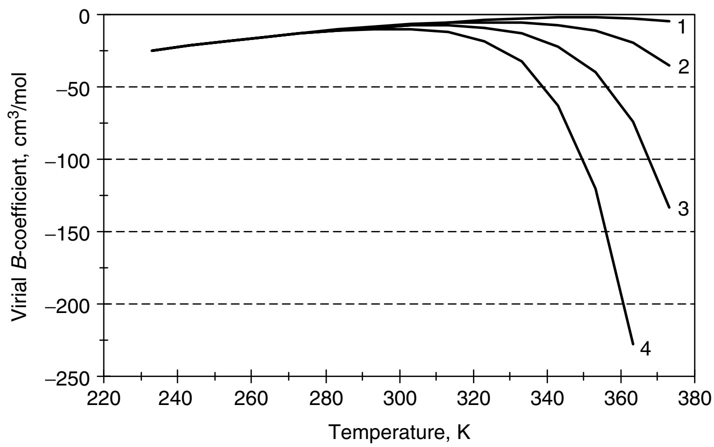

FIGURE 16.8 Virial *B*-coefficient of dry air–water vapor mixtures at constant relative humidity. The relative humidities are 10% for curve 1, 25% for curve 2, 50% for curve 3, 90% for curve 4. The pressure is 1 atm.

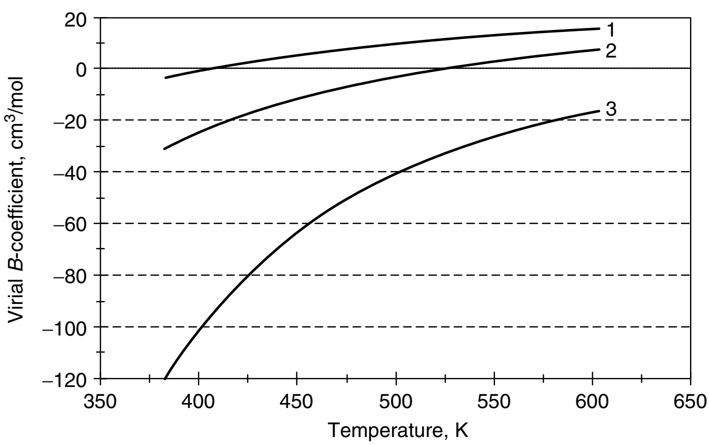

FIGURE 16.9 Virial *B*-coefficient of dry air–water vapor mixtures at constant mole fractions of water vapor. The mole fractions are 0.1 for curve 1, 0.25 for curve 2, 0.5 for curve 3. The pressure is 1 atm.

coefficient B_{dh} (solid and dashed lines). The temperatures cover the range of Hyland's data, and the pressure is 1 atm. As is evident from the figure, the contribution of B_{dh} is very small for both low and high relative humidities, as explained previously. At temperatures above the critical point of water vapor, where larger mole fractions of water vapor are possible, the interaction coefficient

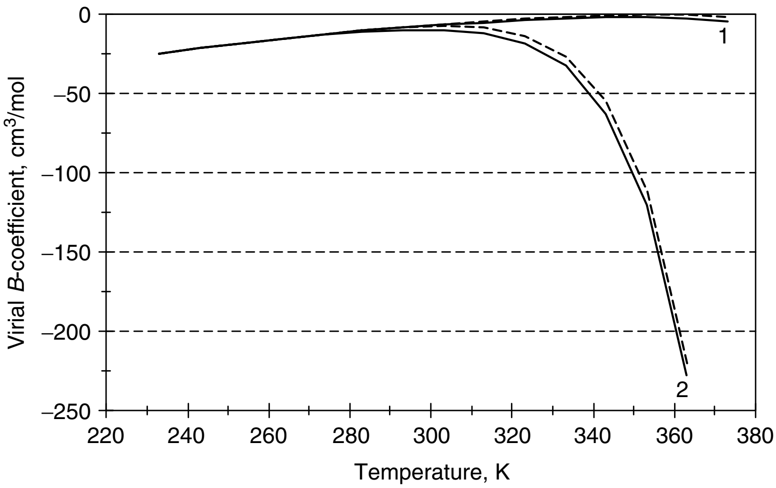

FIGURE 16.10 Virial *B*-coefficient of dry air–water vapor mixtures with (solid line) and without (dashed line) interaction coefficient B_{dh}, respectively. The relative humidity is 10% for curve 1 and 90% for curve 2. The pressure is 1 atm.

may make a more significant contribution; however, any results based on the extrapolation shown in Fig. 16.6 would be highly speculative. Thus the approach taken here is to ignore the interaction coefficient and to make allowance for its omission in the estimate of the uncertainty.

At fixed composition the temperature derivatives of the second virial coefficient follow the same mixing rule as the coefficient itself [Eq. (16.30)]. Consequently, the second acoustical virial coefficient [Eq. (4.23)] of the mixture can be written as

$$K = K_{dd}(1 - x_h)^2 + 2K_{dh}(1 - x_h)x_h + K_{hh}x_h^2 \tag{16.33}$$

in which the individual contributions [Eq. (4.24)] are

$$K_{dd} = 2B_{dd} + 2(\gamma_{od} - 1)T\frac{dB_{dd}}{dT} + \frac{(\gamma_{od} - 1)^2}{\gamma_{od}}T^2\frac{d^2B_{dd}}{dT^2} \tag{16.34a}$$

$$K_{hh} = 2B_{hh} + 2(\gamma_{oh} - 1)T\frac{dB_{hh}}{dT} + \frac{(\gamma_{oh} - 1)^2}{\gamma_{oh}}T^2\frac{d^2B_{hh}}{dT^2} \tag{16.34b}$$

and γ_{od} and γ_{oh} are the ideal specific heat ratios of dry air and water vapor. The acoustical virial interaction coefficient K_{dh} will be ignored. Note that Eqs. (16.33)–(16.34) are independent of a model for *B*. The second acoustical virial pressure coefficient *F*, as in the case of an individual gas, is related to the acoustical density coefficient K through Eq. (4.27a). For a mixture it becomes

$$F = \frac{K_{dd}(1 - x_h)^2 + K_{hh}x_h^2}{RT} \tag{16.35}$$

in which the interaction term is ignored.

The virial C-coefficient obeys the mixing rule (16.19), which for humid air is written:

$$C = C_{ddd}(1 - x_h)^3 + 3C_{ddh}(1 - x_h)^2 x_h + 3C_{dhh}(1 - x_h)x_h^2 + C_{hhh}x_h^3 \tag{16.36}$$

where C_{ddd} and C_{hhh} are the third virial coefficients of dry air and water vapor, and C_{ddh} and C_{dhh} the interaction coefficients. The first two can be represented by the empirically modified square-well function [Eq. (4.35), Vol. I]:

$$C_{ddd} = [d_d - e_d \exp(f_d/T)] \exp(-g_d T) + C_{\infty d} \tag{16.37a}$$

$$C_{hhh} = [d_h - e_h \exp(f_h/T)] \exp(-g_h T) + C_{\infty h}. \tag{16.37b}$$

The third virial coefficient of water vapor was first discussed in Chapter 4 of Vol. I. Values for the modified square-well constants for water vapor are found in Table 4.2:

$$d_h = 39540.1\ (\text{cm}^3/\text{mol})^2, e_h = 124.38\ (\text{cm}^3/\text{mol})^2, f_h = 3595.3\ \text{K}$$

$$g_h = 0.0043\ \text{K}^{-1}, C_{\infty h} = 200.3\ (\text{cm}^3/\text{mol})^2.$$

These values are valid over the temperature range 423–1173 K. The function (16.37b) is plotted in Fig. 4.19b. For temperatures below 423 K values must be obtained by extrapolation.

For the third virial coefficient of dry air, agreement among various sources of data compilation is not so good [13, 15, 16, 17]. Hilsenrath et al. [13], Levelt Sengers et al. [16], and Davis [17] agree reasonably well, but the formula of Sychev et al. [15] yields a much higher virial C-coefficient. The results are plotted in Fig. 16.11. The best fit to Eq. (16.37a), shown as a solid line, corresponds to the following constants in the equation:

$$d_d = 3871.0\ (\text{cm}^3/\text{mol})^2, e_d = 1237.0\ (\text{cm}^3/\text{mol})^2, f_d = 171.1\ \text{K}$$

$$g_d = 0.0058\ \text{K}^{-1}, C_{\infty d} = 1000\ (\text{cm}^3/\text{mol})^2.$$

These constants are valid over the temperature range 230–650 K. The relationship between the high-temperature asymptotic limits for the virial B- and C-coefficients [Eq. (4.71)]

$$C_{\infty d} = \tfrac{5}{8}B_{\infty d}^2 \tag{16.38}$$

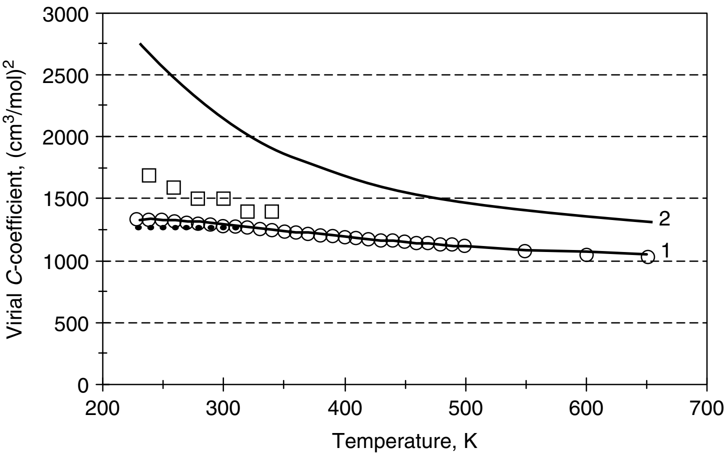

FIGURE 16.11 Virial *C*-coefficient of dry air. Circles: Ref. 13. Squares: Ref. 16. Solid line 1: best fit, Eq. (16.37a). Solid line 2: Ref. 15. Dotted line: Ref. 17.

yields a value $C_{\infty d} = 1044$ (cm^3/mol)^2, which is close to the fitted value, and thus lends some support for the use of the square-well model for dry air.

The relative contributions of dry air and water vapor to the third virial coefficient follow a pattern similar to that of the second virial coefficient. At low humidities the coefficient of dry air is favored, aided by the third-power dependence upon mole fraction; but because of a vast superiority in magnitude, the coefficient of water vapor assumes control when the humidity is still not too high. Figure 16.12 shows the situation in perspective. At 0.1 mole fraction of water vapor, the *C*-coefficient of the mixture (curve 1) differs little from that of dry air (dashed line). At 0.25 mole fraction the deviation is large (curve 2), and at 0.5 mole fraction (curve 3) the *C*-coefficient is completely dominated by the water vapor. The interaction coefficients will be ignored for lack of data.

The third acoustical virial coefficient L for an individual gas consists of two parts, one dependent upon the second density coefficient and the other upon the third density coefficient. For a mixture, the mixing rules (16.18) and (16.19) must be applied. Thus one writes:

$$L = [L_{BBd}(1 - x_h)^2 + L_{BBh}x_h^2]^2 \frac{(\gamma_o - 1)}{\gamma_o} + L_{Cd}(1 - x_h)^3 + L_{Ch}x_h^3 \qquad (16.39)$$

in which γ_o is the ideal specific heat ratio of the mixture, and

$$L_{BBd} = B_{dd} + (2\gamma_{od} - 1)T\frac{dB_{dd}}{dT} + (\gamma_{od} - 1)T^2\frac{d^2B_{dd}}{dT^2} \qquad (16.40a)$$

$$L_{BBh} = B_{hh} + (2\gamma_{oh} - 1)T\frac{dB_{hh}}{dT} + (\gamma_{oh} - 1)T^2\frac{d^2B_{hh}}{dT^2} \qquad (16.40b)$$

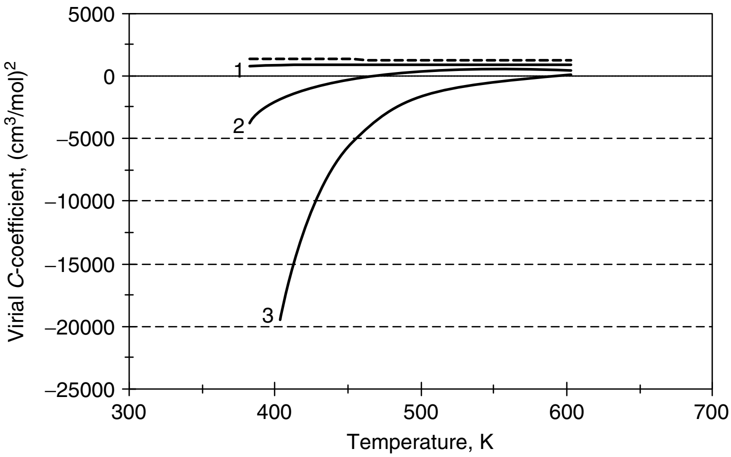

FIGURE 16.12 Virial C-coefficient of dry air–water vapor mixtures at constant mole fraction of water vapor. The mole fractions are 0 for the dashed curve, 0.1 for curve 1, 0.25 for curve 2, 0.5 for curve 3. The pressure is 1 atm.

$$L_{Cd} = \frac{(1+2\gamma_{od})}{\gamma_{od}} C_{ddd} + \frac{(\gamma_{od}^2 - 1)}{\gamma_{od}} T \frac{dC_{ddd}}{dT} + \frac{(\gamma_{od} - 1)^2}{2\gamma_{od}} T^2 \frac{d^2 C_{ddd}}{dT^2} \tag{16.40c}$$

$$L_{Ch} = \frac{(1+2\gamma_{oh})}{\gamma_{oh}} C_{hhh} + \frac{(\gamma_{oh}^2 - 1)}{\gamma_{oh}} T \frac{dC_{hhh}}{dT} + \frac{(\gamma_{oh} - 1)^2}{2\gamma_{oh}} T^2 \frac{d^2 C_{hhh}}{dT^2}. \tag{16.40d}$$

The third acoustical virial pressure coefficient G, as in the case of an individual gas, is related to density coefficients B, K, and L through Eq. (4.27b). For a mixture it becomes

$$G = \frac{[L_{BBd}(1-x_h)^2 + L_{BBh}x_h^2]^2(\gamma_o - 1)/\gamma_o + L_{Cd}(1-x_h)^3 + L_{Ch}x_h^3}{(RT)^2} - \frac{[B_{dd}(1-x_h)^2 + B_{hh}x_h^2][K_{dd}(1-x_h)^2 + K_{hh}x_h^2]}{(RT)^2} \tag{16.41}$$

in which, as before, interaction terms are ignored. The virial correction [Eq. (4.29)] for the mixture remains

$$K_v = FP + GP^2. \tag{16.42}$$

The zero-crossing temperatures of the second and third acoustical pressure coefficients of dry air are $T_F = 249.9$ K and $T_G = 161.6$ K, respectively. The practical meaning of these temperatures lies in the pressure dependence of the sound speed along an isotherm. At temperatures below 161.6 K, the sound speed decreases with increasing pressure. At temperatures between 161.6 K and 249.9 K, the sound speed at first decreases with pressure, reaches a minimum, and then increases. At temperatures above 249.9 K the sound speed increases with pressure. These zero-crossing temperatures are computed with the higher virial coefficients ignored.

It is difficult to quantify the uncertainty of the virial coefficients. Hilsenrath et al. show a departure plot for the compressibility of dry air, where the data appear to be confined to a departure within 0.2%, but do not offer a specification for the virial coefficients [13]. Levelt Sengers et al. note uncertainties of typically 1.5 cm^3/mol and up to 30% for the virial *B*- and *C*-coefficients of various gases, based on interlaboratory comparisons [16]. Sychev et al. show ‘‘tolerance limits’’ for air graphically, which are determined to be 4 cm^3/mol and roughly 2000 $(cm^3/mol)^2$ for the two coefficients [15].

It was noted in Ch. 6, Vol. I that it is not meaningful to specify a relative uncertainty of a quantity near a zero crossing. The approach here is to specify the uncertainty with an absolute term (for the zero crossing) and a relative term proportional to the quantity of interest. For dry air the uncertainties are determined to be

$$\delta B_{dd} = 0.2 + 0.035|B_{dd}| \tag{16.43a}$$

in cm^3/mol for the second virial coefficient, and

$$\delta C_{ddd} = 220 \tag{16.43b}$$

in $(cm^3/mol)^2$ for the third virial coefficient. These determinations are based on interlaboratory differences and deviations from the fits [Eqs. (16.31a) and (16.37a)]. The comparable uncertainties for water vapor are

$$\delta B_{hh} = 0.9 + 0.012|B_{hh}| \tag{16.44a}$$

in cm^3/mol for the second virial coefficient, and

$$\delta C_{hhh} = 86 + 0.25|C_{hhh}| \tag{16.44b}$$

in $(cm^3/mol)^2$ for the third virial coefficient [Ch. 6, Vol. I]. Their relationship to the uncertainty in the speed of sound will be discussed in Section 16.5.

16.4.5 Relaxation

Relaxation in atmospheric air involves basically four active constituents: nitrogen, oxygen, water vapor, and carbon dioxide. Nitrogen and oxygen, constituting together nearly 99% of the molar content in air, are almost exclusively responsible for the absorption (and accompanying dispersion) of sound. Water vapor and carbon dioxide, although contributing negligible sound absorption themselves, play a dominant role in determining the location of the nitrogen and oxygen relaxation peaks on the frequency/pressure axis. The prevailing process is *vibrational–vibrational* (V–V) energy exchange, alluded to briefly in Section 5.3.1. Considering the number of low-lying vibrational levels available for such exchanges, one can easily understand that any scheme for excitation reactions in air is by nature extraordinarily complex.

The approach taken in this handbook is to adopt the methodology and resulting equations of ANSI Standard S1.26-1995 [10]. The relaxation equations are based on 24 excitation reactions among the four active constituents [11]. The most important vibrational–vibrational reactions are the following:

$$\text{Reaction 1:} \quad O_2^* + H_2O \leftrightarrows O_2 + H_2O^*$$

$$\text{Reaction 2:} \quad O_2^* + CO_2 \leftrightarrows O_2 + CO_2^*(010)$$

$$\text{Reaction 3:} \quad N_2^* + H_2O \leftrightarrows N_2 + H_2O^*$$

$$\text{Reaction 4:} \quad N_2^* + CO_2 \leftrightarrows N_2 + CO_2^*(001).$$

An asterisk indicates an excited vibrational level. The numbers in parentheses designate the level of each of the three vibrational modes of carbon dioxide.

The most important *vibrational–translational* (V–T) reactions are of the following form:

$$\text{Reaction 5:} \quad H_2O^* + M \leftrightarrows H_2O + M$$

$$\text{Reaction 6:} \quad CO_2^*(010) + M \leftrightarrows CO_2 + M$$

where M is an omnibus symbol for any of the active constituents. Reactions 5 and 6 provide rapid de-excitation paths to equilibrate the vibrationally excited diatomic molecules with translation. If $M = H_2O$ in Reaction 5, the forward reaction rate is especially rapid (10^9 atm$^{-1} \cdot$ s^{-1}), a fact that leads to the extraordinary effectiveness of water vapor as a de-excitation agent in the atmosphere. Some authors replace Reaction 3 with a comparable V–T reaction [11]; but owing to the rapidity of Reaction 5, this interpretation would not affect the final outcome.

One of the practical consequences of a prevailing V–V reaction scheme is a weak temperature dependence of the relaxation time. In the theory of collision numbers, the characteristic vibrational temperature θ_{vb} of a V–T reaction is replaced by the difference $\Delta\theta_{vb}$ in vibrational temperatures of a V–V reaction in the harmonic oscillator and impact factors [Eqs. (5.101)] and (5.103)] [18]. For example, since $\Delta\theta_{vb} = 55.5$ K for Reaction 1, it follows that $\Delta\theta_{vb}/T \ll 1$ at ordinary laboratory and outdoor temperatures, leading to a reduced temperature dependence of the associated reaction rate. Because this reaction rate has a commanding role in the formulation of the relaxation time, the latter will have a correspondingly weak temperature dependence. On the other hand, $\Delta\theta_{vb} = 1057.4$ K for Reaction 3, in which case a notable temperature dependence may be expected.

For each relaxing gas the ANSI standard specifies a relaxation frequency (reciprocal of 2π times relaxation time) in place of a relaxation time. The relaxation frequency of oxygen is of the form first proposed by Tuesday and Boudart [19]:

$$f_X = (P/P_0^*)\left[a_X(1) + a_X(2)x_h \frac{a_X(3) + x_h}{a_X(4) + x_h}\right] \tag{16.45}$$

where P_0^* is the reference pressure of 1 atm, and f_X is the relaxation frequency in Hz. The ANSI standard specifies the following values for the constants [10]:

$$a_X(1) = 24 \text{ Hz}$$

$$a_X(2) = 4.04 \times 10^6 \text{ Hz}$$

$$a_X(3) = 2 \times 10^{-4}$$

$$a_X(4) = 3.91 \times 10^{-3}$$

which are valid over the temperature range 273–323 K. At zero humidity the relaxation frequency at 1 atm is 24 Hz, as determined primarily by excitation reactions between oxygen and carbon dioxide. The humidity dependence of f_X is linear at low humidities, quadratic at intermediate humidities, and then linear again at high humidities ($\sim$1% mole fraction). Equation (16.45) provides a good fit to the available experimental data over their full ranges of humidity. Earlier proposed dependencies of the relaxation frequency upon humidity (quadratic, polynomial, power-law) proved accurate only over limited ranges of humidity [11].

The constants of Eq. (16.45) all depend upon rate constants among the 24 selected reactions, which together produce a weak temperature dependence over the specified temperature range. At higher temperatures, however, some of the constants reveal a significant temperature dependence that will affect the accuracy of the relaxation frequency. Bass addressed this question and determined the temperature dependence of each of the constants in terms of the associated reaction rates, based on the available data at the time [20]. The results of this analysis, with some minor adjustment to retain the constants of the ANSI standard at 293.15 K, are fitted to yield the following equations (in Hz):

$$a_X(1) = 2.131 \times 10^5 \exp\left(-60.40\,T^{-1/3}\right) \tag{16.46a}$$

$$a_X(3) = 16.46 \exp\left(-75.19T^{-1/3}\right). \tag{16.46b}$$

The temperature dependencies of the constants $a_X(2)$ and $a_X(4)$ are sufficiently weak that they can be ignored over the full temperature range. Thus this handbook will use the values listed previously for $a_X(2)$ and $a_X(4)$, and Eqs. (16.46a, b)

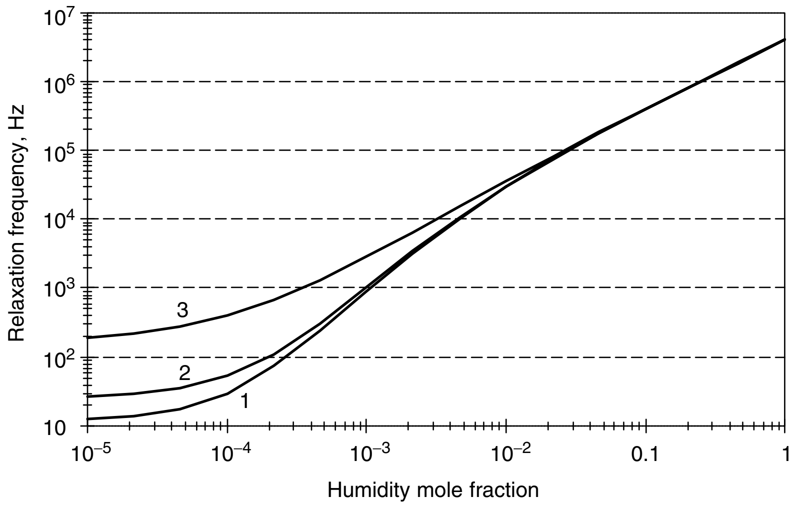

FIGURE 16.13 Vibrational relaxation frequency of oxygen in air versus humidity mole fraction. The temperature is 233.15 K for curve 1, 293.15 K for curve 2, and 603.15 K for curve 3. The pressure is 1 atm.

for $a_X(1)$ and $a_X(3)$, to predict the sound speed over the temperature range 233–603 K. The relaxation frequency of oxygen in air versus humidity at three different temperatures is shown in Fig. 16.13.

The relaxation frequency of nitrogen is written in the form

$$f_N = \left(\frac{P}{P_0^*}\right)\left(\frac{T_0}{T}\right)^{1/2}[a_N\,(1) + a_N\,(2)x_h] \tag{16.47}$$

in which T_0 is the reference temperature of 293.15 K and f_N is the relaxation frequency in Hz. The constants have the following values at the reference temperature:

$$a_N(1) = 9\ \text{Hz}$$

$$a_N(2) = 2.8 \times 10^4\ \text{Hz}.$$

At zero humidity the relaxation frequency at 1 atm has a value of 9 Hz, as determined by excitation reactions between nitrogen and carbon dioxide and to a lesser extent oxygen. Equation (16.47) indicates a linear dependence upon humidity, as would be expected from a V–T reaction; however, there is strong evidence that the slope $a_N(2)$ increases to a value of 3.5×10^4 Hz at high humidities [21], conforming to a V–V reaction, as would be represented by Eq. (16.45). For purposes of this handbook, the representation (16.47) will be retained.

The temperature dependence of $a_N(1)$, as before, is fitted to data provided by Bass [20] but forced to yield the stated reference-temperature value, and the temperature dependence of $a_N(2)$ is already incorporated into the ANSI standard. The temperature dependencies are

$$a_N(1) = 6.614 \times 10^4 \exp\left(-58.90T^{-1/3}\right) \tag{16.48a}$$

$$a_N(2) = 2.8 \times 10^4 \exp\left\{-4.170\left[\left(\frac{T}{T_0}\right)^{-1/3} - 1\right]\right\}. \tag{16.48b}$$

Equations (16.48a, b) will be used later to compute the sound speed over the temperature range 233–603 K, as in the case of oxygen. The relaxation frequency of nitrogen in air versus humidity at the same three temperatures is shown in Fig. 16.14.

In dry CO_2-free air the zero-humidity constants reduce to the following [22]:

$$a_X(1) = 6\ \text{Hz}$$

$$a_N(1) = 5\ \text{Hz}.$$

These values are valid at temperatures only in the vicinity of 293.15 K.

The calculation of relaxation strength in the ANSI standard is based on three assumptions. For each diatomic molecule it is assumed that

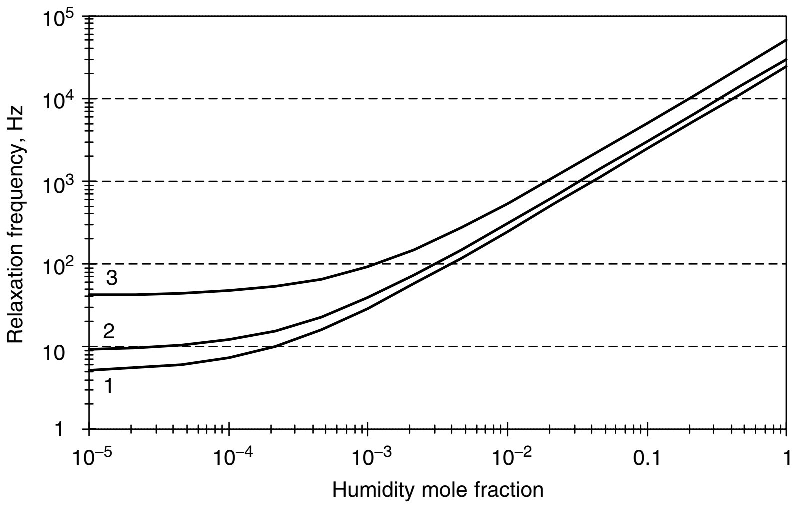

FIGURE 16.14 Vibrational relaxation frequency of nitrogen in air versus humidity mole fraction. The temperature is 233.15 K for curve 1, 293.15 K for curve 2, and 603.15 K for curve 3. The pressure is 1 atm.

1. the vibrational specific heat makes only a small contribution to the total specific heat, $C_i \ll C_P^o$;
2. the characteristic vibrational temperature is much greater than the air temperature, $\theta_{vib} \gg T$;
3. the relaxation strength is much smaller than unity, $\varepsilon \ll 1$.

The first assumption gives the specific heat the value $C_P^o/R = \frac{7}{2}$ in Eq. (5.45); the second eliminates the denominator of Eq. (5.43c); and the third eliminates the denominator of Eq. (5.8). Over the temperature range of the ANSI standard (up to 323 K), these assumptions are valid; but at higher temperatures, the exact versions of these equations are recommended and will be used below.

If the oxygen and nitrogen relaxation peaks were well separated, then the high-frequency limiting sound speed of nitrogen would serve as the low-frequency limiting sound speed of oxygen; however, this is not the case, and an exact solution to the relaxation equations would require rigorous theory [23]. Instead, the following approximation will be used for the high-frequency limiting specific heat, appearing in Eq. (5.41):

$$C_P^\infty = C_P^o - x_X C_X - x_N C_N \tag{16.49}$$

where C_P^o is the low-frequency limiting specific heat of air, C_X the vibrational specific heat of oxygen, and C_N the vibrational specific heat of nitrogen. Then, the relaxation strengths of oxygen and nitrogen, respectively, are written:

$$\varepsilon_X = \frac{x_X C_X}{(C_P^o - x_X C_X - x_N C_N)(C_P^o - R)} \tag{16.50a}$$

and

$$\varepsilon_N = \frac{x_N C_N}{(C_P^o - x_X C_X - x_N C_N)(C_P^o - R)} \tag{16.50b}$$

with

$$C_X = R\left(\frac{2239.1}{T}\right)^2 \frac{\exp\left(-\frac{2239.1}{T}\right)}{\left[1 - \exp\left(-\frac{2239.1}{T}\right)\right]^2} \tag{16.50c}$$

$$C_N = R\left(\frac{3352.0}{T}\right)^2 \frac{\exp\left(-\frac{3352.0}{T}\right)}{\left[1 - \exp\left(-\frac{3352.0}{T}\right)\right]^2} \tag{16.50d}$$

and the relaxation correction for the mixture becomes

$$K_r = \frac{\varepsilon_X}{1-\varepsilon_X}\left[\frac{(f/f_X)^2}{1+(f/f_X)^2}\right] + \frac{\varepsilon_N}{1-\varepsilon_N}\left[\frac{(f/f_N)^2}{1+(f/f_N)^2}\right]. \tag{16.51}$$

The relaxation strength of oxygen and nitrogen versus humidity at the same three temperatures as selected for the relaxation frequencies is shown in Figs. 16.15 and 16.16, respectively.

It is of interest to consider dispersion due to rotational relaxation. According to Bass and Sutherland [20, 24], the rotational relaxation frequency f_{ro} in air can be written in the following form:

$$\frac{f_{ro}}{P} = 458.1\frac{\exp\left(16.8T^{-1/3}\right)}{\mu_a} \tag{16.52}$$

where the pressure P is expressed in atm and the absolute viscosity μ_a in Pa·s. For air at 293.15 K and 1 atm, $\mu_a = 1.814 \times 10^{-5}$ Pa·s, leading to $f_{ro} = 317$ MHz. Thus even at the highest acoustical frequency of 100 kHz considered in this volume, rotational dispersion is negligible. The same conclusion can be reached for translational dispersion (see Section 5.7).

As is the case with relaxation in individual gases, the uncertainty in the relaxation frequencies by far exceeds that of the relaxation strengths; as a result, the uncertainty in the relaxation correction will be attributed entirely to the former. First, consider the relaxation frequency of oxygen in air at 1 atm. Based on

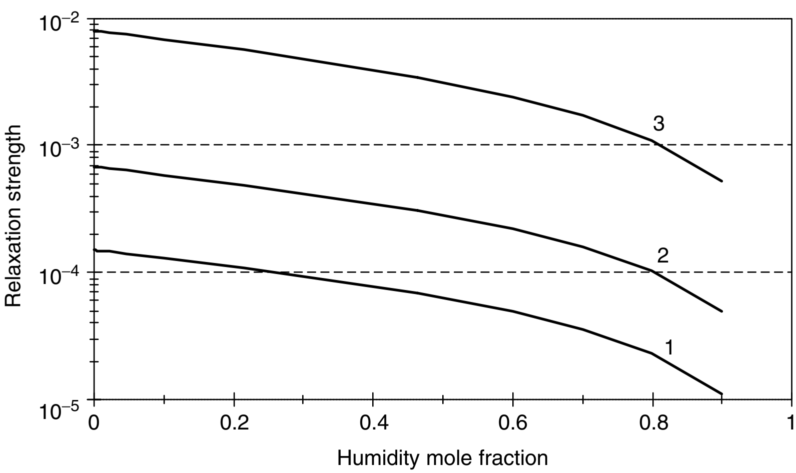

FIGURE 16.15 Vibrational relaxation strength of oxygen in air versus humidity mole fraction. The temperature is 233.15 K for curve 1, 293.15 K for curve 2, and 603.15 K for curve 3.

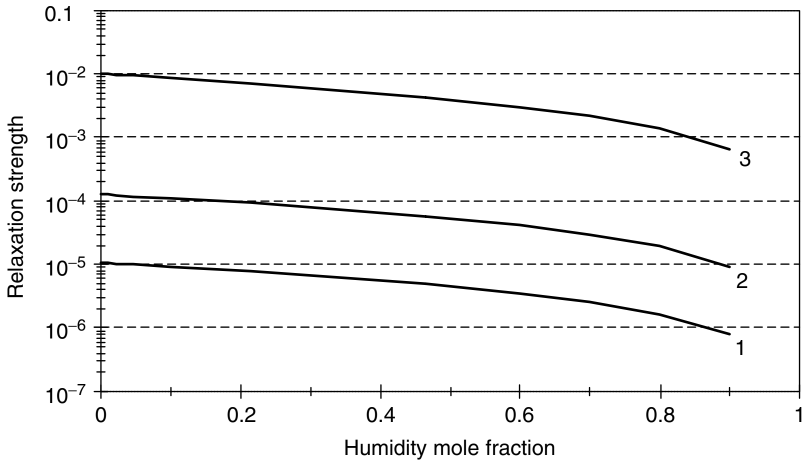

FIGURE 16.16 Vibrational relaxation strength of nitrogen in air versus humidity mole fraction. The temperature is 233.15 K for curve 1, 293.15 K for curve 2, and 603.15 K for curve 3.

their own extensive measurements in the frequency range 4–100 kHz, Bass and Shields specify an uncertainty of 10% in the relaxation frequency, of which their lowest measured value is $f_X = 120$ Hz [25]. The measurements of Zuckerwar and Meredith at lower frequencies reveal the same uncertainty for relaxation frequencies between 30 and 130 Hz [26]; however, there is significant disagreement under conditions where the relaxation frequency lies below 30 Hz [27]. Therefore, until the issue is settled, the uncertainty specification of the oxygen relaxation frequency is listed here as

$$10\% \text{ for } f_X \geq 30 \text{ Hz}$$

$$50\% \text{ for } f_X < 30 \text{ Hz.}$$

The uncertainty for the relaxation frequency of nitrogen at 1 atm is taken from Ref. 26:

$$15\% \text{ for } f_N \geq 200 \text{ Hz}$$

$$25\% \text{ for } f_N < 200 \text{ Hz.}$$

The relationship to the uncertainty in the sound speed is discussed in the next section.

16.5 SPEED OF SOUND IN AIR AND ITS UNCERTAINTY

This section will summarize the analysis of the speed of sound as a binary mixture of standard air and water vapor together with an estimate of its uncertainty.

16.5.1 Introduction

It was shown in Chapter 1 that the sound speed (squared) can be represented in terms of the simple sound speed (squared) and its corrections:

$$W^2 = W_s^2(1 + K_c)(1 + K_v)(1 + K_r) \tag{16.53}$$

where W_s is the simple sound speed,

$$W_s^2 = \frac{\gamma_s RT}{M} \tag{16.54}$$

and K_c, K_v, and K_r are the specific heat, virial, and relaxation corrections, respectively, as in the case of an individual gas [see Eqs. (6.6), (6.8), and (6.30)].

The uncertainty in the predicted sound speed, as before, is expressed in terms of the uncertainties of the supporting parameters; but in the case of mixtures there are two steps to the estimation procedure: first, to express the uncertainty of a supporting parameter of the mixture in terms of the uncertainties of those of the individual constituents; second, to express the uncertainty of the sound speed in terms of the uncertainties of the supporting parameters of the mixture.

16.5.2 Uncertainty of the Supporting Parameters of Atmospheric Air

This first step was already addressed in Sections 16.4.3, 16.4.4, and 16.4.5. The absolute uncertainties of the supporting parameters in atmospheric air are summarized as follows:

$$\delta C_P^o = (0.005x_d + 0.01x_h)C_P^o \tag{16.55a}$$

$$\delta B = (0.2 + 0.035|B_{dd}|)\,x_d^2 + (0.9 + 0.012|B_{hh}|)\,x_h^2 \tag{16.55b}$$

$$\delta C = 200x_d^3 + (86 + 0.0025|C_{hhh}|)\,x_h^3 \tag{16.55c}$$

$$\begin{aligned} \delta f_X &= 0.1 f_X, \quad f_X \geq 30 \text{ Hz} \\ &= 0.5 f_X, \quad f_X < 30 \text{ Hz} \end{aligned} \tag{16.55d}$$

$$\begin{aligned} \delta f_N &= 0.15 f_N, \quad f_N \geq 200 \text{ Hz} \\ &= 0.25 f_N, \quad f_N < 200 \text{ Hz.} \end{aligned} \tag{16.55e}$$

16.5.3 Uncertainty of the Specific Heat, Virial, and Relaxation Corrections

The uncertainty of the sound speed, in terms of the uncertainties of the specific heat, viral, and relaxation corrections as given by Eq. (6.2), holds for a mixture:

$$\frac{\delta W}{W} = \frac{1}{2}\left[\left|\frac{\delta K_c}{1 + K_c}\right| + \left|\frac{\delta K_v}{1 + K_v}\right| + \left|\frac{\delta K_r}{1 + K_r}\right|\right]. \tag{16.56}$$

The uncertainty of the specific heat and virial corrections, as given by Eqs. (6.7) and (6.26), are still valid if Eqs. (16.55a, b, c) are used for the specific heat and virial uncertainties:

$$\frac{\delta K_c}{1+K_c} = \frac{\delta\gamma_o}{\gamma_o} = -\frac{\delta C_P^o}{C_P^o}(\gamma_o - 1) \tag{16.57}$$

$$\frac{\delta K_V}{1+K_V} = \frac{[\psi(1-\psi B)U_v\,(1) - \psi^2 K + \psi^2 U_v\,(2)]\delta B + \psi^2 U_v\,(3)\delta C}{1+K_V} \tag{16.58}$$

where $\psi = P/RT$, and $U_V(1)$, $U_V(2)$, and $U_V(3)$ are combinations of supporting parameters given by Eqs. (6.25a, b, c). For convenience they are rewritten here:

$$U_V\,(1) = \left[2 - 2(\gamma_o - 1)\frac{c_V}{T} + \frac{(\gamma_o - 1)^2}{\gamma_o}\frac{c_V}{T}\left(2 + \frac{c_V}{T}\right)\right] \tag{16.59a}$$

$$U_V\,(2) = \frac{2(\gamma_o - 1)}{\gamma_o}\left[B + \left(1 - \frac{c_V\gamma_o}{T} + \frac{c_V}{T}\right)\frac{b_V c_V}{T}\exp\left(\frac{c_V}{T}\right)\right]$$
$$\times\left[1 - \frac{c_V}{T}\left(1 - \frac{c_V\gamma_o}{T} + \frac{c_V}{T}\right)\right] \tag{16.59b}$$

$$U_V\,(3) = \left[\frac{1+2\gamma_o}{\gamma_o} - \frac{f_V}{T}\frac{(\gamma_o^2 - 1)}{\gamma_o} + \frac{f_V}{T}\left(2 + \frac{f_V}{T}\right)\frac{(\gamma_o - 1)^2}{2\gamma_o}\right]. \tag{16.59c}$$

Any supporting parameter entering Eqs. (16.57)–(16.59) — like the specific heat, virial coefficient, or square-well constant — is subject to the appropriate mixing rule to obtain the required value for the standard air–water vapor mixture.

The relaxation correction, based on properties of individual air constituents, follows a different pattern. The uncertainty δK_r is readily expressed in terms of the uncertainties of the relaxation frequencies δf_X and δf_N from Eq. (16.51):

$$\frac{\delta K_r}{1+K_r} = \frac{-2f^2}{1+K_r}\left[\frac{\varepsilon_N}{1-\varepsilon_N}\frac{f_N\delta f_N}{(f_N^2+f^2)^2} + \frac{\varepsilon_X}{1-\varepsilon_X}\frac{f_X\delta f_X}{(f_X^2+f^2)^2}\right]. \tag{16.60}$$

16.5.4 Uncertainty of the Water Vapor Content

An assessment of the uncertainty of the water vapor content depends upon how it is specified. If it is specified as a mole fraction, then it will entail no uncertainty in the sound speed; however, since the water vapor content is invariably derived from relative humidity or dew point measurements, then the uncertainty ensues from the conversion to mole fraction. The uncertainty follows from Eq. (16.8) in terms of the uncertainties of the enhancement factor and saturation pressure:

$$\frac{\delta x_h}{x_h} = \left|\frac{\delta f_e}{f_e}\right| + \left|\frac{\delta P_{sat}}{P_{sat}}\right| \tag{16.61}$$

where the contributions on the right side are found from Eqs. (16.12b) and (16.14).

The mole fraction of water vapor enters every supporting parameter of the speed of sound. The impact of its uncertainty upon the uncertainty of the speed of sound is therewith of undue complexity, which does not justify its representation in closed form. Rather, the approach taken here is to specify the water vapor content as a relative humidity and to compute the speed of sound using the corresponding mole fraction x_h. Then, the uncertainty in mole fraction δx_h is found from Eq. (16.61), and a new mole fraction $x_h \pm \delta x_h$ is used to recompute the sound speed. The difference in sound speeds $|W(x_h) - W(x_h \pm \delta x_h)|$ constitutes the uncertainty due to the uncertainty in mole fraction. If $W(x_h)$ is taken from a table (see next section), then $W(x_h \pm \delta x_h)$ can be found by interpolation.

16.5.5 Examples

Table 16.8 shows the speed of sound, corrections, and uncertainty under selected conditions. The first four rows depict baseline conditions — 1 atm pressure, zero humidity, zero frequency — at four temperatures. The uncertainty is equal to or slightly greater than 0.1%, a conservative estimate. The real sound speed at 273.15 K is the predicted "standard value" of 331.46 m/s, which agrees well with several measurements yielding values in the range 331.44–331.46 m/s. The measured value 331.45 m/s is considered to be accurate to within ±0.01 m/s (see Section 16.6).

In the second set of rows the pressure is increased to 100 atm. The virial correction increases dramatically, leading to sizable increases in the sound speed. The growth in the uncertainty is related to the growth in the virial correction.

In the third set of rows the relative humidity is increased to 100%. At the three lower temperatures the mole fraction of water vapor remains small, amounting to 2.3% at 293.15 K, and so the impact upon the sound speed is small. At a temperature of 373.15 K, the normal boiling point of water at 1 atm, the enhancement factor causes the mole fraction to exceed unity. If this were the case, then the presence of air effectively depresses the boiling point of water, as mentioned in Section 16.3.3. The given temperature of 373.1183 K is approximately the temperature at which the saturation pressure equals 1 atm. Except at the last temperature, the uncertainties are about the same as for the baseline conditions.

In the final set of rows the frequency is increased to 1000 Hz to determine the dispersion, which remains small at all listed temperatures. It increases with temperature due to increasing relaxation strength. At 1000 Hz and zero humidity the sound speed is very close to its high-frequency limit. Thus for a given temperature, the ratio of sound speeds at zero and 1000 Hz may be considered the frequency reduction factor for frequencies at 1000 Hz and above. For example, at 273.15 K, the reduction factor is found to be 331.46/331.54 = 0.999759, leading to a reduction of 241 ppm. The uncertainty remains the same as for the baseline.

TABLE 16.8 Speed of Sound and Uncertainty in Atmospheric Air Under Selected Conditions

Temperature T	Pressure P	Relative humidity h_r	Frequency f	Corrections K_c	K_v	K_r	Speed of sound: Simple W_s	Real W	Uncertainty $\delta W/W$
(K)	(atm)	(%)	(Hz)	Multiply entry by 0.001			(m/s)	(m/s)	(%)
233.15	1	0	0	0.755	−0.358	0	306.10	306.16	0.11
273.15	1	0	0	0.462	0.368	0	331.32	331.46	0.10
293.15	1	0	0	0.142	0.583	0	343.24	343.36	0.10
373.15	1	0	0	−2.253	0.987	0	387.25	387.00	0.10
233.15	100	0	0	0.755	55.894	0	306.10	314.66	1.32
273.15	100	0	0	0.462	105.869	0	331.32	348.50	0.83
293.15	100	0	0	0.142	117.194	0	343.24	362.82	0.69
373.15	100	0	0	−2.253	130.071	0	387.25	411.20	0.44
233.15	1	100	0	0.754	−0.358	0	306.11	306.17	0.11
273.15	1	100	0	0.441	0.358	0	331.64	331.78	0.10
293.15	1	100	0	0.044	0.508	0	344.52	344.62	0.10
373.1183[a]	1	100	0	−7.632	−21.837	0	479.17	472.10	0.23
233.15	1	0	1000	0.755	−0.358	0.160	306.10	306.19	0.11
273.15	1	0	1000	0.462	0.368	0.508	331.32	331.54	0.10
293.15	1	0	1000	0.142	0.583	0.802	343.24	343.50	0.10
373.15	1	0	1000	−2.253	0.987	3.032	387.25	387.59	0.10

[a] Approximate temperature for which $P_{sat} = P$.

From Eq. (16.61) one finds that the uncertainty of the mole fraction x_h is 0.17% at 233.15 K, 0.15% at 273.15 K, 0.14% at 293.15 K, and 0.10% at 373.12 K. If a negative uncertainty is considered (to prevent $x_h > 1$), then the sound speed remains unchanged, to the fifth significant figure, at temperatures of 293.15 K and below. At 373.12 K the sound speed changes from 472.10 to 471.98 m/s (the predicted sound speed for individual water vapor).

16.5.6 Further Examples

Ener, Gabrysh, and Hubbard made measurements at 2–3 MHz to study rotational relaxation in air at 305.15 K and determined the low-frequency limiting sound speed, reduced to 273.15 K, to be 331.52 m/s [28]. This agrees well with the high-frequency limiting sound speed for vibrational relaxation (i.e., at 1000 Hz) of 331.54 m/s, shown in Table 16.8. Thus the data confirm that the high-frequency limiting sound speed for vibration serves as the low-frequency limiting sound speed for rotation. The sound speed reveals practically no dispersion at frequencies between the vibrational and rotational relaxations.

A final example concerns an interesting effect disclosed by Harris [29]. In a series of measurements in a spherical resonator, primarily for sound absorption, he noted that as humidity is added to dry air the sound speed at first decreases, reaches a minimum, and then increases. He offers the following explanation. The addition of water vapor results in two opposing effects: a shift in the dispersion step of oxygen toward a higher f/P ratio, and a net increase in the ratio γ/M. The dispersion effect, which causes the sound speed to decrease, dominates at low humidities but eventually yields to the effect of water vapor upon γ/M, which causes the sound speed to increase. This explanation is supported qualitatively by the handbook analysis, as shown in Fig. 16.17. The sound speed is plotted versus relative humidity for the two acoustical frequencies considered by Harris (see Fig. 2 of Ref. 29). The handbook analysis predicts that the minimum will occur in the vicinity of 4% relative humidity, but the measurements of Harris show it occurring at about 15%. Morfey and Howell discuss possible causes of this discrepancy [30].

16.5.7 Variation of the Speed of Sound in Air with Carbon Dioxide Content

In Section 16.3.2 the trend of increasing carbon dioxide content in Earth's atmosphere was described. The purpose of this subsection is to evaluate its impact upon the speed of sound. Handbook prediction is based upon Eq. (16.53), in which only the molar mass and specific heat correction are significantly influenced

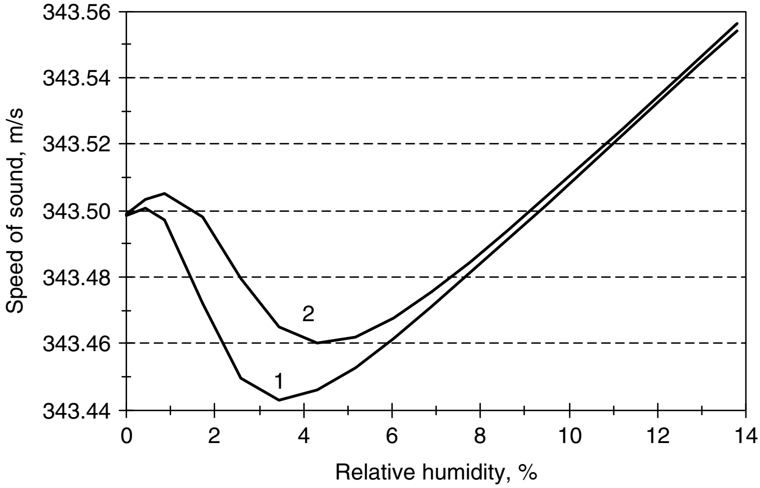

FIGURE 16.17 Speed of sound in air versus relative humidity at 293.15 K, 1 atm. Curve 1: $f = 292$ Hz. Curve 2: $f = 503$ Hz. Compare with measurements of Ref. 29.

by carbon dioxide content. The virial correction is taken to be the same as for standard air, since the contribution of carbon dioxide is negligible. The relaxation correction is zero in the limit to zero frequency, the case considered here. Both the molar mass M and ideal specific heat at constant pressure C_P^o are derived from Eq. (16.20), based on data for standard air (constituent "1") and carbon dioxide (constituent "2").

Wong gives the following equation for the dependence of speed of sound upon carbon dioxide content and temperature [31]:

$$W = W_c(T)\{1.000097 + 10^{-7}(T - 273.15) - x_c[0.309 + 2.7 \times 10^{-4}(T - 273.15)]\} \quad (16.62)$$

where x_c is the mole fraction of carbon dioxide, and $W_c(T)$ is the speed of sound at temperature T referenced to $x_c = 314$ ppm. A comparison between handbook prediction [Eq. (16.53)] and Eq. (16.62) is shown at 273.15 K and 293.15 K in Figures 16.18a and 16.18b, respectively. Sound speed values $W_c(273.15) = 331.45$ m/s and $W_c(293.15) = 343.36$ m/s are used for the reference sound speeds. Agreement between the two formulations is excellent.

From the figures it is concluded that the sound speed decreases by 31 ppm for each positive increment of 100 ppm of carbon dioxide. Because the rate of carbon dioxide increase is 13 ppm per decade, the corresponding decrease in sound speed

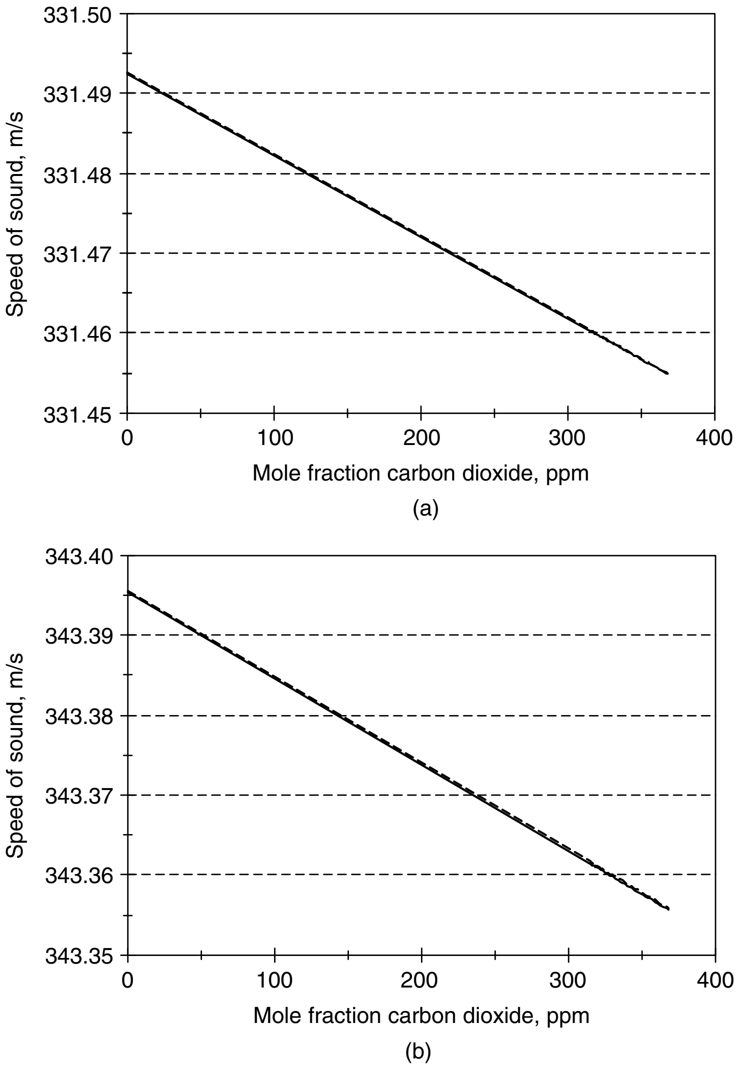

FIGURE 16.18 (a) Speed of sound in dry air versus carbon dioxide content under standard conditions ($T = 273.15$ K, $P = 1$ atm, $f = 0$ Hz). Solid line: handbook prediction based on Eq. (16.53). Dashed line: Ref. 31 with adjustment to yield standard air value of 331.46 m/s at $x_c = 314.5$ ppm. (b) Speed of sound in dry air versus carbon dioxide content under normal conditions ($T = 293.15$ K, $P = 1$ atm, $f = 0$ Hz). Solid line: handbook prediction based on Eq. (16.53). Dashed line: Ref. 31 with adjustment to yield normal air value of 343.36 m/s at $x_c = 314.5$ ppm.

is 31 × 13/100 = 4 ppm or 0.0013 m/s per decade. The practical importance of this information is that corrections for loss of carbon dioxide are not needed for measurements in CO_2-free air in the zero-frequency limit. For sound propagation in dry air at actual excitation frequencies, the relaxation correction may be more sensitive to changes in carbon dioxide content.

16.6 REVIEWS OF SELECTED MEASUREMENTS OF THE STANDARD SPEED OF SOUND IN AIR

Among the vast number of measurements of the speed of sound in air that have appeared in the literature over the years (see Chapter 17), a considerable number report a sound speed for dry air at or near the generally accepted value of 331.45 m/s at standard temperature and pressure (STP: 273.15 K and 1 atm) and zero frequency. Among these sources, those selected for review meet basically the same criteria as established for an individual gas: data presentation in tabular or numerical format, corrections for effects of the apparatus, and a specification of the measurement uncertainty. An excepted criterion is a specification on the sample purity (or analysis of the composition in the case of a mixture), which is replaced by a disclosure of the source of air. Further, the selections necessarily provide the test temperature, pressure, frequency, and humidity for each sound speed measurement.

There are three methods by which investigators reduce measured sound speeds from real air to dry air. The first is to make the humidity so low that its effects will not be measurable. This approach requires an air sample with a dew point (more correctly, ''frost point'') below 231 K (−42 °C) to achieve no measurable effect from the humidity. The second is to account for the sample humidity by compensating analytically for its effects upon the supporting parameters. The third is to measure the sound speed versus humidity and then extrapolate to zero humidity.

Several investigators, especially those reporting in the older literature, resorted to elaborate drying methods through chemical desiccants — they were apparently unaware of the disproportionate effect of a small amount of contaminant upon the relaxation times of the diatomic constituents of air. Others utilized cryogenic drying, which has the drawback that the carbon dioxide content is also removed from the test sample — hence the preponderance of CO_2-free air samples for testing.

The sound speed in dry air at standard conditions (273.15 K, 1 atm) and zero frequency will be called the *standard sound speed*. A sound speed measured in air having nonzero humidity and referred to standard conditions by one of the methods listed will be called the *reduced sound speed*. Thus there is *temperature* *reduction* as well as *humidity reduction*. Often, the temperature reduction consists of nothing other than scaling the sound speed as the square root of the temperature—an approximation that requires appropriate limits of uncertainty. The question arises concerning the error inherent in this procedure. The exact reduction factor must account for contributions from the specific heat, virial, and relaxation corrections in addition to the intrinsic temperature dependence. Table 16.9 compares the *simple-gas reduction factor* (based on the square root of the temperature) with the *real-gas reduction factor* (which includes the various corrections) at different frequencies, all at 1 atm. The real-gas reduction factor refers the sound speed to standard conditions and zero frequency. Consider, for example, a measured sound speed at 303.15 K and 1000 Hz. The simple-gas reduction factor (0.94923) exceeds the real-gas reduction factor (0.94887) by 380 ppm. If an accuracy of 100 ppm is desired in the sound speed, then the real-gas reduction must be applied. Note that there is little difference between the reduction factors at 1000 Hz and 10,000 Hz, because at 1000 Hz the sound speed is already very close to its high-frequency limiting value.

TABLE 16.9 Factors for Reduction of Speed of Sound to Standard Temperature 273.15 K and Zero Frequency for Selected Measurement Temperatures and Frequencies

	Simple gas[a]	Real gas[b]			
Temperature (K)	Reduction factor	Reduction factor	Difference (ppm)	Reduction factor	Difference (ppm)
		$f = 0$ Hz		$f = 100$ Hz	
273.15	1	1	0	0.99975	246
283.15	0.98218	0.98220	−15	0.98189	295
293.15	0.96529	0.96534	−53	0.96497	330
303.15	0.94923	0.94934	−112	0.94890	353
313.15	0.93395	0.93413	−192	0.93361	365
323.15	0.91939	0.91966	−291	0.91905	368
		$f = 1000$ Hz		$f = 10,000$ Hz	
273.15	1	0.99975	254	0.99975	254
283.15	0.98218	0.98188	307	0.98188	307
293.15	0.96529	0.96495	348	0.96495	349
303.15	0.94923	0.94887	380	0.94887	380
313.15	0.93395	0.93357	404	0.93357	405
323.15	0.91939	0.91900	422	0.91900	423

Note: The "difference" column indicates the difference between simple-gas and real-gas reduction factors. The real-gas entries are for a pressure of 1 atm.
[a]Reduction factor $= W_{std}/W = \sqrt{273.15/T}$.
[b]Reduction factor computed from Eq. (16.53).

16.6.1 REFERENCE: T. C. HEBB, PHYS. REV. 14, 74–84 (1919)
METHOD: SONIC INTERFEROMETER — VARIABLE PATH
SOURCE OF AIR: INDOOR (BASEMENT HALL)
MEASUREMENT UNCERTAINTY: 0.12%

This work is best appreciated in its historical context. Arguably it may be said to have ushered in the modern era of sound speed measurement in gases. It probably was the first interferometric measurement of the sound speed in air to appear in the literature and represents the first measurement to yield a value near the standard value of 331.45 m/s within reasonable limits of uncertainty.

The experimental method, one of the few truly free-field methods, utilized a variable-path sonic interferometer. Two coaxial parabolic reflectors terminated the propagation path, with one made movable on a parallel track. The source was an air-driven whistle located at the focal point of the stationary reflector. It was calibrated against tuning forks of different frequencies by a sophisticated mechanical means. Two microphones detected the signal, one located at the focal point of the movable reflector, the other near the focal point of the stationary reflector. The signals from the two receivers were combined in such a way as to provide interference minima and maxima in the sound heard in a headphone as the distance between the two reflectors was varied. The apparatus was located ‘‘indoors in a basement hall’’ to avoid possible disturbances due to wind. There is no indication that the hall was treated anechoically.

The reflectors had a diameter of 1.524 m (5 ft), and the propagation path covered a distance of 24.36–30.48 m (80–100 ft). The corresponding resolution of the wavelength measurement was determined to be 0.1%, which is taken to be the systematic contribution to the measurement uncertainty. This is an order of magnitude greater than the author's estimate of 90 ppm, based on an uncertainty of 0.03 m/s in the measured sound speed. The temperature was determined by 11 thermometers along the propagation path, and the dew point by an ‘‘Alluard’’ hygrometer. The pressure was recorded, although a barometer was not identified. The acoustical frequency ranged from 1280 to 3072 Hz, for which the accuracy was specified as a couple hundredths of a percent. The temperature, dew point, and pressure were recorded to 0.1 °C, 0.5 °C, and 0.1 Torr, respectively. These measurements presumably contributed much less to the uncertainty than the wavelength measurement.

Hebb's measurements are compared with predictions in Table 16.10. The measured sound speed is not given directly but is evaluated here from the frequency and wavelength data provided. Agreement is remarkably good, well within the overlap of the uncertainties (see Table 16.8 for the uncertainty of the prediction). Hebb reduced the average of his measurements to the standard sound speed by the second method just listed, correcting for the specific heat and

TABLE 16.10 Speed of Sound Measurements in Air by Hebb (1919)

Parameters				Speed of sound		
Temperature T (K)	Pressure P (atm)	Humidity mole fraction x_h	Frequency f (Hz)	Measured W_m (m/s)	Predicted W_p (m/s)	Relative difference $\frac{(W_p - W_m)}{W_m}$ (%)
295.25	0.9828	0.01610	1280	345.70	345.48	−0.064
295.25	0.9824	0.01832	1280	345.99	345.60	−0.114
295.25	0.9782	0.01899	1280	345.86	345.64	−0.066
295.55	0.9761	0.02160	1280	346.22	345.95	−0.078
295.25	0.9828	0.01610	1536	345.90	345.48	−0.122
295.25	0.9824	0.01832	1536	345.36	345.60	0.070
295.25	0.9782	0.01899	1536	345.60	345.64	0.011
295.55	0.9761	0.02160	1536	345.90	345.95	0.015
295.25	0.9828	0.01610	2048	345.44	345.48	0.012
295.25	0.9824	0.01832	2048	345.92	345.60	−0.093
295.25	0.9782	0.01899	2048	345.87	345.64	−0.066
295.55	0.9761	0.02160	2048	345.96	345.95	−0.003
295.25	0.9828	0.01831	3072	345.61	345.60	−0.001
295.25	0.9824	0.01891	3072	346.12	345.64	−0.140

Note: Measurement uncertainty = 0.12%.

density according to the following equation:

$$W_{std} = W_m \sqrt{\frac{\rho_m \gamma_{std}}{\rho_{std} \gamma_m}} \tag{16.63a}$$

where the subscripts *std* and *m* refer to standard and measurement conditions, respectively. For the set of measurements listed in Table 16.10 the reduced sound speed evaluates to

$$W_{std} = 331.44 \pm 0.03 \text{ m/s}. \tag{16.63b}$$

The author's own final figure was based on an average with the result from a prior measurement, leading to a slightly lower value; but the result shown in Eq. (16.63b) will be retained here, since it is based on the data in the cited experiment (but not on the advantage of hindsight!). The standard deviation of the sound speed entries in the table amounts to 0.07%, which together with the uncertainty in the wavelength leads to a total uncertainty of 0.12% or 0.40 m/s, a value that is a more realistic assessment of the measurement uncertainty.

16.6.2 REFERENCE: W. G. SHILLING AND J. R. PARTINGTON, PHIL. MAG. 5, 920–939 (1928)

METHOD: SONIC INTERFEROMETER — VARIABLE PATH
SOURCE OF AIR: LABORATORY, DRIED CHEMICALLY (CO_2 REMOVED)
MEASUREMENT UNCERTAINTY: 0.067%

The sound speed measurements in air were part of the same work as described earlier that included gaseous water (Section 11.4.1) and nitrous oxide (Section 11.5.1). A description of the variable-path sonic interferometer was given in the gaseous water review and will not be repeated here. The measurements spanned the temperature range 273–1273 K, all at a pressure of presumably 1 atm and at a frequency of about 3000 Hz; however, only measurements at temperatures up to 600 K will be compared with handbook prediction. The air sample was subjected to an elaborate drying process that included circulating it through sulfuric acid, sodium hydroxide (to remove carbon dioxide), calcium chloride, and phosphorus pentoxide for a period of three days. Although a dew point measurement was not reported, it will be assumed here that the process left the air sample sufficiently dry to preclude the effects of humidity on the sound speed measurement.

There is some ambiguity in regard to the authors' specification on measurement uncertainty. They state a ''probable error in the velocity of sound of one part in 11,000 (0.009%)'' at room temperature, but ''the maximum deviation [of the half-wavelength measurement] from the mean did not exceed 0.004 cm on a half-wavelength of 6 cm (0.067%),'' the latter figure being preferred here as an indicator of the measurement uncertainty. The standard deviation of 20 replications of the half-wavelength measurement at 20 °C was 0.09%, a figure consistent with the aforementioned choice.

The authors made a correction for the boundary layer dispersion, but their treatment was impaired by two erroneous steps in their analysis. First, they ignored the dependence of the boundary layer correction upon tube radius, acoustic frequency, and temperature — an omission clearly at odds with the Kirchhoff formula [see Eq. (8.11)]. Second, since the Kirchhoff correction ''takes no account of the nature of the inner surface of the tube nor of the thermal properties of the material of which it is made,'' they introduced an empirical "tube constant" to "correct for the various factors which cannot be determined theoretically." As a result, the correction factor was "approximately ten times greater than that demanded by Kirchhoff's formula." For reference, a handbook evaluation based on Eq. (8.11) at 293.15 K, 1atm, 3000 Hz yields a boundary layer correction of 0.154%.

The results are summarized in Table 16.11. The pressure and mole fraction of water vapor are assumed to be 1 atm and zero, respectively. The uncertainty of the handbook prediction is about 0.1% for all the test conditions. When the uncertainties of the measurement and prediction are considered jointly, then measurement and prediction are consistent, or nearly so, for all measurements up to 573.15 K. The measurements are all smaller than predictions despite the large boundary layer corrections.

Reduction of the measured values to 273.15 K was accomplished by scaling the sound speed simply as the square root of the temperature. The authors recognized the need to scale also as the square root of the specific heat ratio but assumed this contribution to be negligible. Their final result is summarized as

$$W_{std} = 331.4 \pm 0.03 \text{ m/s} \tag{16.64}$$

although an uncertainty of ±0.2 m/s (±0.067%) is deemed more appropriate.

As a final note, the removal of carbon dioxide increased the sound speed at 288.85 K from 340.97 to 341.00 m/s, based on changes in molar mass and relaxation frequencies; however, this small correction would not alter the value 341.0 m/s listed in Table 16.11.

TABLE 16.11 Speed of Sound Measurements in Air by Shilling and Partington (1928)

Parameters				Speed of sound		
Temperature T (K)	Pressure P (atm)	Humidity mole fraction x_h	Frequency f (Hz)	Measured W_m (m/s)	Predicted W_p (m/s)	Relative difference $\frac{(W_p - W_m)}{W_m}$ (%)
273.15	1	0	3000	331.4	331.5	0.043
288.85	1	0	3000	340.8	341.0	0.048
373.15	1	0	3000	387.2	387.6	0.101
473.15	1	0	3000	435.6	436.5	0.198
573.15	1	0	3000	478.9	480.3	0.290

Note: Measurement uncertainty = 0.067%.

16.6.3 REFERENCE: H. C. HARDY, D. TELFAIR, AND W. H. PIELEMEIER, J. ACOUST. SOC. AM. 13, 226–233 (1942)

METHOD: ULTRASONIC INTERFEROMETER — VARIABLE PATH
SOURCE OF AIR: LABORATORY, DRIED CHEMICALLY AND CRYOGENICALLY (CO_2 REMOVED)
MEASUREMENT UNCERTAINTY: 0.021%

A description of the variable-path ultrasonic interferometer was given in Section 11.2.3 and will not be repeated here. X-cut quartz crystals generated ultrasound at frequencies of 902 and 1081 kHz at room temperature (~297 K), and 551 and 610 kHz at 273.15 K. Measurements were confined to the vicinity of these two temperatures. The pressure remained slightly below 1 atm. The air intake consisted of "a light breeze of fresh outdoor air from a nearby window." The air was dried by passing it through phosphorus pentoxide and then a liquid air trap; hence carbon dioxide was removed. Although a dew point reading was not undertaken, it will be assumed that the test sample was sufficiently dry that the mole fraction of water vapor could be approximated as zero. The uncertainty analysis is exemplary. The contributions, listed in a separate table, sum up to 0.07 m/s, or 0.021% based on a sound speed of 331.45 m/s.

The authors considered a need to make a "tube correction" but apparently deemed it unnecessary at the high frequencies of their experiment; however, from the sketch of the apparatus, ultrasonic propagation is clearly free-field, and a correction for diffraction is appropriate. Based on a path length of 0.08 m, tube radius of 0.034 m, and frequency of 610 kHz, the diffraction correction amounts to 46 ppm, or about one-fifth of the uncertainty specification [see Eq. (8.17)].

The authors do not report their measured sound speeds, rather only sound speeds reduced to 273.15 K (0 °C), but there are two exceptions. They fortunately show the measured sound speed at 297.96 K, used as an example in their table of uncertainty contributions. The second exception is a measurement at 0.00 °C, for which the measured value is the same as the reduced value. These two measured values are compared with handbook predictions in Table 16.12. The measurement at 296.97 K shows excellent consistency with prediction. The measurement at 273.15 K shows a difference comparable to the measurement uncertainty.

In reducing the sound speed data from measured temperatures to standard temperature, the authors, in addition to making the intrinsic $\sqrt{T}$ correction, took into account changes in the virial coefficients, specific heat (and ratio), and carbon dioxide content; however, they did not make a relaxation correction because, citing Knudsen, they erroneously concluded that at zero humidity there

TABLE 16.12 Speed of Sound Measurements in Air by Hardy, Telfair, and Pielemeier (1942)

Parameters				Speed of sound		
Temperature T (K)	Pressure P (atm)	Humidity mole fraction x_h	Frequency f (kHz)	Measured W_m (m/s)	Predicted W_p (m/s)	Relative difference $\frac{(W_p - W_m)}{W_m}$ (%)
273.15	0.954	0	610.61	331.47	331.54	0.021
296.97	0.963	0	1081.26	345.75	345.73	−0.007

Note: Measurement uncertainty = 0.021%.

is no relaxation correction. At 273.15 K the handbook correction for relaxation is 508 ppm, which is more than adequate to account for the difference between measured and handbook values.

Based on known data at the time, the authors' predicted value for the sound speed under standard conditions was found to be 331.45 ± 0.05 m/s. Based on the average of their measurements at room and ice temperatures, the standard sound speed is listed as

$$W_{std} = 331.44 \pm 0.05 \text{ m/s} \tag{16.65}$$

which encloses the most probable value, within the uncertainty limits, to this very day.

16.6.4 Reference: R. L. Abbey and G. E. Barlow, Australian J. Sci. Research A1, 175–189 (1948)

Method: Traveling Wave Tube
Source of Air: Unspecified Pressurized Supply, Dried Chemically (CO_2 Removed)
Measurement Uncertainty: 0.067%

According to the authors, "The method used is based upon the acoustical feedback between a microphone and loudspeaker which are connected to the input and output respectively of a tuned amplifier"—an arrangement that would be called a "phase-locked loop" in today's terminology. The traveling wave tube contained a fixed driver (a dynamic headphone) and a movable receiver (a "crystal cartridge from a J.T. 30 model"). The electrical system was tuned precisely to 1000 Hz. As the receiver was moved away from the driver the proper phase relationship for feedback would occur at integral-wavelength intervals; here the driver would provide a large acoustic output. The receiver was backed by cotton wool to suppress reflections. The tube had a bore diameter of 0.06985 m (2.75 in.) and length of 1.8288 m (6 ft), although the receiver travel distance was 1 m to an accuracy of 0.0001 m. The measurements spanned the pressure range 0.0066–1atm (5–760 Torr), all at a temperature near 293.15 K (20 °C).

The source of air was not disclosed, but the authors explained that the tube was evacuated to a pressure not exceeding 0.2 Torr and then ‘‘filled with gas through a system maintained at a pressure greater than atmospheric.’’ The test air was subsequently dried by passing it through potassium hydroxide to remove carbon dioxide, and phosphorus pentoxide to remove water vapor. Despite the absence of a dew point measurement, the mole fraction of water vapor will be assumed negligible. The test program included measurements in nitrogen, oxygen, carbon dioxide, and methane in addition to air.

The authors corrected their measured sound speeds for boundary layer dispersion according to Eq. (8.11) (omitting the L_{cr} term). Agreement with handbook values is excellent, the correction ranging from 0.15% at 1 atm to 1.8% at 0.0066 atm (5 Torr), all at 293.15 K. Omission of the L_{cr} term by the authors resulted in negligible error.

This is one of the few measurement sets having pressures below 1 atm. Indeed, measurements at pressures down to 0.0066 atm are difficult to find. The results are compared with handbook predictions in Table 16.13. The uncertainty in the prediction being about 0.1% at all pressures, the measurements and predictions are consistent at pressures down to 0.1974 atm. At lower pressures the measured sound speeds rise beyond prediction and experimental uncertainty. The rise cannot be attributed to noncontinuum effects because the highest f/P ratio is 152,000 Hz/atm, which is far too low for such effects to occur (see Table 1.2).

TABLE 16.13 Speed of Sound Measurements in Air by Abbey and Barlow (1948)

Parameters				Speed of sound		
Temperature T (K)	Pressure P (atm)	Humidity mole fraction x_h	Frequency f (Hz)	Measured W_m (m/s)	Predicted W_p (m/s)	Relative difference $\frac{(W_p - W_m)}{W_m}$ (%)
293.15	1.0000	0	1000	343.43	343.50	0.020
293.15	0.5263	0	1000	343.70	343.45	−0.072
293.15	0.1974	0	1000	343.80	343.42	−0.111
293.15	0.0395	0	1000	347.80	343.40	−1.280
293.15	0.0263	0	1000	348.10	343.40	−1.368
293.15	0.0066	0	1000	352.40	343.40	−2.621

Note: Measurement uncertainty = 0.067%.

Smith raised the question [32] ''whether the results indicated actual changes in the free-space velocity of sound, or that the tube correction should have some other pressure dependence.'' At the lowest pressures of the experiment, thermal conduction to the tube walls may have deteriorated to the point at which a ''temperature jump'' correction was needed [33].

The authors reduced their 1-atm measurement from 293.15 to 273.15 K ''following the method of Hardy, Telfair, and Pielemeier'' (see Section 16.6.3). The reduction consists of scaling according to the square root of the temperature plus a ''small gas imperfection correction'' and yields the value

$$W_{std} = 331.40 \pm 0.22 \text{ m/s.} \tag{16.66}$$

16.6.5 REFERENCE: J. M. A. LENIHAN, ACUSTICA 2, 205–212 (1952)

METHOD: SONIC INTERFEROMETER — VARIABLE PATH
SOURCE OF AIR: INDOOR
MEASUREMENT UNCERTAINTY: 0.012%

The variable-path sonic interferometer operated under free-field conditions in an indoor hall, $35 \times 21 \times 20$ m^3, which was ''well insulated from neighbouring buildings.'' The hall was not treated anechoically, and as a result, at low frequencies ''reflections from the walls and floor were troublesome.'' The stationary transmitter and movable receiver of the sound waves were identical moving coil headphones, 0.05 m in diameter. The propagation path could be varied from 0.15 to 1.65 m. The acoustical frequency of 13,500 Hz was sufficiently high to avoid disturbances due to reflections. Harmonic signals generated by an oscillator and the signal at the receiver were both applied to pulse-shaping circuits. As the receiver was moved away from the transmitter the pulse trains coincided at integral multiples of an acoustic wavelength. The method may rightfully be called a ''pulse coincidence method.''

The ambient temperature and humidity were measured carefully, the temperature by mercury thermometers and the humidity by a whirling hygrometer. The temperature varied between 290.15 and 292.15 K, and the humidity between 13.0 and 14.2 mbar. The data were referred to temperature of 291.15 K and 13.6 mbar (0.0133 atm). The pressure apparently was not measured and will be assumed here to be 1 atm. Reduction of the sound speed to zero humidity proceeded by the second method described in Section 16.6.

The source of test sample was indoor air. The author measured the carbon dioxide content and found it to be 0.035%.

The author made corrections for the effect of water vapor on specific heat and density in reducing the sound speed to zero humidity. The corrections for temperature included the effect upon density, compressibility, and specific heat.

TABLE 16.14 Speed of Sound Measurements in Air by Lenihan (1952)

Parameters				Speed of sound		
Temperature T (K)	Pressure P (atm)	Humidity mole fraction x_h	Frequency f (Hz)	Measured W_m (m/s)	Predicted W_p (m/s)	Relative difference $\frac{(W_p - W_m)}{W_m}$ (%)
291.15	1	0.01329	13500	342.88	342.94	0.019

Note: Measurement uncertainty = 0.012%.

The contributions to the uncertainty are listed in a separate table. The total uncertainty was determined to be 0.04 m/s (0.012%).

The author did not make a diffraction correction. A handbook estimate based on Eq. (8.17) for a path length of 1.63 m, transmitter radius of 0.025 m, and frequency of 13,500 Hz yields a correction of 0.36%. Because of the low frequency and relatively long wavelength, the diffraction parameter $S_d = 64.0 \gg 2$, indicating propagation in the Frauenhofer zone.

The author did not give the actual measured sound speed but provided the wavelength, so that the sound speed at 291.15 K could easily be determined. The result is shown in Table 16.14. The difference between measurement and handbook prediction is −0.019%. Measurement and prediction are consistent, since the uncertainty of the prediction is about 0.1%.

The procedures for reducing the measured sound speed to standard temperature and zero humidity yield for the standard sound speed

$$W_{std} = 331.451 \pm 0.04 \text{ m/s}. \tag{16.67}$$

16.6.6 Reference: P. W. Smith, Jr., J. Acoust. Soc. Am. 25, 81–86 (1953)
Method: Sonic Interferometer — Variable Path
Source of Air: Compressed Gas Cylinder, Dried Chemically (CO_2 Removed)
Measurement Uncertainty: 0.0049%

The variable-path sonic interferometer consisted of a brass tube, 0.073025 m (2.875 in.) in bore diameter and 1.524 m (5 ft) in length. Measurements were also conducted in a smaller tube, 0.034925 m (1.375 in.) in bore diameter, but these were not reported. The transmitter was a moving-coil loudspeaker, and the reflector a movable brass piston having the same diameter as the bore of the tube. Operation of the interferometer utilized the principle of the "bridge-stabilized oscillator," whereby the frequency of oscillation depended upon the driving point impedance of the loudspeaker and thus the position of the reflector. Measurements were made at positions where the frequency of oscillation was 1000 Hz. For six reported measurements these positions ranged from 0.341 to 0.344 m, presumably relative to the loudspeaker. The temperature and pressure were in the vicinities of 292 K and 1.07 atm, respectively. The test samples came from a cylinder of compressed air that was subsequently dried through a column of anhydrous calcium sulfate and introduced into the tube, which was evacuated and flushed several times with the treated air. The dew point was not measured but will be assumed sufficiently low to preclude the effects of water vapor upon the speed of sound. The uncertainty specification for measured values, reduced to 295.15 K, is 0.017 m/s, or 0.0049% based on an uncorrected sound speed of 344.157 m/s. This will be taken for the uncertainty specification for the corrected sound speeds also, even though the tube correction exceeds the uncertainty specification (see below).

The author made the tube correction according to Kirchhoff and augmented it by 5% in keeping with some prevailing opinion at the time that the Kirchhoff formula underestimated the correction. He obtained a correction of 31 ppm, which is orders of magnitude too low. An estimate based on Eq. (8.11) for a tube radius of 0.036513 m, path length of 0.343 m, frequency of 1000 Hz, temperature of 294.15 K, and pressure of 1.07 atm is 0.143% (1430 ppm). The latter value of the boundary layer correction was applied in this handbook to the author's uncorrected results.

Measurement and prediction, summarized for six reported measurements in Table 16.15, reveal excellent consistency, far within the bounds of the predicted

TABLE 16.15 Speed of Sound Measurements in Air by Smith (1953)

Parameters				Speed of sound		
Temperature T (K)	Pressure P (atm)	Humidity mole fraction x_h	Frequency f (Hz)	Measured[a] W_m (m/s)	Predicted W_p (m/s)	Relative difference $\frac{(W_p - W_m)}{W_m}$ (%)
295.45	1.0650	0	1000	344.791	344.856	0.0188
294.40	1.0559	0	1000	344.239	344.237	−0.0005
293.59	1.0662	0	1000	343.744	343.765	0.0061
293.61	1.0661	0	1000	343.754	343.777	0.0067
293.68	1.0651	0	1000	343.792	343.815	0.0066
295.00	1.0657	0	1000	344.549	344.590	−0.0119

Note: Measurement uncertainty = 0.0049%.
[a]Corrected for boundary layer dispersion according to Eq. (8.11).

uncertainty (equal to 0.1%). Based on this comparison, the uncertainty specification of 0.0049% for the measurement is well justified. The author reduced the sound speed to standard conditions, based on the method of Hardy, Telfair, and Pielemeier (see Section 16.6.3), defining standard conditions as 0.03% carbon dioxide, 0.00% water vapor, 273.15 K (''ice point''), and 1 atm. He questioned the validity of specifying a sound speed in the limit of zero frequency, citing a statement attributed to Stokes that ''the loss of heat by radiation should make the velocity of an unbounded plane wave tend toward its isothermal value as the frequency is lowered.'' This opinion is known to be erroneous, as argued by Herzfeld and Litovitz, because sound propagation actually behaves more adiabatically with decreasing frequency [34]. Of course, in an enclosure, where the thermal boundary layer grows with decreasing frequency, the sound speed will eventually become isothermal. Thus a free-field sound speed in the limit of zero frequency remains a valid concept. The result of the reduction to standard conditions is

$$W_{std} = 331.45 \pm 0.05 \text{ m/s}. \tag{16.68}$$

The uncertainty bounds were based on random and systematic errors of the measurement and ''inaccuracy in the knowledge of the tube effect.''

16.6.7 Reference: D. H. Smith and R. G. Harlow, Brit. J. Appl. Phys. 14, 102–106 (1963)

Method: Cylindrical Resonator
Source of Air: Outside, ''Deprived of Carbon Dioxide and Dried''
Measurement Uncertainty: 0.0028% (28 ppm)

The cylindrical resonator was described in Section 10.7.5, to which the interested reader is referred. The sound speed measurements in air were part of a study that also included measurements in argon and nitrogen. The test air was ''drawn from outside the building,'' cleaned, and dried, although details are not provided. A dew point measurement was not provided, but it will be assumed that the mole fraction of water vapor was small enough to preclude any effect upon the sound speed. The resonator tube was evacuated and charged with the test air several times. After the final charge provision was made to adjust the pressure to ambient pressure, which was not recorded but will be assumed here to be 1 atm. The temperature was maintained at 304.25 K, but the reported sound speeds were reduced to 303.15 K. The frequencies spanned the range 93.3–1505.2 Hz, corresponding to the fundamental up to the 16th harmonic.

A boundary layer correction was determined by two different methods. In the first, the correction was derived from the experimental attenuation. In the second, it was computed from the Kirchhoff formula [Eq. (8.11)] (but with the resonator length term omitted). The handbook estimate amounts to 0.89% at 93.3 Hz and 0.22% at 1505.2 Hz, in agreement with the authors; however, the authors chose to use the experimental corrections, based on attenuation, which were found to be 16.7% higher.

The results are summarized in Table 16.16. The measurements are slightly lower than prediction but within the bounds of the predictive uncertainty (0.1%). Despite the low measurement frequencies the sound speeds are well into the high-frequency side of the dispersion steps, since the nitrogen and oxygen relaxation frequencies are 4.7 and 6 Hz, respectively. The relaxation correction is correspondingly small and nearly constant over the range of experimental frequencies, as is consistent with the authors' data.

The authors reduced the mean measured sound speed to 273.15 K, made a small correction for carbon dioxide, which had been removed from the test air, and obtained for the standard sound speed

TABLE 16.16 Speed of Sound Measurements in Air by Smith and Harlow (1963)

Parameters				Speed of sound		
Temperature T (K)	Pressure P (atm)	Humidity mole fraction x_h	Frequency f (Hz)	Measured W_m (m/s)	Predicted W_p (m/s)	Relative difference $\frac{(W_p - W_m)}{W_m}$ (%)
303.15	1	0	93.3	349.21	349.32	0.031
303.15	1	0	187.2	349.23	349.32	0.026
303.15	1	0	281.2	349.20	349.32	0.034
303.15	1	0	657.63	349.20	349.32	0.034
303.15	1	0	751.7	349.22	349.32	0.029
303.15	1	0	1034.53	349.23	349.32	0.026
303.15	1	0	1222.58	349.18	349.32	0.040
303.15	1	0	1316.9	349.21	349.32	0.031
303.15	1	0	1410.9	349.19	349.32	0.037
303.15	1	0	1505.2	349.19	349.32	0.037

Note: Measurement uncertainty = 0.0028%.

$$W_{std} = 331.45 \pm 0.01 \text{ m/s}. \tag{16.69}$$

This measurement establishes the most probable value of the standard sound speed to date.

16.7 TABLES OF THE SPEED OF SOUND IN AIR

The tables in this section list the predicted real speed of sound in air [Eq. (16.53)] over a range of pressure from 0.5 to 100 atm in 8 steps, temperature from 233.15 to 603.15 K (-40 to 330 °C) in 16 steps, relative humidity from 0 to 100% in 3 or 6 steps, and frequency from 0 to 100 kHz in 14 steps. The top part of each table lists the pressure, temperature, humidity, specific heat and virial corrections in ppm, and the simple speed of sound. The humidity data include three selected values of relative humidity, organized into three columns, and the corresponding mole fractions of water vapor and enhancement factors. The bottom part of the table lists the frequency, relaxation correction in ppm, and the real speed of sound and its uncertainty.

The selections of relative humidity depend upon whether the saturation pressure of water vapor is less than or greater than the listed air pressure. If the saturation pressure is less, then 100% relative humidity will correspond to a small mole fraction of water vapor. If it is greater, then the relative humidity corresponding to a mole fraction of one will be less than 100%.

The uncertainty includes contributions from the specific heat, virial, and relaxation corrections, plus that due to the conversion from relative humidity to mole fraction. The speed of sound is listed to five significant figures, which are not always justified, since a typical uncertainty of 0.1% will affect the fourth significant figure; however, the fifth significant figure is included to show the dispersion of the sound speed. The specific heat ratio is out of range at temperatures below 250 K, but is so close to the simple value that extrapolation to 233 K results in negligible error compared with the total predictive uncertainty. Further, it is implied that three virial terms are adequate to represent the isothermal compressibility of air up to a pressure of 100 atm.

The pressure–temperature–humidity–frequency window contains significant regions that are not covered by measurements, in which case future measurements may reveal the need to improve the predictive model or to increase the uncertainty.

TABLE 16.17 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5		0.5		0.5	
Temperature T (K)	233.15		233.15		233.15	
Humidity						
RH, h_r (%)	0		50		100	
Mole fraction x_h	0		0.000187		0.000374	
Enhancement factor f_e	1.00300		1.00300		1.00300	
Corrections						
Specific heat K_C (ppm)	755		754		754	
Virial K_V (ppm)	−181		−181		−181	
Simple sound speed W_s (m/s)	306.10		306.11		306.12	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	306.19	0	306.20	0	306.21
10	122	306.21	23	306.20	9	306.21
20	148	306.21	55	306.21	17	306.21
50	158	306.21	119	306.22	48	306.22
100	160	306.21	147	306.22	96	306.22
200	160	306.21	157	306.22	137	306.23
500	160	306.21	160	306.22	156	306.23
1000	160	306.21	160	306.22	159	306.23
2000	160	306.21	160	306.22	160	306.23
5000	160	306.21	160	306.22	160	306.23
10K	160	306.21	160	306.22	160	306.23
20K	160	306.21	160	306.22	160	306.23
50K	160	306.21	160	306.22	160	306.23
100K	160	306.21	160	306.22	160	306.23
Uncertainty $\delta W/W$ (%)		0.10		0.10		0.10

TABLE 16.18 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5	0.5	0.5
Temperature T (K)	243.15	243.15	243.15
Humidity			
RH, h_r (%)	0	50	100
Mole fraction x_h	0	0.000503	0.00101
Enhancement factor f_e	1.00273	1.00273	1.00273
Corrections			
Specific heat K_C (ppm)	725	724	723
Virial K_V (ppm)	−65	−65	−65
Simple sound speed W_s (m/s)	312.60	312.62	312.65

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	312.70	0	312.73	0	312.75
10	158	312.73	11	312.73	5	312.75
20	201	312.73	18	312.73	11	312.75
50	218	312.74	39	312.73	18	312.75
100	221	312.74	83	312.74	26	312.76
200	222	312.74	151	312.75	50	312.76
500	222	312.74	206	312.76	127	312.77
1000	222	312.74	218	312.76	186	312.78
2000	222	312.74	221	312.76	211	312.78
5000	222	312.74	222	312.76	220	312.79
10K	222	312.74	222	312.76	221	312.79
20K	222	312.74	222	312.76	222	312.79
50K	222	312.74	222	312.76	222	312.79
100K	222	312.74	222	312.76	222	312.79
Uncertainty $\delta W/W$ (%)		0.10		0.10		0.10

TABLE 16.19 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5	0.5	0.5
Temperature T (K)	253.15	253.15	253.15
Humidity			
RH, h_r (%)	0	50	100
Mole fraction x_h	0	0.00124	0.00248
Enhancement factor f_e	1.00250	1.00250	1.00250
Corrections			
Specific heat K_C (ppm)	666	663	660
Virial K_V (ppm)	32	32	31
Simple sound speed W_s (m/s)	318.96	319.03	319.09

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	319.07	0	319.14	0	319.20
10	197	319.10	6	319.14	2	319.20
20	264	319.12	15	319.14	7	319.20
50	293	319.12	26	319.14	19	319.20
100	298	319.12	33	319.14	25	319.20
200	299	319.12	50	319.14	30	319.20
500	299	319.12	125	319.16	43	319.21
1000	299	319.12	215	319.17	80	319.21
2000	299	319.12	272	319.18	160	319.22
5000	299	319.12	294	319.18	260	319.24
10K	299	319.12	298	319.18	287	319.24
20K	299	319.12	298	319.18	295	319.25
50K	299	319.12	299	319.18	298	319.25
100K	299	319.12	299	319.18	298	319.25
Uncertainty $\delta W/W$ (%)		0.11		0.10		0.10

TABLE 16.20 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5	0.5	0.5
Temperature T (K)	263.15	263.15	263.15
Humidity			
RH, h_r (%)	0	50	100
Mole fraction x_h	0	0.00283	0.00566
Enhancement factor f_e	1.00229	1.00229	1.00229
Corrections			
Specific heat K_C (ppm)	579	570	561
Virial K_V (ppm)	114	112	109
Simple sound speed W_s (m/s)	325.20	325.35	325.50

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	325.31	0	325.46	0	325.61
10	240	325.35	2	325.46	1	325.61
20	338	325.37	8	325.46	2	325.61
50	384	325.38	25	325.46	12	325.61
100	391	325.38	37	325.47	26	325.61
200	393	325.38	43	325.47	37	325.61
500	394	325.38	55	325.47	43	325.61
1000	394	325.38	90	325.47	49	325.61
2000	394	325.38	178	325.49	69	325.62
5000	394	325.38	322	325.51	162	325.63
10K	394	325.38	372	325.52	278	325.65
20K	394	325.38	387	325.52	354	325.66
50K	394	325.38	392	325.52	385	325.67
100K	394	325.38	392	325.52	389	325.67
Uncertainty $\delta W/W$ (%)		0.11		0.10		0.10

TABLE 16.21 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5		0.5		0.5	
Temperature T (K)	273.15		273.15		273.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00242		0.00483	
Enhancement factor f_e	1.00209		1.00209		1.00209	
Corrections						
Specific heat K_C (ppm)	462		453		445	
Virial K_V (ppm)	182		181		179	
Simple sound speed W_s (m/s)	331.32		331.45		331.58	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	331.43	0	331.56	0	331.68
10	286	331.48	4	331.56	1	331.68
20	422	331.50	14	331.56	5	331.68
50	492	331.51	41	331.56	21	331.69
100	504	331.51	56	331.56	42	331.69
200	507	331.51	65	331.57	56	331.69
500	508	331.51	89	331.57	65	331.69
1000	508	331.51	152	331.58	76	331.70
2000	508	331.51	286	331.60	113	331.70
5000	508	331.51	446	331.63	260	331.73
10K	508	331.51	490	331.64	400	331.75
20K	508	331.51	502	331.64	473	331.76
50K	508	331.51	506	331.64	500	331.77
100K	508	331.51	507	331.64	504	331.77
Uncertainty $\delta W/W$ (%)		0.11		0.10		0.10

TABLE 16.22 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5		0.5		0.5	
Temperature T (K)	273.15		273.15		273.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.00725		0.00966		0.0121	
Enhancement factor f_e	1.00209		1.00209		1.00209	
Corrections						
Specific heat K_C (ppm)	437		428		420	
Virial K_V (ppm)	176		172		167	
Simple sound speed W_s (m/s)	331.71		331.84		331.97	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	331.81	0	331.94	0	332.06
10	1	331.81	0	331.94	0	332.06
20	2	331.81	1	331.94	1	332.06
50	12	331.81	7	331.94	5	332.06
100	30	331.81	21	331.94	16	332.07
200	49	331.82	42	331.94	36	332.07
500	61	331.82	58	331.95	56	332.07
1000	66	331.82	63	331.95	62	332.07
2000	80	331.82	71	331.95	67	332.08
5000	155	331.84	111	331.96	91	332.08
10K	289	331.86	209	331.97	160	332.09
20K	419	331.88	356	332.00	296	332.11
50K	487	331.89	469	332.01	446	332.14
100K	499	331.89	493	332.02	485	332.14
Uncertainty $\delta W/W$ (%)		0.10		0.10		0.10

TABLE 16.23 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5	0.5	0.5
Temperature T (K)	283.15	283.15	283.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.00485	0.00971
Enhancement factor f_e	1.00192	1.00192	1.00192
Corrections			
Specific heat K_C (ppm)	316	297	279
Virial K_V (ppm)	241	237	231
Simple sound speed W_s (m/s)	337.33	337.60	337.86

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	337.43	0	337.69	0	337.95
10	333	337.48	2	337.69	0	337.95
20	516	337.51	6	337.69	2	337.95
50	619	337.53	28	337.69	10	337.95
100	637	337.53	58	337.70	29	337.95
200	642	337.53	80	337.70	59	337.96
500	644	337.53	92	337.70	83	337.96
1000	644	337.53	106	337.70	90	337.96
2000	644	337.53	151	337.71	100	337.96
5000	644	337.53	332	337.74	149	337.97
10K	644	337.53	507	337.77	270	337.99
20K	644	337.53	599	337.79	452	338.02
50K	644	337.53	633	337.79	595	338.05
100K	644	337.53	638	337.79	625	338.05
Uncertainty $\delta W/W$ (%)		0.11		0.10		0.10

TABLE 16.24 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5	0.5	0.5
Temperature T (K)	283.15	283.15	283.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.0146	0.0194	0.0243
Enhancement factor f_e	1.00192	1.00192	1.00192
Corrections			
Specific heat K_C (ppm)	260	242	224
Virial K_V (ppm)	222	210	196
Simple sound speed W_s (m/s)	338.12	338.39	338.66

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	338.21	0	338.47	0	338.73
10	0	338.21	0	338.47	0	338.73
20	1	338.21	0	338.47	0	338.73
50	5	338.21	3	338.47	2	338.73
100	16	338.21	10	338.47	6	338.73
200	41	338.21	29	338.47	21	338.73
500	75	338.22	67	338.48	58	338.74
1000	86	338.22	82	338.48	78	338.74
2000	92	338.22	88	338.48	86	338.74
5000	112	338.22	100	338.48	95	338.74
10K	172	338.23	134	338.49	116	338.75
20K	317	338.26	233	338.51	185	338.76
50K	533	338.30	464	338.54	398	338.79
100K	603	338.31	574	338.56	541	338.82
Uncertainty $\delta W/W$ (%)		0.10		0.10		0.10

TABLE 16.25 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5		0.5		0.5	
Temperature T (K)	293.15		293.15		293.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00924		0.0185	
Enhancement factor f_e	1.00177		1.00177		1.00177	
Corrections						
Specific heat K_C (ppm)	142		103		64	
Virial K_V (ppm)	290		281		264	
Simple sound speed W_s (m/s)	343.24		343.75		344.26	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	343.31	0	343.81	0	344.32
10	383	343.38	1	343.81	0	344.32
20	618	343.42	2	343.81	1	344.32
50	765	343.44	14	343.82	4	344.32
100	793	343.45	41	343.82	14	344.32
200	800	343.45	83	343.83	42	344.33
500	802	343.45	117	343.83	94	344.33
1000	802	343.45	126	343.84	115	344.34
2000	802	343.45	139	343.84	124	344.34
5000	802	343.45	206	343.85	140	344.34
10K	802	343.45	363	343.88	185	344.35
20K	802	343.45	585	343.91	316	344.37
50K	802	343.45	748	343.94	598	344.42
100K	802	343.45	781	343.95	724	344.44
Uncertainty $\delta W/W$ (%)		0.11		0.10		0.10

TABLE 16.26 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5	0.5	0.5
Temperature T (K)	293.15	293.15	293.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.0277	0.0370	0.0462
Enhancement factor f_e	1.00177	1.00177	1.00177
Corrections			
Specific heat K_C (ppm)	25	−13	−51
Virial K_V (ppm)	240	208	168
Simple sound speed W_s (m/s)	344.78	345.30	345.82

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	344.82	0	345.33	0	345.84
10	0	344.82	0	345.33	0	345.84
20	0	344.82	0	345.33	0	345.84
50	2	344.82	1	345.33	1	345.84
100	7	344.83	4	345.33	2	345.84
200	23	344.83	14	345.33	9	345.84
500	72	344.84	54	345.34	41	345.85
1000	104	344.84	92	345.35	80	345.86
2000	118	344.84	112	345.35	106	345.86
5000	128	344.85	122	345.35	119	345.86
10K	147	344.85	134	345.36	126	345.86
20K	213	344.86	171	345.36	151	345.87
50K	451	344.90	346	345.39	278	345.89
100K	644	344.94	560	345.43	481	345.93
Uncertainty $\delta W/W$ (%)		0.10		0.11		0.11

TABLE 16.27 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5	0.5	0.5
Temperature T (K)	303.15	303.15	303.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.0168	0.0336
Enhancement factor f_e	1.00162	1.00162	1.00162
Corrections			
Specific heat K_C (ppm)	−61	−138	−215
Virial K_V (ppm)	332	311	270
Simple sound speed W_s (m/s)	349.04	349.99	350.94

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	349.09	0	350.02	0	350.95
10	434	349.17	0	350.02	0	350.95
20	727	349.22	1	350.02	0	350.95
50	930	349.25	6	350.02	2	350.95
100	971	349.26	21	350.02	6	350.95
200	982	349.26	62	350.03	21	350.96
500	985	349.26	132	350.04	79	350.97
1000	985	349.26	159	350.05	130	350.97
2000	985	349.26	170	350.05	155	350.98
5000	985	349.26	193	350.05	168	350.98
10K	985	349.26	259	350.06	184	350.98
20K	985	349.26	439	350.09	240	350.99
50K	985	349.26	775	350.15	476	351.04
100K	985	349.26	906	350.18	729	351.08
Uncertainty $\delta W/W$ (%)		0.11		0.10		0.11

TABLE 16.28 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5		0.5		0.5	
Temperature T (K)	303.15		303.15		303.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.0503		0.0671		0.0839	
Enhancement factor f_e	1.00162		1.00162		1.00162	
Corrections						
Specific heat K_C (ppm)	−290		−365		−438	
Virial K_V (ppm)	209		127		25	
Simple sound speed W_s (m/s)	351.91		352.89		353.87	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	351.89	0	352.84	0	353.80
10	0	351.89	0	352.84	0	353.80
20	0	351.89	0	352.84	0	353.80
50	1	351.89	0	352.84	0	353.80
100	3	351.89	1	352.84	1	353.80
200	10	351.90	6	352.84	4	353.80
500	47	351.90	30	352.85	20	353.80
1000	100	351.91	76	352.86	58	353.81
2000	140	351.92	124	352.87	108	353.82
5000	159	351.92	152	352.87	144	353.83
10K	168	351.92	160	352.87	153	353.83
20K	193	351.93	174	352.87	163	353.83
50K	326	351.95	254	352.89	216	353.84
100K	560	351.99	436	352.92	352	353.86
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.29 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5	0.5	0.5
Temperature T (K)	313.15	313.15	313.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.0292	0.0583
Enhancement factor f_e	1.00149	1.00149	1.00149
Corrections			
Specific heat K_C (ppm)	−292	−438	−580
Virial K_V (ppm)	368	322	227
Simple sound speed W_s (m/s)	354.75	356.43	358.14

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	354.77	0	356.41	0	358.08
10	487	354.85	0	356.41	0	358.08
20	843	354.92	0	356.41	0	358.08
50	1116	354.96	3	356.41	1	358.08
100	1173	354.97	10	356.41	2	358.08
200	1189	354.98	35	356.41	9	358.08
500	1193	354.98	119	356.43	48	358.08
1000	1194	354.98	182	356.44	114	358.10
2000	1194	354.98	211	356.45	175	358.11
5000	1194	354.98	227	356.45	207	358.11
10K	1194	354.98	253	356.45	217	358.11
20K	1194	354.98	338	356.47	239	358.12
50K	1194	354.98	662	356.53	362	358.14
100K	1194	354.98	947	356.58	610	358.18
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.30 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5		0.5		0.5	
Temperature T (K)	313.15		313.15		313.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.0875		0.117		0.146	
Enhancement factor f_e	1.00149		1.00149		1.00149	
Corrections						
Specific heat K_C (ppm)	−720		−857		−991	
Virial K_V (ppm)	83		−112		−357	
Simple sound speed W_s (m/s)	359.88		361.66		363.47	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	359.77	0	361.48	0	363.23
10	0	359.77	0	361.48	0	363.23
20	0	359.77	0	361.48	0	363.23
50	0	359.77	0	361.49	0	363.23
100	1	359.77	1	361.49	0	363.23
200	4	359.77	2	361.49	1	363.23
500	23	359.77	13	361.49	8	363.23
1000	70	359.78	44	361.49	30	363.23
2000	137	359.79	105	361.50	80	363.24
5000	189	359.80	172	361.52	154	363.26
10K	202	359.80	190	361.52	178	363.26
20K	214	359.81	199	361.52	187	363.26
50K	271	359.82	231	361.53	209	363.27
100K	422	359.84	325	361.54	270	363.28
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.31 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5	0.5	0.5
Temperature T (K)	323.15	323.15	323.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.049	0.098
Enhancement factor f_e	1.00137	1.00137	1.00137
Corrections			
Specific heat K_C (ppm)	−551	−813	−1066
Virial K_V (ppm)	398	303	96
Simple sound speed W_s (m/s)	360.37	363.24	366.20

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	360.34	0	363.15	0	366.02
10	543	360.44	0	363.15	0	366.02
20	965	360.52	0	363.15	0	366.02
50	1320	360.58	1	363.15	0	366.02
100	1400	360.60	4	363.15	1	366.02
200	1422	360.60	17	363.15	4	366.02
500	1428	360.60	80	363.16	24	366.03
1000	1429	360.60	172	363.18	75	366.04
2000	1429	360.60	243	363.19	161	366.05
5000	1429	360.60	277	363.20	238	366.07
10K	1429	360.60	291	363.20	258	366.07
20K	1429	360.60	328	363.21	270	366.07
50K	1429	360.60	522	363.24	325	366.08
100K	1429	360.60	853	363.30	474	366.11
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.32 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5		0.5		0.5	
Temperature T (K)	323.15		323.15		323.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.146		0.195		0.244	
Enhancement factor f_e	1.00137		1.00137		1.00137	
Corrections						
Specific heat K_C (ppm)	−1310		−1546		−1773	
Virial K_V (ppm)	−225		−662		−1216	
Simple sound speed W_s (m/s)	369.26		372.43		375.71	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	368.98	0	372.02	0	375.15
10	0	368.98	0	372.02	0	375.15
20	0	368.98	0	372.02	0	375.15
50	0	368.98	0	372.02	0	375.15
100	0	368.98	0	372.02	0	375.15
200	2	368.98	1	372.02	1	375.15
500	10	368.98	6	372.02	3	375.15
1000	37	368.99	20	372.02	13	375.15
2000	101	369.00	64	372.03	42	375.15
5000	199	369.02	161	372.05	128	375.17
10K	231	369.02	205	372.06	180	375.18
20K	244	369.03	222	372.06	201	375.18
50K	269	369.03	238	372.06	214	375.19
100K	340	369.04	277	372.07	239	375.19
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.33 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5	0.5	0.5
Temperature T (K)	373.15	373.15	373.15
Humidity			
RH, h_r (%)	0	10	20
Mole fraction x_h	0	0.200	0.400
Enhancement factor f_e	1.00090	1.00090	1.00090
Corrections			
Specific heat K_C (ppm)	−2253	−3669	−4888
Virial K_V (ppm)	493	−102	−1499
Simple sound speed W_s (m/s)	387.25	400.57	415.89

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	386.91	0	399.81	0	414.56
10	865	387.08	0	399.81	0	414.56
20	1645	387.23	0	399.81	0	414.56
50	2609	387.41	0	399.81	0	414.56
100	2914	387.47	1	399.81	0	414.56
200	3005	387.49	2	399.81	0	414.56
500	3032	387.49	12	399.82	2	414.56
1000	3036	387.50	47	399.82	9	414.56
2000	3037	387.50	155	399.84	33	414.57
5000	3037	387.50	436	399.90	149	414.59
10K	3038	387.50	589	399.93	303	414.62
20K	3038	387.50	648	399.94	409	414.65
50K	3038	387.50	686	399.95	457	414.65
100K	3038	387.50	758	399.96	477	414.66
Uncertainty $\delta W/W$ (%)		0.13		0.12		0.15

TABLE 16.34 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5		0.5		0.5	
Temperature T (K)	373.15		373.15		373.15	
Humidity						
RH, h_r (%)	30		40		49.95	
Mole fraction x_h	0.601		0.801		1.000	
Enhancement factor f_e	1.00090		1.00090		1.00090	
Corrections						
Specific heat K_C (ppm)	−5940		−6849		−7632	
Virial K_V (ppm)	−3713		−6760		−10635	
Simple sound speed W_s (m/s)	433.66		454.51		479.18	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	431.57	0	451.42	0	474.80
10	0	431.57	0	451.42	0	474.80
20	0	431.57	0	451.42	0	474.80
50	0	431.57	0	451.42	0	474.80
100	0	431.57	0	451.42	0	474.80
200	0	431.57	0	451.42	0	474.80
500	1	431.57	0	451.42	0	474.80
1000	2	431.57	1	451.42	0	474.80
2000	9	431.57	2	451.42	0	474.80
5000	50	431.58	14	451.42	0	474.80
10K	131	431.60	43	451.43	0	474.80
20K	221	431.62	87	451.44	0	474.80
50K	275	431.63	123	451.44	0	474.80
100K	288	431.63	132	451.45	0	474.80
Uncertainty $\delta W/W$ (%)		0.17		0.18		0.21

TABLE 16.35 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5	0.5	0.5
Temperature T (K)	423.15	423.15	423.15
Humidity			
RH, h_r (%)	0	5	10.63
Mole fraction x_h	0	0.470	1.000
Enhancement factor f_e	1.00057	1.00057	1.00057
Corrections			
Specific heat K_C (ppm)	−4607	−8440	−11386
Virial K_V (ppm)	531	−1054	−5471
Simple sound speed W_s (m/s)	412.38	449.16	510.27

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	411.54	0	447.03	0	505.97
10	1231	411.79	0	447.03	0	505.97
20	2441	412.04	0	447.03	0	505.97
50	4224	412.41	0	447.03	0	505.97
100	5006	412.57	0	447.03	0	505.97
200	5279	412.62	0	447.03	0	505.97
500	5363	412.64	3	447.03	0	505.97
1000	5376	412.64	10	447.03	0	505.97
2000	5379	412.64	39	447.04	0	505.97
5000	5380	412.64	196	447.07	0	505.97
10K	5380	412.64	470	447.13	0	505.97
20K	5380	412.64	723	447.19	0	505.97
50K	5380	412.64	854	447.22	0	505.97
100K	5380	412.64	888	447.23	0	505.97
Uncertainty $\delta W/W$ (%)		0.14		0.16		0.23

TABLE 16.36 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5	0.5	0.5
Temperature T (K)	473.15	473.15	473.15
Humidity			
RH, h_r (%)	0	1.5	3.24
Mole fraction x_h	0	0.463	1.000
Enhancement factor f_e	1.00033	1.00033	1.00033
Corrections			
Specific heat K_C (ppm)	−7566	−12062	−15566
Virial K_V (ppm)	542	−528	−3200
Simple sound speed W_s (m/s)	436.06	474.23	539.56

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	434.53	0	471.24	0	534.48
10	1569	434.87	0	471.24	0	534.48
20	3329	435.25	0	471.24	0	534.48
50	6003	435.83	0	471.24	0	534.48
100	7511	436.16	0	471.24	0	534.48
200	8140	436.29	1	471.24	0	534.48
500	8349	436.34	4	471.24	0	534.48
1000	8380	436.34	16	471.24	0	534.48
2000	8388	436.35	63	471.26	0	534.48
5000	8390	436.35	329	471.32	0	534.48
10K	8390	436.35	818	471.43	0	534.48
20K	8391	436.35	1302	471.55	0	534.48
50K	8391	436.35	1565	471.61	1	534.48
100K	8391	436.35	1628	471.62	1	534.48
Uncertainty $\delta W/W$ (%)		0.15		0.18		0.28

TABLE 16.37 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5	0.5	0.5
Temperature T (K)	523.15	523.15	523.15
Humidity			
RH, h_r (%)	0	0.5	1.251
Mole fraction x_h	0	0.400	1.000
Enhancement factor f_e	1.00015	1.00015	1.00015
Corrections			
Specific heat K_C (ppm)	−11077	−15562	−20028
Virial K_V (ppm)	538	−130	−2033
Simple sound speed W_s (m/s)	458.52	492.36	567.36

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	456.10	0	488.48	0	561.07
10	1820	456.52	0	488.48	0	561.07
20	4204	457.06	0	488.48	0	561.07
50	7848	457.89	0	488.48	0	561.07
100	10207	458.42	0	488.48	0	561.07
200	11398	458.69	1	488.48	0	561.07
500	11832	458.79	9	488.48	0	561.07
1000	11899	458.81	35	488.49	0	561.07
2000	11916	458.81	135	488.51	0	561.07
5000	11921	458.81	678	488.65	0	561.07
10K	11921	458.81	1602	488.87	0	561.07
20K	11922	458.81	2431	489.08	0	561.07
50K	11922	458.81	2852	489.18	1	561.07
100K	11922	458.81	2956	489.20	1	561.07
Uncertainty $\delta W/W$ (%)		0.16		0.33		0.87

TABLE 16.38 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5		0.5		0.5	
Temperature T (K)	573.15		573.15		573.15	
Humidity						
RH, h_r (%)	0		0.25		0.565	
Mole fraction x_h	0		0.442		1.000	
Enhancement factor f_e	1.00001		1.00001		1.00001	
Corrections						
Specific heat K_C (ppm)	−15083		−20338		−24639	
Virial K_V (ppm)	526		−104		−1367	
Simple sound speed W_s (m/s)	479.94		519.79		593.88	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	476.43	0	514.45	0	586.12
10	1967	476.90	0	514.45	0	586.12
20	4947	477.61	0	514.45	0	586.12
50	9690	478.73	0	514.45	0	586.12
100	12897	479.49	0	514.45	0	586.12
200	14825	479.95	1	514.45	0	586.12
500	15613	480.13	8	514.45	0	586.12
1000	15740	480.16	33	514.46	0	586.12
2000	15772	480.17	129	514.48	0	586.12
5000	15781	480.17	686	514.63	0	586.12
10K	15782	480.17	1783	514.91	0	586.12
20K	15782	480.17	2969	515.21	0	586.12
50K	15783	480.17	3657	515.39	0	586.12
100K	15783	480.17	3811	515.43	0	586.12
Uncertainty $\delta W/W$ (%)		0.17		0.55		1.47

TABLE 16.39 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	0.5		0.5		0.5	
Temperature T (K)	603.15		603.15		603.15	
Humidity						
RH, h_r (%)	0		0.2		0.3693	
Mole fraction x_h	0		0.541		1.000	
Enhancement factor f_e	1.000		1.000		1.000	
Corrections						
Specific heat K_C (ppm)	−17700		−24013		−27424	
Virial K_V (ppm)	517		−213		−1097	
Simple sound speed W_s (m/s)	492.34		544.29		609.15	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	488.09	0	537.66	0	600.41
10	2008	488.58	0	537.66	0	600.41
20	5294	489.38	0	537.66	0	600.41
50	10759	490.70	0	537.66	0	600.41
100	14448	491.60	0	537.66	0	600.41
200	16870	492.19	1	537.66	0	600.41
500	17938	492.44	5	537.66	0	600.41
1000	18114	492.49	20	537.66	0	600.41
2000	18159	492.50	77	537.68	0	600.41
5000	18172	492.50	434	537.77	0	600.41
10K	18174	492.50	1272	538.00	0	600.41
20K	18174	492.50	2460	538.32	1	600.41
50K	18174	492.50	3335	538.55	3	600.41
100K	18174	492.50	3530	538.61	3	600.41
Uncertainty $\delta W/W$ (%)		0.18		0.81		1.84

TABLE 16.40 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1	1	1
Temperature T (K)	233.15	233.15	233.15
Humidity			
RH, h_r (%)	0	50	100
Mole fraction x_h	0	0.000094	0.000188
Enhancement factor f_e	1.00588	1.00588	1.00588
Corrections			
Specific heat K_C (ppm)	755	754	754
Virial K_V (ppm)	−358	−358	−358
Simple sound speed W_s (m/s)	306.10	306.11	306.11

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	306.16	0	306.17	0	306.17
10	72	306.17	24	306.17	9	306.17
20	122	306.18	59	306.18	23	306.18
50	153	306.19	124	306.19	70	306.18
100	158	306.19	149	306.19	119	306.19
200	160	306.19	157	306.19	147	306.20
500	160	306.19	160	306.19	158	306.20
1000	160	306.19	160	306.19	160	306.20
2000	160	306.19	160	306.19	160	306.20
5000	160	306.19	160	306.19	160	306.20
10K	160	306.19	160	306.19	160	306.20
20K	160	306.19	160	306.19	160	306.20
50K	160	306.19	160	306.19	160	306.20
100K	160	306.19	160	306.19	160	306.20
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.41 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	243.15		243.15		243.15	
Humidity						
RH, h_r (%)	0		50		100	
Mole fraction x_h	0		0.000252		0.000505	
Enhancement factor f_e	1.00539		1.00539		1.00539	
Corrections						
Specific heat K_C (ppm)	725		725		724	
Virial K_V (ppm)	−126		−126		−126	
Simple sound speed W_s (m/s)	312.60		312.61		312.62	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	312.69	0	312.70	0	312.72
10	87	312.71	9	312.71	4	312.72
20	158	312.72	21	312.71	11	312.72
50	208	312.72	58	312.71	21	312.72
100	218	312.73	121	312.72	39	312.72
200	221	312.73	182	312.73	83	312.73
500	222	312.73	214	312.74	170	312.74
1000	222	312.73	220	312.74	206	312.75
2000	222	312.73	221	312.74	218	312.75
5000	222	312.73	222	312.74	221	312.75
10K	222	312.73	222	312.74	222	312.75
20K	222	312.73	222	312.74	222	312.75
50K	222	312.73	222	312.74	222	312.75
100K	222	312.73	222	312.74	222	312.75
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.42 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1	1	1
Temperature T (K)	253.15	253.15	253.15
Humidity			
RH, h_r (%)	0	50	100
Mole fraction x_h	0	0.000622	0.00124
Enhancement factor f_e	1.00494	1.00494	1.00494
Corrections			
Specific heat K_C (ppm)	666	665	663
Virial K_V (ppm)	68	68	67
Simple sound speed W_s (m/s)	318.96	318.99	319.03

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	319.08	0	319.11	0	319.14
10	102	319.09	5	319.11	2	319.14
20	197	319.11	13	319.11	6	319.14
50	276	319.12	27	319.11	18	319.14
100	293	319.13	41	319.12	26	319.15
200	298	319.13	77	319.12	33	319.15
500	299	319.13	186	319.14	61	319.15
1000	299	319.13	258	319.15	125	319.16
2000	299	319.13	287	319.16	215	319.18
5000	299	319.13	297	319.16	281	319.19
10K	299	319.13	299	319.16	294	319.19
20K	299	319.13	299	319.16	298	319.19
50K	299	319.13	299	319.16	299	319.19
100K	299	319.13	299	319.16	299	319.19
Uncertainty $\delta W/W$ (%)		0.11		0.10		0.10

TABLE 16.43 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	263.15		263.15		263.15	
Humidity						
RH, h_r (%)	0		50		100	
Mole fraction x_h	0		0.00142		0.00284	
Enhancement factor f_e	1.00455		1.00455		1.00455	
Corrections						
Specific heat K_C (ppm)	579		574		570	
Virial K_V (ppm)	231		230		228	
Simple sound speed W_s (m/s)	325.20		325.27		325.35	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	325.33	0	325.41	0	325.48
10	118	325.35	2	325.41	1	325.48
20	240	325.37	7	325.41	2	325.48
50	356	325.39	24	325.41	11	325.48
100	384	325.39	37	325.41	25	325.48
200	391	325.40	45	325.41	37	325.48
500	394	325.40	71	325.42	45	325.49
1000	394	325.40	134	325.43	55	325.49
2000	394	325.40	248	325.45	90	325.49
5000	394	325.40	358	325.46	215	325.51
10K	394	325.40	384	325.47	321	325.53
20K	394	325.40	391	325.47	372	325.54
50K	394	325.40	393	325.47	389	325.54
100K	394	325.40	393	325.47	392	325.54
Uncertainty $\delta W/W$ (%)		0.11		0.10		0.10

TABLE 16.44 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	273.15		273.15		273.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00121		0.00242	
Enhancement factor f_e	1.00419		1.00419		1.00419	
Corrections						
Specific heat K_C (ppm)	462		457		453	
Virial K_V (ppm)	368		367		366	
Simple sound speed W_s (m/s)	331.32		331.39		331.45	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	331.46	0	331.52	0	331.59
10	134	331.48	3	331.52	1	331.59
20	286	331.51	12	331.52	4	331.59
50	449	331.53	38	331.53	19	331.59
100	492	331.54	56	331.53	40	331.59
200	504	331.54	70	331.53	56	331.60
500	508	331.54	118	331.54	68	331.60
1000	508	331.54	225	331.56	89	331.60
2000	508	331.54	373	331.58	152	331.61
5000	508	331.54	479	331.60	334	331.64
10K	508	331.54	500	331.61	446	331.66
20K	508	331.54	506	331.61	490	331.67
50K	508	331.54	507	331.61	504	331.67
100K	508	331.54	508	331.61	506	331.67
Uncertainty $\delta W/W$ (%)		0.11		0.10		0.10

TABLE 16.45 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1	1	1
Temperature T (K)	273.15	273.15	273.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.00363	0.00484	0.00605
Enhancement factor f_e	1.00419	1.00419	1.00419
Corrections			
Specific heat K_C (ppm)	449	445	441
Virial K_V (ppm)	364	361	359
Simple sound speed W_s (m/s)	331.52	331.58	331.64

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	331.65	0	331.71	0	331.78
10	1	331.65	0	331.71	0	331.78
20	2	331.65	1	331.71	1	331.78
50	11	331.65	7	331.71	5	331.78
100	29	331.65	21	331.72	15	331.78
200	49	331.66	42	331.72	35	331.78
500	62	331.66	59	331.72	56	331.79
1000	70	331.66	65	331.72	63	331.79
2000	93	331.67	76	331.73	70	331.79
5000	202	331.68	136	331.74	105	331.79
10K	350	331.71	259	331.76	195	331.81
20K	453	331.72	400	331.78	342	331.83
50K	496	331.73	484	331.79	467	331.85
100K	504	331.73	500	331.80	494	331.86
Uncertainty $\delta W/W$ (%)		0.10		0.10		0.10

TABLE 16.46 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	283.15		283.15		283.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00243		0.00486	
Enhancement factor f_e	1.00386		1.00386		1.00386	
Corrections						
Specific heat K_C (ppm)	316		307		297	
Virial K_V (ppm)	485		482		477	
Simple sound speed W_s (m/s)	337.33		337.46		337.60	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	337.47	0	337.60	0	337.73
10	152	337.49	1	337.60	0	337.73
20	333	337.52	6	337.60	2	337.73
50	555	337.56	26	337.60	9	337.73
100	619	337.57	56	337.61	28	337.73
200	637	337.57	80	337.61	58	337.74
500	643	337.58	96	337.61	84	337.74
1000	644	337.58	121	337.62	92	337.74
2000	644	337.58	198	337.63	106	337.74
5000	644	337.58	423	337.67	180	337.76
10K	644	337.58	564	337.69	331	337.78
20K	644	337.58	620	337.70	507	337.81
50K	644	337.58	638	337.70	613	337.83
100K	644	337.58	641	337.70	633	337.83
Uncertainty $\delta W/W$ (%)		0.11		0.10		0.10

TABLE 16.47 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	283.15		283.15		283.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.00729		0.00973		0.0122	
Enhancement factor f_e	1.00386		1.00386		1.00386	
Corrections						
Specific heat K_C (ppm)	288		279		269	
Virial K_V (ppm)	472		464		456	
Simple sound speed W_s (m/s)	337.73		337.86		337.99	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	337.86	0	337.99	0	338.12
10	0	337.86	0	337.99	0	338.12
20	1	337.86	0	337.99	0	338.12
50	4	337.86	3	337.99	2	338.12
100	15	337.86	10	337.99	6	338.12
200	41	337.86	29	337.99	21	338.12
500	76	337.87	67	338.00	59	338.13
1000	87	337.87	83	338.00	79	338.13
2000	94	337.87	90	338.00	88	338.13
5000	123	337.88	105	338.00	98	338.13
10K	202	337.89	149	338.01	125	338.14
20K	368	337.92	269	338.03	209	338.15
50K	564	337.95	501	338.07	436	338.19
100K	617	337.96	594	338.09	566	338.21
Uncertainty $\delta W/W$ (%)		0.10		0.10		0.10

TABLE 16.48 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	293.15		293.15		293.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00463		0.00926	
Enhancement factor f_e	1.00357		1.00357		1.00357	
Corrections						
Specific heat K_C (ppm)	142		122		103	
Virial K_V (ppm)	583		576		565	
Simple sound speed W_s (m/s)	343.24		343.49		343.75	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	343.36	0	343.61	0	343.86
10	170	343.39	1	343.61	0	343.86
20	383	343.43	2	343.61	1	343.86
50	672	343.48	13	343.61	4	343.86
100	765	343.49	40	343.62	14	343.87
200	793	343.50	82	343.63	41	343.87
500	801	343.50	117	343.63	95	343.88
1000	802	343.50	129	343.63	117	343.88
2000	802	343.50	148	343.64	126	343.88
5000	802	343.50	248	343.65	147	343.89
10K	802	343.50	442	343.69	206	343.90
20K	802	343.50	650	343.72	363	343.93
50K	802	343.50	768	343.74	643	343.97
100K	802	343.50	790	343.75	747	343.99
Uncertainty $\delta W/W$ (%)		0.11		0.10		0.10

TABLE 16.49 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	293.15		293.15		293.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.0139		0.0185		0.0231	
Enhancement factor f_e	1.00357		1.00357		1.00357	
Corrections						
Specific heat K_C (ppm)	83		64		44	
Virial K_V (ppm)	550		531		508	
Simple sound speed W_s (m/s)	344.01		344.26		344.52	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	344.11	0	344.37	0	344.62
10	0	344.11	0	344.37	0	344.62
20	0	344.11	0	344.37	0	344.62
50	2	344.11	1	344.37	1	344.62
100	7	344.12	4	344.37	2	344.62
200	23	344.12	14	344.37	9	344.62
500	73	344.13	55	344.38	42	344.62
1000	106	344.13	94	344.38	83	344.63
2000	120	344.14	115	344.39	110	344.64
5000	132	344.14	126	344.39	123	344.64
10K	156	344.14	139	344.39	132	344.64
20K	236	344.15	185	344.40	160	344.64
50K	495	344.20	381	344.43	304	344.67
100K	678	344.23	597	344.47	519	344.71
Uncertainty $\delta W/W$ (%)		0.10		0.11		0.11

TABLE 16.50 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	303.15		303.15		303.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00840		0.0168	
Enhancement factor f_e	1.00330		1.00330		1.00330	
Corrections						
Specific heat K_C (ppm)	−61		−100		−139	
Virial K_V (ppm)	667		651		624	
Simple sound speed W_s (m/s)	349.04		349.51		349.99	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	349.15	0	349.61	0	350.07
10	189	349.18	0	349.61	0	350.07
20	434	349.22	1	349.61	0	350.07
50	800	349.29	6	349.61	2	350.07
100	930	349.31	21	349.61	6	350.07
200	971	349.32	61	349.62	21	350.08
500	983	349.32	133	349.63	80	350.09
1000	985	349.32	161	349.64	132	350.10
2000	985	349.32	173	349.64	159	350.10
5000	985	349.32	204	349.65	173	350.10
10K	985	349.32	291	349.66	193	350.11
20K	985	349.32	503	349.70	259	350.12
50K	985	349.32	825	349.75	522	350.17
100K	985	349.32	931	349.77	774	350.21
Uncertainty $\delta W/W$ (%)		0.11		0.10		0.11

TABLE 16.51 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	303.15		303.15		303.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.0252		0.0336		0.0420	
Enhancement factor f_e	1.00330		1.00330		1.00330	
Corrections						
Specific heat K_C (ppm)	−177		−215		−253	
Virial K_V (ppm)	588		541		484	
Simple sound speed W_s (m/s)	350.47		350.95		351.43	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	350.54	0	351.00	0	351.47
10	0	350.54	0	351.00	0	351.47
20	0	350.54	0	351.00	0	351.47
50	1	350.54	0	351.00	0	351.47
100	3	350.54	2	351.00	1	351.47
200	10	350.54	6	351.00	4	351.47
500	48	350.55	31	351.01	21	351.47
1000	103	350.56	79	351.02	61	351.48
2000	145	350.56	130	351.03	115	351.49
5000	165	350.57	159	351.03	153	351.50
10K	175	350.57	168	351.03	163	351.50
20K	204	350.57	184	351.04	174	351.50
50K	355	350.60	275	351.05	234	351.51
100K	605	350.64	475	351.09	386	351.54
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.52 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	313.15		313.15		313.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.0146		0.0292	
Enhancement factor f_e	1.00305		1.00305		1.00305	
Corrections						
Specific heat K_C (ppm)	−292		−365		−438	
Virial K_V (ppm)	738		704		646	
Simple sound speed W_s (m/s)	354.75		355.59		356.43	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	354.83	0	355.65	0	356.47
10	210	354.87	0	355.65	0	356.47
20	487	354.92	0	355.65	0	356.47
50	939	355.00	3	355.65	1	356.47
100	1116	355.03	10	355.65	3	356.47
200	1173	355.04	35	355.65	10	356.47
500	1191	355.04	120	355.67	49	356.48
1000	1193	355.04	185	355.68	118	356.49
2000	1194	355.04	215	355.69	182	356.50
5000	1194	355.04	234	355.69	215	356.51
10K	1194	355.04	265	355.70	227	356.51
20K	1194	355.04	368	355.71	253	356.51
50K	1194	355.04	723	355.78	392	356.54
100K	1194	355.04	997	355.83	661	356.59
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.53 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	313.15		313.15		313.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.0438		0.0584		0.0730	
Enhancement factor f_e	1.00305		1.00305		1.00305	
Corrections						
Specific heat K_C (ppm)	−510		−581		−651	
Virial K_V (ppm)	562		454		320	
Simple sound speed W_s (m/s)	357.28		358.14		359.01	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	357.29	0	358.12	0	358.95
10	0	357.29	0	358.12	0	358.95
20	0	357.29	0	358.12	0	358.95
50	0	357.29	0	358.12	0	358.95
100	1	357.29	1	358.12	0	358.95
200	4	357.29	2	358.12	2	358.95
500	25	357.30	14	358.12	9	358.95
1000	74	357.31	48	358.13	33	358.96
2000	146	357.32	114	358.14	89	358.97
5000	202	357.33	187	358.15	171	358.98
10K	216	357.33	207	358.16	198	358.99
20K	229	357.33	217	358.16	209	358.99
50K	294	357.35	254	358.17	234	359.00
100K	463	357.38	361	358.19	305	359.01
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.54 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	323.15		323.15		323.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.0244		0.0488	
Enhancement factor f_e	1.00282		1.00282		1.00282	
Corrections						
Specific heat K_C (ppm)	−551		−683		−813	
Virial K_V (ppm)	798		731		608	
Simple sound speed W_s (m/s)	360.37		361.80		363.24	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	360.42	0	361.80	0	363.21
10	231	360.46	0	361.80	0	363.21
20	543	360.51	0	361.80	0	363.21
50	1086	360.61	1	361.80	0	363.21
100	1320	360.65	4	361.81	1	363.21
200	1400	360.67	17	361.81	4	363.21
500	1425	360.67	82	361.82	25	363.21
1000	1428	360.67	177	361.84	80	363.22
2000	1429	360.67	251	361.85	172	363.24
5000	1429	360.67	287	361.86	256	363.25
10K	1429	360.67	303	361.86	277	363.26
20K	1429	360.67	346	361.87	291	363.26
50K	1429	360.67	566	361.91	353	363.27
100K	1429	360.67	917	361.97	521	363.30
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.55 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1	1	1
Temperature T (K)	323.15	323.15	323.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.0733	0.0977	0.122
Enhancement factor f_e	1.00282	1.00282	1.00282
Corrections			
Specific heat K_C (ppm)	−941	−1067	−1190
Virial K_V (ppm)	427	189	−109
Simple sound speed W_s (m/s)	364.71	366.21	367.73

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	364.62	0	366.05	0	367.49
10	0	364.62	0	366.05	0	367.49
20	0	364.62	0	366.05	0	367.49
50	0	364.62	0	366.05	0	367.49
100	0	364.62	0	366.05	0	367.49
200	2	364.62	1	366.05	1	367.49
500	11	364.62	6	366.05	4	367.49
1000	41	364.63	24	366.05	15	367.50
2000	112	364.64	74	366.06	51	367.50
5000	221	364.66	187	366.08	155	367.52
10K	258	364.67	238	366.09	218	367.53
20K	272	364.67	258	366.10	244	367.54
50K	301	364.68	277	366.10	261	367.54
100K	384	364.69	324	366.11	291	367.55
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.56 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	373.15		373.15		373.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.200		0.401	
Enhancement factor f_e	1.00191		1.00191		1.00191	
Corrections						
Specific heat K_C (ppm)	−2253		−3671		−4891	
Virial K_V (ppm)	987		−208		−3037	
Simple sound speed W_s (m/s)	387.25		400.58		415.92	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	387.00	0	399.81	0	414.27
10	344	387.07	0	399.81	0	414.27
20	865	387.17	0	399.81	0	414.27
50	1921	387.38	0	399.81	0	414.27
100	2609	387.51	0	399.81	0	414.27
200	2914	387.57	1	399.81	0	414.27
500	3017	387.59	3	399.81	1	414.27
1000	3032	387.59	12	399.81	2	414.27
2000	3036	387.59	47	399.81	9	414.28
5000	3037	387.59	214	399.85	49	414.28
10K	3037	387.59	435	399.89	149	414.30
20K	3038	387.59	588	399.92	303	414.34
50K	3038	387.59	657	399.94	427	414.36
100K	3038	387.59	686	399.94	457	414.37
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.15

TABLE 16.57 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	373.15		373.15		373.15	
Humidity						
RH, h_r (%)	60		80		99.8	
Mole fraction x_h	0.601		0.802		1.000	
Enhancement factor f_e	1.00191		1.00191		1.00191	
Corrections						
Specific heat K_C (ppm)	−5943		−6853		−7632	
Virial K_V (ppm)	−7553		−13822		−21822	
Simple sound speed W_s (m/s)	433.72		454.60		479.18	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	430.79	0	449.90	0	472.11
10	0	430.79	0	449.90	0	472.11
20	0	430.79	0	449.90	0	472.11
50	0	430.79	0	449.90	0	472.11
100	0	430.79	0	449.90	0	472.11
200	0	430.79	0	449.90	0	472.11
500	0	430.79	0	449.90	0	472.11
1000	1	430.79	0	449.90	0	472.11
2000	2	430.79	1	449.90	0	472.11
5000	14	430.80	4	449.90	0	472.11
10K	50	430.80	14	449.90	0	472.11
20K	131	430.82	43	449.91	0	472.11
50K	241	430.84	99	449.92	0	472.11
100K	274	430.85	123	449.93	0	472.11
Uncertainty $\delta W/W$ (%)		0.18		0.19		0.23

TABLE 16.58 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	423.15		423.15		423.15	
Humidity						
RH, h_r (%)	0		10		21.25	
Mole fraction x_h	0		0.471		1.000	
Enhancement factor f_e	1.00128		1.00128		1.00128	
Corrections						
Specific heat K_C (ppm)	−4607		−8442		−11387	
Virial K_V (ppm)	1063		−2121		−11053	
Simple sound speed W_s (m/s)	412.38		449.19		510.31	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	411.65	0	446.82	0	504.58
10	448	411.74	0	446.82	−0	504.58
20	1231	411.90	0	446.82	−0	504.58
50	2888	412.24	0	446.82	−0	504.58
100	4224	412.52	0	446.82	−0	504.58
200	5006	412.68	0	446.82	−0	504.58
500	5315	412.74	1	446.82	−0	504.58
1000	5363	412.75	3	446.82	−0	504.58
2000	5376	412.75	10	446.82	−0	504.58
5000	5379	412.75	59	446.83	−0	504.58
10K	5380	412.75	196	446.86	−0	504.58
20K	5380	412.75	470	446.92	−0	504.58
50K	5380	412.75	772	446.99	−0	504.58
100K	5380	412.75	853	447.01	−0	504.58
Uncertainty $\delta W/W$ (%)		0.15		0.16		0.23

TABLE 16.59 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	473.15		473.15		473.15	
Humidity						
RH, h_r (%)	0		3.2		6.4	
Mole fraction x_h	0		0.494		0.988	
Enhancement factor f_e	1.00081		1.00081		1.00081	
Corrections						
Specific heat K_C (ppm)	−7566		−12308		−15504	
Virial K_V (ppm)	1084		−1283		−6275	
Simple sound speed W_s (m/s)	436.06		477.29		537.75	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	434.65	0	474.03	0	531.89
10	523	434.76	0	474.03	0	531.89
20	1569	434.99	0	474.03	0	531.89
50	3967	435.51	0	474.03	0	531.89
100	6003	435.95	0	474.03	0	531.89
200	7511	436.27	0	474.03	0	531.89
500	8227	436.43	1	474.04	0	531.89
1000	8349	436.46	3	474.04	0	531.89
2000	8380	436.46	13	474.04	0	531.89
5000	8389	436.46	80	474.05	0	531.89
10K	8390	436.46	276	474.10	2	531.89
20K	8390	436.46	712	474.20	5	531.89
50K	8391	436.46	1280	474.34	17	531.90
100K	8391	436.46	1447	474.38	25	531.90
Uncertainty $\delta W/W$ (%)		0.14		0.18		0.28

TABLE 16.60 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	523.15		523.15		523.15	
Humidity						
RH, h_r (%)	0		1.25		2.5	
Mole fraction x_h	0		0.500		0.999	
Enhancement factor f_e	1.00045		1.00045		1.00045	
Corrections						
Specific heat K_C (ppm)	−11077		−16469		−20025	
Virial K_V (ppm)	1076		−745		−4071	
Simple sound speed W_s (m/s)	458.52		502.47		567.27	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	456.22	0	498.13	0	560.42
10	566	456.35	0	498.13	0	560.42
20	1820	456.64	0	498.13	0	560.42
50	5085	457.38	0	498.13	0	560.42
100	7848	458.01	0	498.13	0	560.42
200	10207	458.55	0	498.13	0	560.42
500	11577	458.86	1	498.13	0	560.42
1000	11832	458.91	4	498.13	0	560.42
2000	11899	458.93	18	498.13	0	560.42
5000	11918	458.93	107	498.15	0	560.42
10K	11921	458.93	378	498.22	0	560.42
20K	11921	458.93	1018	498.38	0	560.42
50K	11922	458.93	1940	498.61	2	560.42
100K	11922	458.93	2232	498.68	2	560.42
Uncertainty $\delta W/W$ (%)		0.14		0.40		0.87

TABLE 16.61 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	573.15		573.15		573.15	
Humidity						
RH, h_r (%)	0		0.55		1.1	
Mole fraction x_h	0		0.487		0.974	
Enhancement factor f_e	1.00017		1.00017		1.00017	
Corrections						
Specific heat K_C (ppm)	−15083		−20761		−24479	
Virial K_V (ppm)	1053		−370		−2593	
Simple sound speed W_s (m/s)	479.94		524.53		589.50	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	476.55	0	518.96	0	581.49
10	581	476.69	0	518.96	0	581.49
20	1967	477.02	0	518.96	0	581.49
50	6115	478.01	0	518.96	0	581.49
100	9690	478.86	0	518.96	0	581.49
200	12897	479.62	0	518.96	0	581.49
500	15144	480.15	2	518.96	0	581.49
1000	15613	480.26	6	518.96	0	581.49
2000	15740	480.29	25	518.97	0	581.49
5000	15776	480.30	149	519.00	2	581.49
10K	15781	480.30	528	519.10	6	581.49
20K	15782	480.30	1447	519.33	22	581.49
50K	15783	480.30	2820	519.69	76	581.51
100K	15783	480.30	3267	519.81	118	581.52
Uncertainty $\delta W/W$ (%)		0.15		0.60		1.41

TABLE 16.62 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	1		1		1	
Temperature T (K)	603.15		603.15		603.15	
Humidity						
RH, h_r (%)	0		0.36		0.72	
Mole fraction x_h	0		0.487		0.974	
Enhancement factor f_e	1.00003		1.00003		1.00003	
Corrections						
Specific heat K_C (ppm)	−17700		−23510		−27271	
Virial K_V (ppm)	1035		−249		−2086	
Simple sound speed W_s (m/s)	492.34		538.13		604.87	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	488.21	0	531.70	0	595.95
10	579	488.35	0	531.70	0	595.95
20	2008	488.70	0	531.70	0	595.95
50	6641	489.83	0	531.70	0	595.95
100	10759	490.83	0	531.70	0	595.95
200	14448	491.73	0	531.70	0	595.95
500	17296	492.42	2	531.70	0	595.95
1000	17938	492.57	7	531.70	0	595.95
2000	18114	492.61	28	531.71	0	595.95
5000	18165	492.63	168	531.74	2	595.95
10K	18172	492.63	597	531.86	7	595.95
20K	18174	492.63	1661	532.14	24	595.95
50K	18174	492.63	3317	532.58	85	595.97
100K	18174	492.63	3874	532.73	134	595.99
Uncertainty $\delta W/W$ (%)		0.16		0.72		1.76

TABLE 16.63 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	233.15		233.15		233.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000019		0.000038	
Enhancement factor f_e	1.00850		1.00850		1.00850	
Corrections						
Specific heat K_C (ppm)	755		755		755	
Virial K_V (ppm)	−697		−697		−697	
Simple sound speed W_s (m/s)	306.10		306.10		306.10	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	306.11	0	306.11	0	306.11
10	29	306.12	23	306.12	17	306.12
20	72	306.12	61	306.12	49	306.12
50	133	306.13	126	306.13	115	306.13
100	153	306.13	150	306.14	146	306.14
200	158	306.14	158	306.14	156	306.14
500	160	306.14	160	306.14	160	306.14
1000	160	306.14	160	306.14	160	306.14
2000	160	306.14	160	306.14	160	306.14
5000	160	306.14	160	306.14	160	306.14
10K	160	306.14	160	306.14	160	306.14
20K	160	306.14	160	306.14	160	306.14
50K	160	306.14	160	306.14	160	306.14
100K	160	306.14	160	306.14	160	306.14
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.64 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2	2	2
Temperature T (K)	233.15	233.15	233.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.000056	0.000075	0.000094
Enhancement factor f_e	1.00850	1.00850	1.00850
Corrections			
Specific heat K_C (ppm)	754	754	754
Virial K_V (ppm)	−697	−697	−697
Simple sound speed W_s (m/s)	306.11	306.11	306.11

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	306.11	0	306.12	0	306.12
10	13	306.12	10	306.12	8	306.12
20	38	306.12	30	306.12	24	306.12
50	103	306.13	89	306.13	75	306.13
100	140	306.14	133	306.14	124	306.13
200	155	306.14	152	306.14	149	306.14
500	159	306.14	159	306.14	158	306.14
1000	160	306.14	160	306.14	160	306.14
2000	160	306.14	160	306.14	160	306.14
5000	160	306.14	160	306.14	160	306.14
10K	160	306.14	160	306.14	160	306.14
20K	160	306.14	160	306.14	160	306.14
50K	160	306.14	160	306.14	160	306.14
100K	160	306.14	160	306.14	160	306.14
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.65 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2	2	2
Temperature T (K)	243.15	243.15	243.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.000051	0.000101
Enhancement factor f_e	1.00852	1.00852	1.00852
Corrections			
Specific heat K_C (ppm)	725	725	725
Virial K_V (ppm)	−235	−235	−235
Simple sound speed W_s (m/s)	312.60	312.60	312.60

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	312.67	0	312.68	0	312.68
10	33	312.68	17	312.68	9	312.68
20	87	312.69	50	312.69	27	312.68
50	176	312.70	136	312.70	89	312.69
100	208	312.71	191	312.71	158	312.70
200	218	312.71	213	312.71	201	312.71
500	221	312.71	221	312.71	218	312.71
1000	222	312.71	222	312.71	221	312.71
2000	222	312.71	222	312.71	222	312.71
5000	222	312.71	222	312.71	222	312.71
10K	222	312.71	222	312.71	222	312.71
20K	222	312.71	222	312.71	222	312.71
50K	222	312.71	222	312.71	222	312.71
100K	222	312.71	222	312.71	222	312.71
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.66 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	243.15		243.15		243.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000152		0.000203		0.000253	
Enhancement factor f_e	1.00852		1.00852		1.00852	
Corrections						
Specific heat K_C (ppm)	725		725		725	
Virial K_V (ppm)	−235		−235		−235	
Simple sound speed W_s (m/s)	312.61		312.61		312.61	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	312.68	0	312.68	0	312.69
10	6	312.68	4	312.69	3	312.69
20	17	312.68	12	312.69	9	312.69
50	55	312.69	36	312.69	26	312.69
100	117	312.70	82	312.70	58	312.70
200	180	312.71	151	312.71	120	312.71
500	214	312.72	206	312.72	194	312.72
1000	220	312.72	218	312.72	214	312.72
2000	221	312.72	221	312.72	220	312.72
5000	222	312.72	222	312.72	222	312.72
10K	222	312.72	222	312.72	222	312.72
20K	222	312.72	222	312.72	222	312.72
50K	222	312.72	222	312.72	222	312.72
100K	222	312.72	222	312.72	222	312.72
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.67 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2	2	2
Temperature T (K)	253.15	253.15	253.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.000125	0.000250
Enhancement factor f_e	1.00855	1.00855	1.00855
Corrections			
Specific heat K_C (ppm)	666	666	666
Virial K_V (ppm)	152	152	152
Simple sound speed W_s (m/s)	318.96	318.97	318.97

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	319.09	0	319.10	0	319.10
10	37	319.10	9	319.10	4	319.11
20	102	319.11	27	319.10	13	319.11
50	224	319.13	88	319.11	37	319.11
100	276	319.14	177	319.13	78	319.12
200	293	319.14	253	319.14	159	319.13
500	298	319.14	291	319.14	260	319.15
1000	299	319.14	297	319.15	288	319.15
2000	299	319.14	299	319.15	296	319.15
5000	299	319.14	299	319.15	299	319.15
10K	299	319.14	299	319.15	299	319.15
20K	299	319.14	299	319.15	299	319.15
50K	299	319.14	299	319.15	299	319.15
100K	299	319.14	299	319.15	299	319.15
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.68 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	253.15		253.15		253.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000374		0.000499		0.000624	
Enhancement factor f_e	1.00855		1.00855		1.00855	
Corrections						
Specific heat K_C (ppm)	665		665		665	
Virial K_V (ppm)	152		152		151	
Simple sound speed W_s (m/s)	318.98		318.99		318.99	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	319.11	0	319.12	0	319.12
10	3	319.11	2	319.12	1	319.12
20	9	319.11	6	319.12	5	319.12
50	25	319.11	19	319.12	16	319.13
100	43	319.12	32	319.12	27	319.13
200	87	319.12	55	319.13	41	319.13
500	201	319.14	141	319.14	97	319.14
1000	266	319.15	229	319.15	185	319.15
2000	290	319.16	277	319.16	257	319.16
5000	298	319.16	295	319.16	291	319.17
10K	299	319.16	298	319.16	297	319.17
20K	299	319.16	299	319.16	299	319.17
50K	299	319.16	299	319.17	299	319.17
100K	299	319.16	299	319.17	299	319.17
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.69 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2	2	2
Temperature T (K)	263.15	263.15	263.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.000285	0.000570
Enhancement factor f_e	1.00859	1.00859	1.00859
Corrections			
Specific heat K_C (ppm)	579	578	577
Virial K_V (ppm)	477	476	476
Simple sound speed W_s (m/s)	325.20	325.22	325.23

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	325.37	0	325.39	0	325.40
10	42	325.38	5	325.39	2	325.40
20	118	325.39	16	325.39	7	325.40
50	278	325.42	44	325.39	25	325.41
100	356	325.43	84	325.40	42	325.41
200	384	325.43	170	325.41	64	325.41
500	392	325.44	318	325.44	149	325.43
1000	394	325.44	371	325.45	266	325.44
2000	394	325.44	388	325.45	350	325.46
5000	394	325.44	393	325.45	386	325.46
10K	394	325.44	394	325.45	392	325.47
20K	394	325.44	394	325.45	393	325.47
50K	394	325.44	394	325.45	394	325.47
100K	394	325.44	394	325.45	394	325.47
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.70 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	263.15		263.15		263.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0		0.00114		0.00142	
Enhancement factor f_e	1.00859		1.00859		1.00859	
Corrections						
Specific heat K_C (ppm)	576		575		574	
Virial K_V (ppm)	476		475		475	
Simple sound speed W_s (m/s)	325.24		325.26		325.27	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	325.42	0	325.43	0	325.45
10	1	325.42	1	325.43	1	325.45
20	4	325.42	3	325.43	2	325.45
50	18	325.42	13	325.43	10	325.45
100	33	325.42	28	325.44	24	325.45
200	46	325.42	40	325.44	37	325.45
500	79	325.43	57	325.44	49	325.45
1000	154	325.44	96	325.45	70	325.46
2000	271	325.46	190	325.46	133	325.47
5000	366	325.48	330	325.48	283	325.49
10K	386	325.48	375	325.49	357	325.50
20K	392	325.48	389	325.49	384	325.51
50K	393	325.48	393	325.49	392	325.51
100K	394	325.48	393	325.49	393	325.51
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.71 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2	2	2
Temperature T (K)	273.15	273.15	273.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.000608	0.00122
Enhancement factor f_e	1.00863	1.00863	1.00863
Corrections			
Specific heat K_C (ppm)	462	460	457
Virial K_V (ppm)	751	750	748
Simple sound speed W_s (m/s)	331.32	331.35	331.39

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	331.52	0	331.55	0	331.59
10	47	331.53	3	331.55	1	331.59
20	134	331.54	9	331.56	3	331.59
50	337	331.58	34	331.56	17	331.59
100	449	331.60	57	331.56	38	331.59
200	492	331.60	82	331.57	56	331.60
500	506	331.61	174	331.58	77	331.60
1000	508	331.61	317	331.61	118	331.61
2000	508	331.61	438	331.63	223	331.62
5000	508	331.61	495	331.64	409	331.65
10K	508	331.61	505	331.64	478	331.67
20K	508	331.61	507	331.64	500	331.67
50K	508	331.61	508	331.64	506	331.67
100K	508	331.61	508	331.64	507	331.67
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.72 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	273.15		273.15		273.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0		0.00243		0.00304	
Enhancement factor f_e	1.00863		1.00863		1.00863	
Corrections						
Specific heat K_C (ppm)	455		453		451	
Virial K_V (ppm)	747		745		743	
Simple sound speed W_s (m/s)	331.42		331.45		331.48	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	331.62	0	331.65	0	331.68
10	0	331.62	0	331.65	0	331.68
20	2	331.62	1	331.65	1	331.68
50	10	331.62	6	331.65	4	331.68
100	27	331.62	19	331.65	14	331.68
200	48	331.63	40	331.66	34	331.69
500	64	331.63	59	331.66	56	331.69
1000	79	331.63	68	331.66	64	331.69
2000	122	331.64	88	331.66	76	331.69
5000	280	331.66	187	331.68	135	331.70
10K	415	331.69	332	331.70	257	331.72
20K	480	331.70	445	331.72	399	331.75
50K	503	331.70	496	331.73	485	331.76
100K	506	331.70	504	331.73	501	331.76
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.73 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	283.15		283.15		283.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00122		0.00244	
Enhancement factor f_e	1.00867		1.00867		1.00867	
Corrections						
Specific heat K_C (ppm)	316		311		307	
Virial K_V (ppm)	982		979		976	
Simple sound speed W_s (m/s)	337.33		337.40		337.46	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	337.55	0	337.62	0	337.68
10	53	337.56	1	337.62	0	337.68
20	152	337.58	5	337.62	1	337.68
50	399	337.62	23	337.62	8	337.68
100	555	337.64	52	337.62	26	337.69
200	619	337.66	79	337.63	56	337.69
500	640	337.66	106	337.63	84	337.69
1000	643	337.66	155	337.64	96	337.70
2000	644	337.66	283	337.66	121	337.70
5000	644	337.66	516	337.70	240	337.72
10K	644	337.66	605	337.72	421	337.75
20K	644	337.66	633	337.72	563	337.78
50K	644	337.66	641	337.72	627	337.79
100K	644	337.66	643	337.72	638	337.79
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.74 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	283.15		283.15		283.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0		0.00489		0.00611	
Enhancement factor f_e	1.00867		1.00867		1.00867	
Corrections						
Specific heat K_C (ppm)	302		297		293	
Virial K_V (ppm)	972		967		962	
Simple sound speed W_s (m/s)	337.53		337.60		337.66	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	337.75	0	337.81	0	337.88
10	0	337.75	0	337.81	0	337.88
20	1	337.75	0	337.81	0	337.88
50	4	337.75	2	337.81	2	337.88
100	15	337.75	9	337.81	6	337.88
200	39	337.75	28	337.82	20	337.88
500	75	337.76	67	337.82	58	337.88
1000	88	337.76	84	337.82	80	337.89
2000	99	337.76	92	337.83	89	337.89
5000	145	337.77	115	337.83	103	337.89
10K	259	337.79	179	337.84	142	337.90
20K	442	337.82	330	337.87	251	337.92
50K	595	337.85	545	337.90	486	337.96
100K	629	337.85	613	337.91	591	337.97
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.75 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2	2	2
Temperature T (K)	293.15	293.15	293.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.00233	0.00465
Enhancement factor f_e	1.00873	1.00873	1.00873
Corrections			
Specific heat K_C (ppm)	142	132	122
Virial K_V (ppm)	1178	1172	1163
Simple sound speed W_s (m/s)	343.24	343.37	343.49

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	343.46	0	343.59	0	343.71
10	58	343.47	1	343.59	0	343.71
20	170	343.49	2	343.59	1	343.71
50	464	343.54	12	343.59	4	343.72
100	672	343.58	37	343.60	13	343.72
200	765	343.59	79	343.60	40	343.72
500	796	343.60	118	343.61	94	343.73
1000	801	343.60	134	343.61	117	343.73
2000	802	343.60	168	343.62	129	343.74
5000	802	343.60	327	343.65	160	343.74
10K	802	343.60	551	343.68	246	343.76
20K	802	343.60	714	343.71	440	343.79
50K	802	343.60	784	343.72	694	343.83
100K	802	343.60	796	343.73	768	343.85
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.76 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	293.15		293.15		293.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.00698		0.00931		0.0116	
Enhancement factor f_e	1.00873		1.00873		1.00873	
Corrections						
Specific heat K_C (ppm)	112		102		93	
Virial K_V (ppm)	1153		1141		1127	
Simple sound speed W_s (m/s)	343.62		343.75		343.88	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	343.84	0	343.96	0	344.09
10	0	343.84	0	343.96	0	344.09
20	0	343.84	0	343.96	0	344.09
50	2	343.84	1	343.97	1	344.09
100	6	343.84	4	343.97	2	344.09
200	22	343.84	14	343.97	9	344.09
500	72	343.85	54	343.97	41	344.10
1000	106	343.86	94	343.98	83	344.10
2000	122	343.86	116	343.98	111	344.11
5000	136	343.86	129	343.99	125	344.11
10K	170	343.87	147	343.99	137	344.11
20K	275	343.89	205	344.00	173	344.12
50K	556	343.94	432	344.04	343	344.15
100K	713	343.96	641	344.08	564	344.19
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.77 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	303.15		303.15		303.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00422		0.00845	
Enhancement factor f_e	1.00878		1.00878		1.00878	
Corrections						
Specific heat K_C (ppm)	−61		−81		−100	
Virial K_V (ppm)	1345		1331		1312	
Simple sound speed W_s (m/s)	349.04		349.28		349.52	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	349.27	0	349.50	0	349.73
10	64	349.28	0	349.50	0	349.73
20	189	349.30	1	349.50	0	349.73
50	532	349.36	5	349.50	1	349.73
100	800	349.41	20	349.50	6	349.73
200	930	349.43	58	349.51	21	349.73
500	976	349.44	131	349.52	79	349.74
1000	983	349.44	161	349.53	133	349.75
2000	985	349.44	177	349.53	160	349.76
5000	985	349.44	225	349.54	177	349.76
10K	985	349.44	351	349.56	203	349.76
20K	985	349.44	602	349.60	289	349.78
50K	985	349.44	880	349.65	589	349.83
100K	985	349.44	952	349.66	824	349.87
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.78 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	303.15		303.15		303.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.0127		0.0169		0.0211	
Enhancement factor f_e	1.00878		1.00878		1.00878	
Corrections						
Specific heat K_C (ppm)	−120		−139		−158	
Virial K_V (ppm)	1288		1258		1224	
Simple sound speed W_s (m/s)	349.75		349.99		350.23	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	349.96	0	350.19	0	350.42
10	0	349.96	0	350.19	0	350.42
20	0	349.96	0	350.19	0	350.42
50	1	349.96	0	350.19	0	350.42
100	3	349.96	2	350.19	1	350.42
200	10	349.96	6	350.19	4	350.42
500	48	349.97	31	350.20	21	350.42
1000	104	349.98	80	350.20	61	350.43
2000	147	349.98	132	350.21	117	350.44
5000	168	349.99	163	350.22	158	350.45
10K	181	349.99	173	350.22	168	350.45
20K	217	350.00	192	350.22	181	350.45
50K	395	350.03	300	350.24	251	350.46
100K	658	350.07	519	350.28	421	350.49
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.79 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	313.15		313.15		313.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00734		0.0147	
Enhancement factor f_e	1.00883		1.00883		1.00883	
Corrections						
Specific heat K_C (ppm)	−292		−329		−366	
Virial K_V (ppm)	1486		1458		1417	
Simple sound speed W_s (m/s)	354.75		355.17		355.59	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	354.96	0	355.37	0	355.78
10	69	354.98	0	355.37	0	355.78
20	210	355.00	0	355.37	0	355.78
50	602	355.07	2	355.37	1	355.78
100	939	355.13	9	355.37	2	355.78
200	1116	355.16	33	355.38	10	355.78
500	1181	355.17	118	355.39	49	355.79
1000	1191	355.18	185	355.40	119	355.80
2000	1193	355.18	217	355.41	184	355.81
5000	1194	355.18	240	355.41	220	355.82
10K	1194	355.18	283	355.42	234	355.82
20K	1194	355.18	417	355.45	265	355.83
50K	1194	355.18	808	355.52	429	355.86
100K	1194	355.18	1049	355.56	720	355.91
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.80 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	313.15		313.15		313.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.0220		0.0294		0.0367	
Enhancement factor f_e	1.00883		1.00883		1.00883	
Corrections						
Specific heat K_C (ppm)	−402		−439		−475	
Virial K_V (ppm)	1364		1298		1220	
Simple sound speed W_s (m/s)	356.02		356.44		356.87	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	356.19	0	356.59	0	357.00
10	0	356.19	0	356.59	0	357.00
20	0	356.19	0	356.59	0	357.00
50	0	356.19	0	356.59	0	357.00
100	1	356.19	1	356.59	0	357.00
200	4	356.19	2	356.59	2	357.00
500	25	356.19	15	356.60	10	357.00
1000	75	356.20	49	356.60	34	357.01
2000	149	356.21	118	356.62	93	357.02
5000	208	356.22	194	356.63	180	357.03
10K	223	356.23	215	356.63	208	357.04
20K	238	356.23	227	356.63	220	357.04
50K	313	356.24	269	356.64	248	357.05
100K	503	356.28	390	356.66	329	357.06
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.81 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2	2	2
Temperature T (K)	323.15	323.15	323.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.0123	0.0246
Enhancement factor f_e	1.00889	1.00889	1.00889
Corrections			
Specific heat K_C (ppm)	−551	−618	−684
Virial K_V (ppm)	1606	1552	1470
Simple sound speed W_s (m/s)	360.37	361.09	361.80

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	360.56	0	361.25	0	361.95
10	75	360.58	0	361.25	0	361.95
20	231	360.60	0	361.25	0	361.95
50	676	360.68	1	361.25	0	361.95
100	1086	360.76	4	361.25	1	361.95
200	1320	360.80	17	361.26	4	361.95
500	1411	360.82	81	361.27	26	361.95
1000	1425	360.82	177	361.29	81	361.96
2000	1428	360.82	254	361.30	176	361.98
5000	1429	360.82	292	361.31	264	361.99
10K	1429	360.82	312	361.31	287	362.00
20K	1429	360.82	365	361.32	303	362.00
50K	1429	360.82	624	361.37	374	362.01
100K	1429	360.82	991	361.43	563	362.05
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.82 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	323.15		323.15		323.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.0369		0.0491		0.0614	
Enhancement factor f_e	1.00889		1.00889		1.00889	
Corrections						
Specific heat K_C (ppm)	−750		−815		−879	
Virial K_V (ppm)	1359		1218		1048	
Simple sound speed W_s (m/s)	362.53		363.26		364.00	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	362.64	0	363.33	0	364.03
10	0	362.64	0	363.33	0	364.03
20	0	362.64	0	363.33	0	364.03
50	0	362.64	0	363.33	0	364.03
100	0	362.64	0	363.33	0	364.03
200	2	362.64	1	363.33	1	364.03
500	12	362.64	7	363.34	4	364.03
1000	42	362.65	25	363.34	16	364.03
2000	117	362.66	79	363.35	55	364.04
5000	232	362.68	199	363.37	168	364.06
10K	271	362.69	255	363.38	238	364.07
20K	287	362.69	276	363.38	267	364.08
50K	320	362.70	298	363.39	285	364.08
100K	413	362.71	352	363.40	320	364.09
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.83 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	373.15		373.15		373.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.101		0.202	
Enhancement factor f_e	1.00917		1.00917		1.00917	
Corrections						
Specific heat K_C (ppm)	−2253		−2994		−3680	
Virial K_V (ppm)	1981		1175		−457	
Simple sound speed W_s (m/s)	387.25		393.74		400.69	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	387.20	0	393.38	0	399.86
10	104	387.22	0	393.38	0	399.86
20	344	387.26	0	393.38	0	399.86
50	1092	387.41	0	393.38	0	399.86
100	1921	387.57	0	393.38	0	399.86
200	2609	387.70	1	393.38	0	399.86
500	2957	387.77	4	393.38	1	399.86
1000	3017	387.78	14	393.38	3	399.86
2000	3032	387.78	54	393.39	12	399.86
5000	3037	387.78	247	393.43	69	399.87
10K	3037	387.78	506	393.48	211	399.90
20K	3037	387.78	686	393.51	432	399.94
50K	3038	387.78	768	393.53	612	399.98
100K	3038	387.78	802	393.54	655	399.99
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.12

TABLE 16.84 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2	2	2
Temperature T (K)	373.15	373.15	373.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.303	0.404	0.505
Enhancement factor f_e	1.00917	1.00917	1.00917
Corrections			
Specific heat K_C (ppm)	−4317	−4907	−5455
Virial K_V (ppm)	−2941	−6305	−10579
Simple sound speed W_s (m/s)	408.14	416.16	424.80

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	406.66	0	413.83	0	421.39
10	0	406.66	0	413.83	0	421.39
20	0	406.66	0	413.83	0	421.39
50	0	406.66	0	413.83	0	421.39
100	0	406.66	0	413.83	0	421.39
200	0	406.66	0	413.83	0	421.39
500	0	406.66	0	413.83	0	421.39
1000	1	406.66	1	413.83	0	421.39
2000	5	406.66	2	413.83	1	421.39
5000	28	406.67	13	413.83	7	421.40
10K	96	406.68	48	413.84	26	421.40
20K	253	406.71	146	413.86	85	421.41
50K	468	406.76	342	413.90	240	421.45
100K	534	406.77	424	413.92	325	421.46
Uncertainty $\delta W/W$ (%)		0.15		0.15		0.16

TABLE 16.85 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	423.15		423.15		423.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.474		0.949	
Enhancement factor f_e	1.00943		1.00943		1.00943	
Corrections						
Specific heat K_C (ppm)	−4607		−8468		−11151	
Virial K_V (ppm)	2131		−4365		−20227	
Simple sound speed W_s (m/s)	412.38		449.55		503.09	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	411.87	0	446.66	0	495.19
10	128	411.89	0	446.66	0	495.19
20	448	411.96	0	446.66	0	495.19
50	1585	412.19	0	446.66	0	495.19
100	2888	412.46	0	446.66	0	495.19
200	4224	412.73	0	446.66	0	495.19
500	5132	412.92	0	446.66	0	495.19
1000	5315	412.96	1	446.66	0	495.19
2000	5363	412.97	2	446.66	0	495.19
5000	5377	412.97	15	446.67	0	495.19
10K	5379	412.97	57	446.68	1	495.19
20K	5380	412.97	192	446.71	5	495.19
50K	5380	412.97	556	446.79	22	495.20
100K	5380	412.97	764	446.83	45	495.20
Uncertainty $\delta W/W$ (%)		0.15		0.16		0.23

TABLE 16.86 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2		2		2	
Temperature T (K)	473.15		473.15		473.15	
Humidity						
RH, h_r (%)	0		6		12	
Mole fraction x_h	0		0.467		0.934	
Enhancement factor f_e	1.00967		1.00967		1.00967	
Corrections						
Specific heat K_C (ppm)	−7566		−12097		−15215	
Virial K_V (ppm)	2171		−2182		−11298	
Simple sound speed W_s (m/s)	436.06		474.65		529.87	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	434.88	0	471.26	0	522.85
10	143	434.91	0	471.26	0	522.85
20	523	434.99	0	471.26	0	522.85
50	2080	435.33	0	471.26	0	522.85
100	3967	435.74	0	471.26	0	522.85
200	6003	436.18	0	471.26	0	522.85
500	7792	436.57	0	471.26	0	522.85
1000	8227	436.67	1	471.26	0	522.85
2000	8349	436.69	4	471.26	0	522.85
5000	8384	436.70	25	471.26	1	522.85
10K	8389	436.70	94	471.28	3	522.85
20K	8390	436.70	321	471.33	10	522.85
50K	8391	436.70	979	471.49	46	522.86
100K	8391	436.70	1384	471.58	101	522.87
Uncertainty $\delta W/W$ (%)		0.14		0.18		0.27

TABLE 16.87 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2	2	2
Temperature T (K)	523.15	523.15	523.15
Humidity			
RH, h_r (%)	0	2.4	4.8
Mole fraction x_h	0	0.484	0.968
Enhancement factor f_e	1.00989	1.00989	1.00989
Corrections			
Specific heat K_C (ppm)	−11077	−16334	−19845
Virial K_V (ppm)	2154	−1334	−7673
Simple sound speed W_s (m/s)	458.52	500.86	562.38

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	456.47	0	496.42	0	554.64
10	151	456.50	0	496.42	0	554.64
20	566	456.60	0	496.42	0	554.64
50	2487	457.04	0	496.42	0	554.64
100	5085	457.63	0	496.42	0	554.64
200	7848	458.26	0	496.42	0	554.64
500	10720	458.91	0	496.42	0	554.64
1000	11577	459.10	1	496.42	0	554.64
2000	11832	459.16	5	496.42	0	554.64
5000	11907	459.18	31	496.42	0	554.64
10K	11918	459.18	118	496.45	2	554.64
20K	11921	459.18	413	496.52	6	554.64
50K	11922	459.18	1364	496.76	30	554.64
100K	11922	459.18	2035	496.92	69	554.65
Uncertainty $\delta W/W$ (%)		0.14		0.38		0.82

TABLE 16.88 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2	2	2
Temperature T (K)	573.15	573.15	573.15
Humidity			
RH, h_r (%)	0	1.1	2.2
Mole fraction x_h	0	0.492	0.983
Enhancement factor f_e	1.01008	1.01008	1.01008
Corrections			
Specific heat K_C (ppm)	−15083	−20806	−24538
Virial K_V (ppm)	2107	−776	−5302
Simple sound speed W_s (m/s)	479.94	525.05	591.09

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	476.80	0	519.36	0	582.24
10	152	476.84	0	519.36	0	582.24
20	581	476.94	0	519.36	0	582.24
50	2759	477.46	0	519.36	0	582.24
100	6115	478.26	0	519.36	0	582.24
200	9690	479.11	0	519.36	0	582.24
500	13691	480.06	0	519.36	0	582.24
1000	15144	480.40	2	519.36	0	582.24
2000	15613	480.51	6	519.36	0	582.24
5000	15755	480.55	37	519.37	0	582.24
10K	15776	480.55	145	519.40	1	582.24
20K	15781	480.55	513	519.49	4	582.24
50K	15782	480.55	1790	519.83	20	582.25
100K	15783	480.55	2777	520.08	48	582.26
Uncertainty $\delta W/W$ (%)		0.15		0.60		1.43

TABLE 16.89 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	2	2	2
Temperature T (K)	603.15	603.15	603.15
Humidity			
RH, h_r (%)	0	0.7	1.4
Mole fraction x_h	0	0.478	0.957
Enhancement factor f_e	1.01018	1.01018	1.01018
Corrections			
Specific heat K_C (ppm)	−17700	−23427	−27163
Virial K_V (ppm)	2071	−442	−4028
Simple sound speed W_s (m/s)	492.34	537.16	601.96

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	488.46	0	530.71	0	592.53
10	151	488.50	0	530.71	0	592.53
20	579	488.61	0	530.71	0	592.53
50	2855	489.16	0	530.71	0	592.53
100	6641	490.08	0	530.71	0	592.53
200	10759	491.09	0	530.71	0	592.53
500	15417	492.22	0	530.71	0	592.53
1000	17296	492.67	2	530.71	0	592.53
2000	17938	492.83	7	530.71	0	592.53
5000	18136	492.87	46	530.72	1	592.53
10K	18165	492.88	177	530.76	3	592.53
20K	18172	492.88	628	530.88	12	592.54
50K	18174	492.88	2195	531.29	61	592.55
100K	18174	492.88	3410	531.61	147	592.58
Uncertainty $\delta W/W$ (%)		0.16		0.71		1.70

TABLE 16.90 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	233.15		233.15		233.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000008		0.000015	
Enhancement factor f_e	1.02400		1.02400		1.02400	
Corrections						
Specific heat K_C (ppm)	755		755		755	
Virial K_V (ppm)	−1604		−1604		−1604	
Simple sound speed W_s (m/s)	306.10		306.10		306.10	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	305.97	0	305.97	0	305.97
10	6	305.97	5	305.97	5	305.97
20	20	305.98	18	305.98	16	305.98
50	72	305.98	68	305.98	63	305.98
100	122	305.99	118	305.99	114	305.99
200	148	306.00	147	306.00	145	306.00
500	158	306.00	158	306.00	158	306.00
1000	160	306.00	160	306.00	160	306.00
2000	160	306.00	160	306.00	160	306.00
5000	160	306.00	160	306.00	160	306.00
10K	160	306.00	160	306.00	160	306.00
20K	160	306.00	160	306.00	160	306.00
50K	160	306.00	160	306.00	160	306.00
100K	160	306.00	160	306.00	160	306.00
Uncertainty $\delta W/W$ (%)		0.13		0.13		0.13

TABLE 16.91 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	233.15		233.15		233.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000023		0.000031		0.000038	
Enhancement factor f_e	1.02400		1.02400		1.02400	
Corrections						
Specific heat K_C (ppm)	755		755		755	
Virial K_V (ppm)	−1604		−1604		−1604	
Simple sound speed W_s (m/s)	306.10		306.10		306.10	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	305.97	0	305.97	0	305.97
10	4	305.97	4	305.97	3	305.97
20	15	305.98	13	305.98	12	305.98
50	58	305.98	53	305.98	49	305.98
100	110	305.99	105	305.99	100	305.99
200	144	306.00	141	306.00	139	306.00
500	157	306.00	157	306.00	156	306.00
1000	160	306.00	159	306.00	159	306.00
2000	160	306.00	160	306.00	160	306.00
5000	160	306.00	160	306.00	160	306.00
10K	160	306.00	160	306.00	160	306.00
20K	160	306.00	160	306.00	160	306.00
50K	160	306.00	160	306.00	160	306.00
100K	160	306.00	160	306.00	160	306.00
Uncertainty $\delta W/W$ (%)		0.13		0.13		0.13

TABLE 16.92 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	243.15		243.15		243.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000021		0.000041	
Enhancement factor f_e	1.02230		1.02230		1.02230	
Corrections						
Specific heat K_C (ppm)	725		725		725	
Virial K_V (ppm)	−457		−457		−457	
Simple sound speed W_s (m/s)	312.60		312.60		312.60	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	312.64	0	312.64	0	312.64
10	6	312.64	5	312.64	4	312.64
20	23	312.64	18	312.64	13	312.64
50	87	312.65	71	312.65	56	312.65
100	158	312.66	142	312.66	123	312.66
200	201	312.67	194	312.67	183	312.67
500	218	312.67	217	312.68	215	312.68
1000	221	312.67	221	312.68	220	312.68
2000	222	312.67	222	312.68	221	312.68
5000	222	312.67	222	312.68	222	312.68
10K	222	312.67	222	312.68	222	312.68
20K	222	312.67	222	312.68	222	312.68
50K	222	312.67	222	312.68	222	312.68
100K	222	312.67	222	312.68	222	312.68
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.93 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	243.15		243.15		243.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000062		0.000082		0.000103	
Enhancement factor f_e	1.02230		1.02230		1.02230	
Corrections						
Specific heat K_C (ppm)	725		725		725	
Virial K_V (ppm)	−457		−457		−457	
Simple sound speed W_s (m/s)	312.60		312.60		312.60	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	312.64	0	312.64	0	312.65
10	3	312.64	2	312.64	2	312.65
20	10	312.64	8	312.65	6	312.65
50	44	312.65	34	312.65	27	312.65
100	102	312.66	84	312.66	68	312.66
200	170	312.67	153	312.67	136	312.67
500	211	312.68	207	312.68	201	312.68
1000	219	312.68	218	312.68	216	312.68
2000	221	312.68	221	312.68	220	312.68
5000	222	312.68	222	312.68	222	312.68
10K	222	312.68	222	312.68	222	312.68
20K	222	312.68	222	312.68	222	312.68
50K	222	312.68	222	312.68	222	312.68
100K	222	312.68	222	312.68	222	312.68
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.94 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5	5	5
Temperature T (K)	253.15	253.15	253.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.000051	0.000101
Enhancement factor f_e	1.02096	1.02096	1.02096
Corrections			
Specific heat K_C (ppm)	666	666	666
Virial K_V (ppm)	501	501	501
Simple sound speed W_s (m/s)	318.96	318.96	318.97

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	319.15	0	319.15	0	319.15
10	7	319.15	4	319.15	2	319.15
20	26	319.15	14	319.15	8	319.15
50	102	319.16	59	319.16	34	319.16
100	197	319.18	138	319.17	85	319.17
200	264	319.19	228	319.19	173	319.18
500	293	319.19	285	319.20	266	319.20
1000	298	319.20	295	319.20	290	319.20
2000	299	319.20	298	319.20	297	319.20
5000	299	319.20	299	319.20	299	319.20
10K	299	319.20	299	319.20	299	319.20
20K	299	319.20	299	319.20	299	319.20
50K	299	319.20	299	319.20	299	319.20
100K	299	319.20	299	319.20	299	319.20
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.95 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	253.15		253.15		253.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000152		0.000202		0.000253	
Enhancement factor f_e	1.02096		1.02096		1.02096	
Corrections						
Specific heat K_C (ppm)	666		666		666	
Virial K_V (ppm)	501		501		501	
Simple sound speed W_s (m/s)	318.97		318.97		318.97	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	319.16	0	319.16	0	319.16
10	1	319.16	1	319.16	1	319.16
20	5	319.16	4	319.16	3	319.16
50	22	319.16	16	319.16	13	319.16
100	54	319.16	38	319.16	29	319.17
200	120	319.17	82	319.17	60	319.17
500	236	319.19	196	319.19	157	319.19
1000	280	319.20	263	319.20	240	319.20
2000	294	319.20	289	319.20	282	319.21
5000	298	319.20	298	319.21	296	319.21
10K	299	319.20	299	319.21	298	319.21
20K	299	319.20	299	319.21	299	319.21
50K	299	319.20	299	319.21	299	319.21
100K	299	319.20	299	319.21	299	319.21
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.96 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	263.15		263.15		263.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000115		0.000230	
Enhancement factor f_e	1.01993		1.01993		1.01993	
Corrections						
Specific heat K_C (ppm)	579		578		578	
Virial K_V (ppm)	1305		1305		1304	
Simple sound speed W_s (m/s)	325.20		325.21		325.21	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	325.51	0	325.51	0	325.52
10	8	325.51	2	325.51	1	325.52
20	29	325.51	9	325.51	4	325.52
50	118	325.53	37	325.52	19	325.52
100	240	325.55	90	325.53	44	325.53
200	338	325.56	192	325.54	88	325.53
500	384	325.57	333	325.57	220	325.55
1000	391	325.57	376	325.57	325	325.57
2000	393	325.57	389	325.58	374	325.58
5000	394	325.57	393	325.58	391	325.58
10K	394	325.57	394	325.58	393	325.58
20K	394	325.57	394	325.58	394	325.58
50K	394	325.57	394	325.58	394	325.58
100K	394	325.57	394	325.58	394	325.58
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.97 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	263.15		263.15		263.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000346		0.000461		0.000576	
Enhancement factor f_e	1.01993		1.01993		1.01993	
Corrections						
Specific heat K_C (ppm)	577		577		577	
Virial K_V (ppm)	1304		1303		1303	
Simple sound speed W_s (m/s)	325.22		325.22		325.23	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	325.52	0	325.53	0	325.54
10	1	325.52	0	325.53	0	325.54
20	3	325.52	2	325.53	1	325.54
50	13	325.53	9	325.53	7	325.54
100	30	325.53	24	325.53	20	325.54
200	54	325.53	42	325.54	36	325.54
500	129	325.55	84	325.54	63	325.55
1000	242	325.56	167	325.56	117	325.56
2000	338	325.58	284	325.58	225	325.57
5000	384	325.59	370	325.59	349	325.59
10K	391	325.59	388	325.59	381	325.60
20K	393	325.59	392	325.59	391	325.60
50K	394	325.59	394	325.59	393	325.60
100K	394	325.59	394	325.59	394	325.60
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.98 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	273.15		273.15		273.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000246		0.000491	
Enhancement factor f_e	1.01915		1.01915		1.01915	
Corrections						
Specific heat K_C (ppm)	462		461		460	
Virial K_V (ppm)	1981		1980		1979	
Simple sound speed W_s (m/s)	331.32		331.33		331.35	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	331.73	0	331.74	0	331.75
10	9	331.73	1	331.74	1	331.75
20	32	331.73	5	331.74	2	331.75
50	134	331.75	24	331.74	12	331.75
100	286	331.77	55	331.75	31	331.76
200	422	331.80	104	331.76	56	331.76
500	492	331.81	255	331.78	102	331.77
1000	504	331.81	398	331.81	193	331.78
2000	507	331.81	475	331.82	341	331.81
5000	508	331.81	502	331.82	469	331.83
10K	508	331.81	507	331.82	498	331.83
20K	508	331.81	508	331.82	505	331.84
50K	508	331.81	508	331.82	508	331.84
100K	508	331.81	508	331.82	508	331.84
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.99 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	273.15		273.15		273.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000737		0.000983		0.00123	
Enhancement factor f_e	1.01915		1.01915		1.01915	
Corrections						
Specific heat K_C (ppm)	459		458		457	
Virial K_V (ppm)	1978		1977		1975	
Simple sound speed W_s (m/s)	331.36		331.37		331.39	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	331.76	0	331.78	0	331.79
10	0	331.76	0	331.78	0	331.79
20	1	331.76	1	331.78	1	331.79
50	7	331.77	5	331.78	3	331.79
100	22	331.77	16	331.78	12	331.79
200	44	331.77	36	331.78	30	331.80
500	71	331.78	61	331.79	56	331.80
1000	108	331.78	80	331.79	70	331.80
2000	203	331.80	131	331.80	98	331.81
5000	393	331.83	299	331.83	220	331.83
10K	472	331.84	427	331.85	368	331.85
20K	498	331.85	484	331.86	462	331.87
50K	506	331.85	504	331.86	500	331.87
100K	508	331.85	507	331.86	506	331.87
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.100 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	283.15		283.15		283.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000493		0.000987	
Enhancement factor f_e	1.01857		1.01857		1.01857	
Corrections						
Specific heat K_C (ppm)	316		314		312	
Virial K_V (ppm)	2552		2550		2547	
Simple sound speed W_s (m/s)	337.33		337.36		337.39	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	337.82	0	337.84	0	337.87
10	10	337.82	1	337.84	0	337.87
20	36	337.82	3	337.84	1	337.87
50	152	337.84	15	337.84	6	337.87
100	333	337.87	42	337.85	21	337.87
200	516	337.90	77	337.85	50	337.88
500	619	337.92	134	337.86	86	337.88
1000	637	337.92	242	337.88	110	337.89
2000	642	337.92	424	337.91	170	337.90
5000	644	337.92	591	337.94	376	337.93
10K	644	337.92	629	337.95	538	337.96
20K	644	337.92	640	337.95	613	337.97
50K	644	337.92	643	337.95	638	337.98
100K	644	337.92	643	337.95	642	337.98
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.101 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	283.15		283.15		283.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.00148		0.00197		0.00247	
Enhancement factor f_e	1.01857		1.01857		1.01857	
Corrections						
Specific heat K_C (ppm)	310		308		306	
Virial K_V (ppm)	2543		2540		2536	
Simple sound speed W_s (m/s)	337.41		337.44		337.47	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	337.89	0	337.92	0	337.95
10	0	337.89	0	337.92	0	337.95
20	1	337.89	0	337.92	0	337.95
50	3	337.89	2	337.92	1	337.95
100	12	337.90	8	337.92	5	337.95
200	35	337.90	25	337.92	18	337.95
500	73	337.91	64	337.93	56	337.95
1000	91	337.91	84	337.93	79	337.96
2000	113	337.91	98	337.94	92	337.96
5000	214	337.93	147	337.94	120	337.97
10K	387	337.96	265	337.96	194	337.98
20K	545	337.99	449	338.00	356	338.01
50K	624	338.00	599	338.02	561	338.04
100K	638	338.00	631	338.03	619	338.05
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.102 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	293.15		293.15		293.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000939		0.00188	
Enhancement factor f_e	1.01815		1.01815		1.01815	
Corrections						
Specific heat K_C (ppm)	142		138		134	
Virial K_V (ppm)	3035		3029		3022	
Simple sound speed W_s (m/s)	343.24		343.29		343.34	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	343.78	0	343.83	0	343.88
10	11	343.78	0	343.83	0	343.88
20	39	343.79	1	343.83	0	343.88
50	170	343.81	9	343.83	3	343.88
100	383	343.85	29	343.84	11	343.88
200	618	343.89	69	343.84	35	343.89
500	765	343.91	119	343.85	90	343.90
1000	793	343.92	153	343.86	118	343.90
2000	800	343.92	234	343.87	137	343.91
5000	802	343.92	493	343.92	204	343.92
10K	802	343.92	684	343.95	359	343.94
20K	802	343.92	768	343.96	584	343.98
50K	802	343.92	796	343.97	753	344.01
100K	802	343.92	800	343.97	788	344.02
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.103 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	293.15		293.15		293.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.00282		0.00376		0.00470	
Enhancement factor f_e	1.01815		1.01815		1.01815	
Corrections						
Specific heat K_C (ppm)	130		126		122	
Virial K_V (ppm)	3014		3006		2996	
Simple sound speed W_s (m/s)	343.39		343.44		343.50	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	343.93	0	343.98	0	344.03
10	0	343.93	0	343.98	0	344.03
20	0	343.93	0	343.98	0	344.03
50	1	343.93	1	343.98	1	344.03
100	6	343.93	3	343.98	2	344.03
200	20	343.94	12	343.98	8	344.03
500	68	343.94	51	343.99	39	344.04
1000	105	343.95	93	344.00	81	344.05
2000	124	343.95	117	344.00	111	344.05
5000	150	343.96	135	344.00	129	344.05
10K	215	343.97	166	344.01	147	344.06
20K	381	344.00	264	344.03	206	344.07
50K	659	344.05	542	344.07	435	344.11
100K	758	344.06	708	344.10	645	344.14
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.104 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	303.15		303.15		303.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00170		0.00341	
Enhancement factor f_e	1.01788		1.01788		1.01788	
Corrections						
Specific heat K_C (ppm)	−61		−69		−77	
Virial K_V (ppm)	3444		3431		3416	
Simple sound speed W_s (m/s)	349.04		349.14		349.23	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	349.63	0	349.72	0	349.82
10	12	349.63	0	349.72	0	349.82
20	43	349.64	1	349.72	0	349.82
50	189	349.67	4	349.73	1	349.82
100	434	349.71	16	349.73	5	349.82
200	727	349.76	51	349.73	19	349.82
500	930	349.79	126	349.75	75	349.83
1000	971	349.80	163	349.75	130	349.84
2000	982	349.80	190	349.76	161	349.84
5000	985	349.80	292	349.78	186	349.85
10K	985	349.80	505	349.81	234	349.86
20K	985	349.80	769	349.86	376	349.88
50K	985	349.80	939	349.89	721	349.94
100K	985	349.80	972	349.89	895	349.97
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.105 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5	5	5
Temperature T (K)	303.15	303.15	303.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.00511	0.00682	0.00852
Enhancement factor f_e	1.01788	1.01788	1.01788
Corrections			
Specific heat K_C (ppm)	−85	−93	−101
Virial K_V (ppm)	3399	3380	3358
Simple sound speed W_s (m/s)	349.33	349.43	349.52

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	349.91	0	350.00	0	350.09
10	0	349.91	0	350.00	0	350.09
20	0	349.91	0	350.00	0	350.09
50	1	349.91	0	350.00	0	350.09
100	2	349.91	1	350.00	1	350.09
200	9	349.91	6	350.00	4	350.09
500	45	349.92	30	350.00	20	350.09
1000	101	349.93	78	350.01	60	350.10
2000	147	349.93	132	350.02	117	350.11
5000	172	349.94	166	350.03	160	350.12
10K	191	349.94	179	350.03	173	350.12
20K	249	349.95	208	350.04	191	350.12
50K	494	349.99	359	350.06	287	350.14
100K	758	350.04	613	350.11	495	350.18
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.106 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	313.23		313.23		313.23	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00298		0.00595	
Enhancement factor f_e	1.01772		1.01772		1.01772	
Corrections						
Specific heat K_C (ppm)	−294		−309		−324	
Virial K_V (ppm)	3794		3768		3738	
Simple sound speed W_s (m/s)	354.80		354.97		355.14	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	355.42	0	355.58	0	355.74
10	12	355.42	0	355.58	0	355.74
20	47	355.43	0	355.58	0	355.74
50	210	355.46	2	355.58	1	355.74
100	488	355.50	8	355.58	2	355.74
200	844	355.57	29	355.59	9	355.74
500	1117	355.62	110	355.60	46	355.75
1000	1175	355.63	182	355.61	116	355.76
2000	1190	355.63	220	355.62	184	355.78
5000	1195	355.63	256	355.63	224	355.78
10K	1196	355.63	335	355.64	243	355.79
20K	1196	355.63	548	355.68	290	355.79
50K	1196	355.63	957	355.75	518	355.84
100K	1196	355.63	1119	355.78	836	355.89
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.107 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	313.23		313.23		313.23	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.00893		0.0119		0.0149	
Enhancement factor f_e	1.01772		1.01772		1.01772	
Corrections						
Specific heat K_C (ppm)	−339		−354		−369	
Virial K_V (ppm)	3702		3661		3615	
Simple sound speed W_s (m/s)	355.31		355.48		355.65	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	355.90	0	356.07	0	356.23
10	0	355.90	0	356.07	0	356.23
20	0	355.90	0	356.07	0	356.23
50	0	355.90	0	356.07	0	356.23
100	1	355.90	1	356.07	0	356.23
200	4	355.91	2	356.07	2	356.23
500	24	355.91	14	356.07	9	356.23
1000	73	355.92	48	356.07	33	356.23
2000	149	355.93	118	356.09	93	356.24
5000	211	355.94	198	356.10	184	356.26
10K	229	355.95	221	356.10	215	356.26
20K	249	355.95	236	356.11	229	356.27
50K	352	355.97	291	356.12	264	356.27
100K	585	356.01	441	356.14	363	356.29
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.108 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	323.15		323.15		323.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00496		0.00991	
Enhancement factor f_e	1.01766		1.01766		1.01766	
Corrections						
Specific heat K_C (ppm)	−551		−578		−605	
Virial K_V (ppm)	4085		4038		3980	
Simple sound speed W_s (m/s)	360.37		360.66		360.95	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	361.01	0	361.28	0	361.56
10	13	361.01	0	361.28	0	361.56
20	50	361.02	0	361.28	0	361.56
50	231	361.05	1	361.28	0	361.56
100	543	361.11	4	361.28	1	361.56
200	965	361.18	15	361.29	4	361.56
500	1320	361.25	76	361.30	25	361.56
1000	1400	361.26	172	361.31	79	361.57
2000	1422	361.26	253	361.33	176	361.59
5000	1428	361.27	298	361.34	268	361.60
10K	1429	361.27	327	361.34	293	361.61
20K	1429	361.27	412	361.36	314	361.61
50K	1429	361.27	763	361.42	410	361.63
100K	1429	361.27	1127	361.49	645	361.67
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.109 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	323.15		323.15		323.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.0149		0.0198		0.0248	
Enhancement factor f_e	1.01766		1.01766		1.01766	
Corrections						
Specific heat K_C (ppm)	−632		−658		−685	
Virial K_V (ppm)	3910		3828		3734	
Simple sound speed W_s (m/s)	361.24		361.53		361.82	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	361.83	0	362.10	0	362.37
10	0	361.83	0	362.10	0	362.37
20	0	361.83	0	362.10	0	362.37
50	0	361.83	0	362.10	0	362.37
100	0	361.83	0	362.10	0	362.37
200	2	361.83	1	362.10	1	362.37
500	12	361.83	7	362.10	4	362.37
1000	42	361.84	25	362.10	17	362.37
2000	117	361.85	80	362.11	57	362.38
5000	237	361.87	205	362.14	175	362.40
10K	279	361.88	265	362.15	250	362.41
20K	297	361.88	288	362.15	281	362.42
50K	339	361.89	314	362.16	302	362.42
100K	455	361.91	380	362.17	344	362.43
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.110 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	373.15		373.15		373.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.0407		0.0815	
Enhancement factor f_e	1.01830		1.01830		1.01830	
Corrections						
Specific heat K_C (ppm)	−2253		−2559		−2856	
Virial K_V (ppm)	4999		4424		3515	
Simple sound speed W_s (m/s)	387.25		389.82		392.45	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	387.78	0	390.18	0	392.58
10	18	387.78	0	390.18	0	392.58
20	68	387.79	0	390.18	0	392.58
50	344	387.85	0	390.18	0	392.58
100	865	387.95	0	390.18	0	392.58
200	1645	388.10	1	390.18	0	392.58
500	2609	388.28	4	390.18	1	392.58
1000	2914	388.34	15	390.18	4	392.58
2000	3005	388.36	57	390.19	14	392.58
5000	3032	388.37	264	390.23	82	392.60
10K	3036	388.37	547	390.28	251	392.63
20K	3037	388.37	747	390.32	517	392.68
50K	3037	388.37	839	390.34	737	392.72
100K	3038	388.37	879	390.35	790	392.73
Uncertainty $\delta W/W$ (%)		0.11		0.11		0.11

TABLE 16.111 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	373.15		373.15		373.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.122		0.163		0.204	
Enhancement factor f_e	1.01830		1.01830		1.01830	
Corrections						
Specific heat K_C (ppm)	−3143		−3422		−3692	
Virial K_V (ppm)	2261		651		−1324	
Simple sound speed W_s (m/s)	395.16		397.95		400.82	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	394.99	0	397.40	0	399.81
10	0	394.99	0	397.40	0	399.81
20	0	394.99	0	397.40	0	399.81
50	0	394.99	0	397.40	0	399.81
100	0	394.99	0	397.40	0	399.81
200	0	394.99	0	397.40	0	399.81
500	0	394.99	0	397.40	0	399.81
1000	2	394.99	1	397.40	0	399.81
2000	6	394.99	3	397.40	2	399.81
5000	36	394.99	20	397.40	12	399.81
10K	127	395.01	73	397.41	45	399.82
20K	338	395.05	222	397.44	150	399.84
50K	629	395.11	524	397.50	428	399.90
100K	720	395.13	651	397.53	583	399.93
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.13

TABLE 16.112 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	423.15		423.15		423.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.192		0.383	
Enhancement factor f_e	1.01978		1.01978		1.01978	
Corrections						
Specific heat K_C (ppm)	−4607		−6341		−7833	
Virial K_V (ppm)	5362		1484		−6161	
Simple sound speed W_s (m/s)	412.38		425.92		441.41	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	412.53	0	424.89	0	438.32
10	21	412.53	0	424.89	0	438.32
20	83	412.55	0	424.89	0	438.32
50	448	412.62	0	424.89	0	438.32
100	1231	412.78	0	424.89	0	438.32
200	2441	413.03	0	424.89	0	438.32
500	4224	413.40	0	424.89	0	438.32
1000	5006	413.56	1	424.89	0	438.32
2000	5279	413.62	4	424.89	1	438.32
5000	5363	413.63	25	424.89	5	438.32
10K	5376	413.64	97	424.91	18	438.32
20K	5379	413.64	324	424.95	68	438.33
50K	5380	413.64	949	425.09	319	438.39
100K	5380	413.64	1310	425.16	671	438.47
Uncertainty $\delta W/W$ (%)		0.12		0.13		0.16

TABLE 16.113 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5	5	5
Temperature T (K)	423.15	423.15	423.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.575	0.767	0.959
Enhancement factor f_e	1.01978	1.01978	1.01978
Corrections			
Specific heat K_C (ppm)	−9121	−10234	−11197
Virial K_V (ppm)	−17820	−33786	−54399
Simple sound speed W_s (m/s)	459.24	479.99	504.44

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	453.05	0	469.39	0	487.77
10	0	453.05	0	469.39	0	487.77
20	0	453.05	0	469.39	0	487.77
50	0	453.05	0	469.39	0	487.77
100	0	453.05	0	469.39	0	487.77
200	0	453.05	0	469.39	0	487.77
500	0	453.05	0	469.39	0	487.77
1000	0	453.05	0	469.39	0	487.77
2000	0	453.05	0	469.39	0	487.77
5000	1	453.05	0	469.39	0	487.77
10K	5	453.05	1	469.39	0	487.77
20K	20	453.06	6	469.39	1	487.77
50K	109	453.08	34	469.40	4	487.77
100K	294	453.12	105	469.42	12	487.77
Uncertainty $\delta W/W$ (%)		0.19		0.19		0.26

TABLE 16.114 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	473.15		473.15		473.15	
Humidity						
RH, h_r (%)	0		15		30	
Mole fraction x_h	0		0.473		0.945	
Enhancement factor f_e	1.02154		1.02154		1.02154	
Corrections						
Specific heat K_C (ppm)	−7566		−12141		−15275	
Virial K_V (ppm)	5452		−5708		−29615	
Simple sound speed W_s (m/s)	436.06		475.19		531.46	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	435.59	0	470.95	0	519.51
10	24	435.60	0	470.95	0	519.51
20	93	435.61	0	470.95	0	519.51
50	523	435.71	0	470.95	0	519.51
100	1569	435.93	0	470.95	0	519.51
200	3329	436.32	0	470.95	0	519.51
500	6003	436.90	0	470.95	0	519.51
1000	7511	437.23	0	470.95	0	519.51
2000	8140	437.36	1	470.95	0	519.51
5000	8349	437.41	4	470.95	0	519.51
10K	8380	437.41	15	470.95	0	519.51
20K	8388	437.42	60	470.96	1	519.51
50K	8390	437.42	311	471.02	8	519.52
100K	8390	437.42	783	471.13	27	519.52
Uncertainty $\delta W/W$ (%)		0.15		0.19		0.29

TABLE 16.115 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	523.15		523.15		523.15	
Humidity						
RH, h_r (%)	0		6		12	
Mole fraction x_h	0		0.491		0.981	
Enhancement factor f_e	1.02337		1.02337		1.02337	
Corrections						
Specific heat K_C (ppm)	−11077		−16391		−19921	
Virial K_V (ppm)	5402		−3514		−19957	
Simple sound speed W_s (m/s)	458.52		501.53		564.41	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	457.21	0	496.53	0	553.16
10	25	457.21	0	496.53	0	553.16
20	97	457.23	0	496.53	0	553.16
50	566	457.34	0	496.53	0	553.16
100	1820	457.62	0	496.53	0	553.16
200	4204	458.17	0	496.53	0	553.16
500	7848	459.00	0	496.53	0	553.16
1000	10207	459.54	0	496.53	0	553.16
2000	11398	459.81	1	496.53	0	553.16
5000	11832	459.90	5	496.53	0	553.16
10K	11899	459.92	19	496.53	0	553.16
20K	11916	459.92	74	496.54	1	553.16
50K	11921	459.92	398	496.62	3	553.16
100K	11921	459.93	1062	496.79	12	553.16
Uncertainty $\delta W/W$ (%)		0.15		0.39		0.83

TABLE 16.116 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5	5	5
Temperature T (K)	573.15	573.15	573.15
Humidity			
RH, h_r (%)	0	2.75	5.5
Mole fraction x_h	0	0.499	0.998
Enhancement factor f_e	1.02514	1.02514	1.02514
Corrections			
Specific heat K_C (ppm)	−15083	−20874	−24626
Virial K_V (ppm)	5281	−2080	−13754
Simple sound speed W_s (m/s)	479.94	525.86	593.53

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	477.56	0	519.80	0	582.13
10	25	477.56	0	519.80	0	582.13
20	98	477.58	0	519.80	0	582.13
50	581	477.70	0	519.80	0	582.13
100	1967	478.03	0	519.80	0	582.13
200	4947	478.74	0	519.80	0	582.13
500	9690	479.87	0	519.80	0	582.13
1000	12897	480.63	0	519.80	0	582.13
2000	14825	481.09	1	519.80	0	582.13
5000	15613	481.27	6	519.80	0	582.13
10K	15740	481.30	23	519.80	0	582.13
20K	15772	481.31	90	519.82	0	582.13
50K	15781	481.31	492	519.92	0	582.13
100K	15782	481.31	1365	520.15	2	582.13
Uncertainty $\delta W/W$ (%)		0.16		0.60		1.43

TABLE 16.117 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	5		5		5	
Temperature T (K)	603.15		603.15		603.15	
Humidity						
RH, h_r (%)	0		1.8		3.6	
Mole fraction x_h	0		0.500		1.000	
Enhancement factor f_e	1.02616		1.02616		1.02616	
Corrections						
Specific heat K_C (ppm)	−17700		−23631		−27426	
Virial K_V (ppm)	5190		−1447		−11061	
Simple sound speed W_s (m/s)	492.34		539.55		609.21	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	489.22	0	532.76	0	597.47
10	24	489.23	0	532.76	0	597.47
20	97	489.25	0	532.76	0	597.47
50	579	489.37	0	532.76	0	597.47
100	2008	489.72	0	532.76	0	597.47
200	5294	490.52	0	532.76	0	597.47
500	10759	491.85	0	532.76	0	597.47
1000	14448	492.75	0	532.76	0	597.47
2000	16870	493.33	1	532.76	0	597.47
5000	17938	493.59	6	532.76	0	597.47
10K	18114	493.64	26	532.76	0	597.47
20K	18159	493.65	100	532.78	0	597.47
50K	18172	493.65	553	532.90	0	597.47
100K	18174	493.65	1561	533.17	0	597.47
Uncertainty $\delta W/W$ (%)		0.17		0.73		1.79

TABLE 16.118 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	233.15		233.15		233.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000004		0.000008	
Enhancement factor f_e	1.05093		1.05093		1.05093	
Corrections						
Specific heat K_C (ppm)	755		755		755	
Virial K_V (ppm)	−2745		−2745		−2745	
Simple sound speed W_s (m/s)	306.10		306.10		306.10	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	305.80	0	305.80	0	305.80
10	2	305.80	1	305.80	1	305.80
20	6	305.80	5	305.80	5	305.80
50	29	305.80	27	305.80	26	305.80
100	72	305.81	70	305.81	67	305.81
200	122	305.82	120	305.82	118	305.82
500	153	305.82	152	305.82	152	305.82
1000	158	305.82	158	305.82	158	305.82
2000	160	305.82	160	305.82	160	305.82
5000	160	305.82	160	305.82	160	305.82
10K	160	305.82	160	305.82	160	305.82
20K	160	305.82	160	305.82	160	305.82
50K	160	305.82	160	305.82	160	305.82
100K	160	305.82	160	305.82	160	305.82
Uncertainty $\delta W/W$ (%)		0.16		0.16		0.16

TABLE 16.119 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	233.15		233.15		233.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000012		0.000016		0.000020	
Enhancement factor f_e	1.05093		1.05093		1.05093	
Corrections						
Specific heat K_C (ppm)	755		755		755	
Virial K_V (ppm)	−2745		−2745		−2745	
Simple sound speed W_s (m/s)	306.10		306.10		306.10	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	305.80	0	305.80	0	305.80
10	1	305.80	1	305.80	1	305.80
20	5	305.80	5	305.80	4	305.80
50	25	305.80	24	305.80	22	305.80
100	65	305.81	63	305.81	60	305.81
200	116	305.82	114	305.82	112	305.82
500	151	305.82	150	305.82	150	305.82
1000	158	305.82	158	305.82	158	305.82
2000	160	305.82	160	305.82	160	305.82
5000	160	305.82	160	305.82	160	305.82
10K	160	305.82	160	305.82	160	305.82
20K	160	305.82	160	305.82	160	305.82
50K	160	305.82	160	305.82	160	305.82
100K	160	305.82	160	305.82	160	305.82
Uncertainty $\delta W/W$ (%)		0.16		0.16		0.16

TABLE 16.120 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	243.15		243.15		243.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000011		0.000021	
Enhancement factor f_e	1.04650		1.04650		1.04650	
Corrections						
Specific heat K_C (ppm)	725		725		725	
Virial K_V (ppm)	−479		−479		−479	
Simple sound speed W_s (m/s)	312.60		312.60		312.60	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	312.64	0	312.64	0	312.64
10	2	312.64	1	312.64	1	312.64
20	6	312.64	6	312.64	5	312.64
50	33	312.64	29	312.64	25	312.64
100	87	312.65	79	312.65	71	312.65
200	158	312.66	150	312.66	141	312.66
500	208	312.67	206	312.67	203	312.67
1000	218	312.67	218	312.67	217	312.67
2000	221	312.67	221	312.67	221	312.67
5000	222	312.67	222	312.67	222	312.67
10K	222	312.67	222	312.67	222	312.67
20K	222	312.67	222	312.67	222	312.67
50K	222	312.67	222	312.67	222	312.67
100K	222	312.67	222	312.67	222	312.67
Uncertainty $\delta W/W$ (%)		0.15		0.15		0.15

TABLE 16.121 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	243.15		243.15		243.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000032		0.000042		0.000053	
Enhancement factor f_e	1.04650		1.04650		1.04650	
Corrections						
Specific heat K_C (ppm)	725		725		725	
Virial K_V (ppm)	−479		−479		−479	
Simple sound speed W_s (m/s)	312.60		312.60		312.60	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	312.64	0	312.64	0	312.64
10	1	312.64	1	312.64	1	312.64
20	4	312.64	4	312.64	3	312.64
50	22	312.64	19	312.64	17	312.64
100	63	312.65	55	312.65	49	312.65
200	132	312.66	122	312.66	111	312.66
500	199	312.67	195	312.67	190	312.67
1000	216	312.67	215	312.67	213	312.67
2000	220	312.67	220	312.67	220	312.67
5000	222	312.67	222	312.67	222	312.67
10K	222	312.67	222	312.67	222	312.67
20K	222	312.67	222	312.67	222	312.67
50K	222	312.67	222	312.67	222	312.67
100K	222	312.67	222	312.67	222	312.67
Uncertainty $\delta W/W$ (%)		0.15		0.15		0.15

TABLE 16.122 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	253.15		253.15		253.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000026		0.000052	
Enhancement factor f_e	1.04286		1.04286		1.04286	
Corrections						
Specific heat K_C (ppm)	666		666		666	
Virial K_V (ppm)	1408		1408		1408	
Simple sound speed W_s (m/s)	318.96		318.96		318.96	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	319.29	0	319.29	0	319.29
10	2	319.29	1	319.29	1	319.30
20	7	319.29	5	319.29	4	319.30
50	37	319.30	27	319.30	20	319.30
100	102	319.31	78	319.31	58	319.30
200	197	319.32	168	319.32	136	319.32
500	276	319.34	265	319.34	248	319.33
1000	293	319.34	290	319.34	284	319.34
2000	298	319.34	297	319.34	295	319.34
5000	299	319.34	299	319.34	299	319.34
10K	299	319.34	299	319.34	299	319.34
20K	299	319.34	299	319.34	299	319.34
50K	299	319.34	299	319.34	299	319.34
100K	299	319.34	299	319.34	299	319.34
Uncertainty $\delta W/W$ (%)		0.14		0.14		0.14

TABLE 16.123 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	253.15		253.15		253.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000077		0.000103		0.000129	
Enhancement factor f_e	1.04286		1.04286		1.04286	
Corrections						
Specific heat K_C (ppm)	666		666		666	
Virial K_V (ppm)	1408		1408		1408	
Simple sound speed W_s (m/s)	318.97		318.97		318.97	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	319.30	0	319.30	0	319.30
10	1	319.30	1	319.30	0	319.30
20	3	319.30	2	319.30	2	319.30
50	15	319.30	11	319.30	9	319.30
100	43	319.30	33	319.30	27	319.30
200	107	319.31	83	319.31	65	319.31
500	226	319.33	200	319.33	172	319.33
1000	276	319.34	265	319.34	251	319.34
2000	293	319.34	290	319.34	285	319.34
5000	298	319.34	298	319.35	297	319.35
10K	299	319.34	299	319.35	299	319.35
20K	299	319.34	299	319.35	299	319.35
50K	299	319.34	299	319.35	299	319.35
100K	299	319.34	299	319.35	299	319.35
Uncertainty $\delta W/W$ (%)		0.14		0.14		0.14

TABLE 16.124 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10	10	10
Temperature T (K)	263.15	263.15	263.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.000059	0.000117
Enhancement factor f_e	1.03986	1.03986	1.03986
Corrections			
Specific heat K_C (ppm)	579	578	578
Virial K_V (ppm)	2986	2986	2986
Simple sound speed W_s (m/s)	325.20	325.20	325.21

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	325.78	0	325.78	0	325.79
10	2	325.78	1	325.78	1	325.79
20	8	325.78	4	325.78	2	325.79
50	42	325.79	21	325.79	12	325.79
100	118	325.80	63	325.79	37	325.79
200	240	325.82	152	325.81	89	325.80
500	356	325.84	306	325.83	229	325.82
1000	384	325.84	367	325.84	331	325.84
2000	391	325.84	387	325.85	376	325.85
5000	394	325.84	393	325.85	391	325.85
10K	394	325.84	394	325.85	393	325.85
20K	394	325.84	394	325.85	394	325.85
50K	394	325.84	394	325.85	394	325.85
100K	394	325.84	394	325.85	394	325.85
Uncertainty $\delta W/W$ (%)		0.14		0.14		0.14

TABLE 16.125 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10	10	10
Temperature T (K)	263.15	263.15	263.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.000176	0.000235	0.000294
Enhancement factor f_e	1.03986	1.03986	1.03986
Corrections			
Specific heat K_C (ppm)	578	578	578
Virial K_V (ppm)	2985	2985	2984
Simple sound speed W_s (m/s)	325.21	325.21	325.22

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	325.79	0	325.79	0	325.79
10	0	325.79	0	325.79	0	325.79
20	2	325.79	1	325.79	1	325.79
50	8	325.79	6	325.79	5	325.80
100	25	325.79	19	325.79	15	325.80
200	58	325.80	43	325.80	35	325.80
500	157	325.81	109	325.81	80	325.81
1000	276	325.83	215	325.83	163	325.82
2000	355	325.85	322	325.84	281	325.84
5000	387	325.85	380	325.85	369	325.85
10K	392	325.85	390	325.86	387	325.86
20K	394	325.85	393	325.86	392	325.86
50K	394	325.85	394	325.86	394	325.86
100K	394	325.85	394	325.86	394	325.86
Uncertainty $\delta W/W$ (%)		0.14		0.14		0.14

TABLE 16.126 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	273.15		273.15		273.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000125		0.000250	
Enhancement factor f_e	1.03741		1.03741		1.03741	
Corrections						
Specific heat K_C (ppm)	462		461		461	
Virial K_V (ppm)	4311		4310		4309	
Simple sound speed W_s (m/s)	331.32		331.33		331.34	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	332.11	0	332.12	0	332.12
10	2	332.11	1	332.12	0	332.12
20	9	332.11	3	332.12	1	332.12
50	47	332.12	15	332.12	7	332.13
100	134	332.13	43	332.13	23	332.13
200	286	332.16	102	332.14	54	332.13
500	449	332.19	265	332.16	127	332.15
1000	492	332.19	407	332.19	250	332.17
2000	504	332.20	478	332.20	394	332.19
5000	508	332.20	503	332.20	485	332.21
10K	508	332.20	507	332.20	502	332.21
20K	508	332.20	508	332.20	507	332.21
50K	508	332.20	508	332.20	508	332.21
100K	508	332.20	508	332.20	508	332.21
Uncertainty $\delta W/W$ (%)		0.13		0.13		0.13

TABLE 16.127 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	273.15		273.15		273.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000375		0.000500		0.000625	
Enhancement factor f_e	1.03741		1.03741		1.03741	
Corrections						
Specific heat K_C (ppm)	460		460		459	
Virial K_V (ppm)	4308		4306		4305	
Simple sound speed W_s (m/s)	331.34		331.35		331.35	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	332.13	0	332.14	0	332.14
10	0	332.13	0	332.14	0	332.14
20	1	332.13	1	332.14	0	332.14
50	5	332.13	3	332.14	2	332.14
100	16	332.13	12	332.14	9	332.15
200	39	332.14	31	332.14	25	332.15
500	81	332.14	64	332.15	56	332.15
1000	146	332.16	100	332.15	80	332.16
2000	279	332.18	188	332.17	135	332.17
5000	444	332.20	380	332.20	308	332.19
10K	490	332.21	467	332.21	432	332.22
20K	504	332.21	497	332.22	486	332.22
50K	507	332.22	506	332.22	504	332.23
100K	508	332.22	508	332.22	507	332.23
Uncertainty $\delta W/W$ (%)		0.13		0.13		0.13

TABLE 16.128 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	283.15		283.15		283.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000251		0.000502	
Enhancement factor f_e	1.03539		1.03539		1.03539	
Corrections						
Specific heat K_C (ppm)	316		315		314	
Virial K_V (ppm)	5427		5424		5421	
Simple sound speed W_s (m/s)	337.33		337.35		337.36	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	338.30	0	338.31	0	338.33
10	2	338.30	0	338.31	0	338.33
20	10	338.30	2	338.31	1	338.33
50	53	338.31	9	338.31	4	338.33
100	152	338.33	30	338.32	15	338.33
200	333	338.36	70	338.32	41	338.33
500	555	338.39	159	338.34	87	338.34
1000	619	338.40	304	338.36	132	338.35
2000	637	338.41	487	338.39	236	338.37
5000	643	338.41	611	338.42	474	338.41
10K	644	338.41	635	338.42	588	338.42
20K	644	338.41	642	338.42	629	338.43
50K	644	338.41	643	338.42	641	338.43
100K	644	338.41	644	338.42	643	338.43
Uncertainty $\delta W/W$ (%)		0.13		0.13		0.13

TABLE 16.129 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10	10	10
Temperature T (K)	283.15	283.15	283.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.000752	0.00100	0.00125
Enhancement factor f_e	1.03539	1.03539	1.03539
Corrections			
Specific heat K_C (ppm)	313	312	311
Virial K_V (ppm)	5417	5414	5410
Simple sound speed W_s (m/s)	337.37	337.39	337.40

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	338.34	0	338.35	0	338.36
10	0	338.34	0	338.35	0	338.36
20	0	338.34	0	338.35	0	338.36
50	2	338.34	2	338.35	1	338.36
100	9	338.34	6	338.35	4	338.36
200	28	338.34	20	338.35	15	338.37
500	70	338.35	60	338.36	51	338.37
1000	97	338.35	85	338.37	78	338.38
2000	140	338.36	109	338.37	97	338.38
5000	305	338.39	202	338.39	150	338.39
10K	488	338.42	369	338.41	273	338.41
20K	594	338.44	534	338.44	457	338.44
50K	635	338.45	622	338.46	601	338.47
100K	641	338.45	638	338.46	632	338.47
Uncertainty $\delta W/W$ (%)		0.13		0.13		0.13

TABLE 16.130 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	293.15		293.15		293.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000477		0.000954	
Enhancement factor f_e	1.03375		1.03375		1.03375	
Corrections						
Specific heat K_C (ppm)	142		140		138	
Virial K_V (ppm)	6368		6361		6354	
Simple sound speed W_s (m/s)	343.24		343.26		343.29	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	344.35	0	344.38	0	344.40
10	3	344.35	0	344.38	0	344.40
20	11	344.35	1	344.38	0	344.40
50	58	344.36	6	344.38	2	344.40
100	170	344.38	20	344.38	9	344.40
200	383	344.42	57	344.39	28	344.41
500	672	344.47	120	344.40	83	344.42
1000	765	344.48	180	344.41	118	344.42
2000	793	344.49	314	344.43	152	344.43
5000	801	344.49	604	344.48	275	344.45
10K	802	344.49	739	344.50	485	344.49
20K	802	344.49	785	344.51	680	344.52
50K	802	344.49	799	344.52	778	344.54
100K	802	344.49	801	344.52	796	344.54
Uncertainty $\delta W/W$ (%)		0.13		0.12		0.13

TABLE 16.131 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	293.15		293.15		293.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.00143		0.00191		0.00238	
Enhancement factor f_e	1.03375		1.03375		1.03375	
Corrections						
Specific heat K_C (ppm)	136		133		131	
Virial K_V (ppm)	6347		6339		6331	
Simple sound speed W_s (m/s)	343.32		343.34		343.37	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	344.43	0	344.45	0	344.48
10	0	344.43	0	344.45	0	344.48
20	0	344.43	0	344.45	0	344.48
50	1	344.43	1	344.45	0	344.48
100	5	344.43	3	344.45	2	344.48
200	17	344.43	11	344.45	7	344.48
500	62	344.44	46	344.46	36	344.48
1000	102	344.44	89	344.47	77	344.49
2000	127	344.45	117	344.47	110	344.50
5000	174	344.46	145	344.48	133	344.50
10K	287	344.48	201	344.49	165	344.50
20K	501	344.51	352	344.51	262	344.52
50K	724	344.55	638	344.56	539	344.57
100K	780	344.56	751	344.58	708	344.60
Uncertainty $\delta W/W$ (%)		0.12		0.13		0.13

TABLE 16.132 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	303.15		303.15		303.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000865		0.00173	
Enhancement factor f_e	1.03241		1.03241		1.03241	
Corrections						
Specific heat K_C (ppm)	−61		−65		−69	
Virial K_V (ppm)	7163		7150		7135	
Simple sound speed W_s (m/s)	349.04		349.09		349.14	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	350.28	0	350.33	0	350.37
10	3	350.28	0	350.33	0	350.37
20	12	350.28	1	350.33	0	350.37
50	64	350.29	3	350.33	1	350.37
100	189	350.31	12	350.33	4	350.37
200	434	350.36	41	350.33	16	350.37
500	800	350.42	116	350.35	67	350.38
1000	930	350.44	164	350.35	125	350.39
2000	971	350.45	212	350.36	162	350.40
5000	983	350.45	390	350.39	202	350.41
10K	985	350.45	655	350.44	287	350.42
20K	985	350.45	866	350.48	496	350.46
50K	985	350.45	963	350.49	826	350.52
100K	985	350.45	979	350.50	937	350.53
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.133 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	303.15		303.15		303.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.00259		0.00346		0.00432	
Enhancement factor f_e	1.03241		1.03241		1.03241	
Corrections						
Specific heat K_C (ppm)	−73		−77		−81	
Virial K_V (ppm)	7120		7103		7085	
Simple sound speed W_s (m/s)	349.19		349.24		349.28	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	350.42	0	350.46	0	350.51
10	0	350.42	0	350.46	0	350.51
20	0	350.42	0	350.46	0	350.51
50	1	350.42	0	350.46	0	350.51
100	2	350.42	1	350.46	1	350.51
200	8	350.42	5	350.46	3	350.51
500	41	350.42	27	350.47	19	350.51
1000	96	350.43	74	350.47	57	350.52
2000	145	350.44	129	350.48	114	350.53
5000	176	350.45	167	350.49	161	350.53
10K	208	350.45	186	350.49	177	350.54
20K	302	350.47	232	350.50	204	350.54
50K	613	350.52	444	350.54	342	350.57
100K	842	350.56	714	350.59	589	350.61
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.134 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	313.15		313.15		313.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00150		0.00300	
Enhancement factor f_e	1.03134		1.03134		1.03134	
Corrections						
Specific heat K_C (ppm)	−292		−300		−307	
Virial K_V (ppm)	7835		7810		7782	
Simple sound speed W_s (m/s)	354.75		354.84		354.92	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	356.09	0	356.17	0	356.25
10	3	356.09	0	356.17	0	356.25
20	12	356.09	0	356.17	0	356.25
50	69	356.10	2	356.17	1	356.25
100	210	356.12	7	356.17	2	356.25
200	487	356.17	25	356.17	8	356.25
500	939	356.25	99	356.19	42	356.25
1000	1116	356.29	174	356.20	109	356.27
2000	1173	356.30	221	356.21	181	356.28
5000	1191	356.30	283	356.22	226	356.29
10K	1193	356.30	421	356.24	255	356.29
20K	1194	356.30	710	356.29	332	356.31
50K	1194	356.30	1059	356.36	642	356.36
100K	1194	356.30	1154	356.37	950	356.42
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.135 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	313.15		313.15		313.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.00451		0.00601		0.00751	
Enhancement factor f_e	1.03134		1.03134		1.03134	
Corrections						
Specific heat K_C (ppm)	−315		−322		−330	
Virial K_V (ppm)	7751		7717		7681	
Simple sound speed W_s (m/s)	355.01		355.10		355.18	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	356.33	0	356.41	0	356.48
10	0	356.33	0	356.41	0	356.48
20	0	356.33	0	356.41	0	356.48
50	0	356.33	0	356.41	0	356.48
100	1	356.33	1	356.41	0	356.48
200	4	356.33	2	356.41	1	356.48
500	22	356.33	13	356.41	9	356.49
1000	69	356.34	46	356.41	32	356.49
2000	145	356.35	114	356.43	90	356.50
5000	211	356.36	198	356.44	183	356.52
10K	232	356.37	223	356.45	217	356.52
20K	262	356.37	242	356.45	233	356.53
50K	410	356.40	319	356.46	280	356.53
100K	692	356.45	513	356.50	409	356.56
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.136 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	323.15		323.15		323.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00251		0.00502	
Enhancement factor f_e	1.03049		1.03049		1.03049	
Corrections						
Specific heat K_C (ppm)	−551		−565		−578	
Virial K_V (ppm)	8404		8358		8306	
Simple sound speed W_s (m/s)	360.37		360.52		360.66	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	361.78	0	361.92	0	362.05
10	3	361.78	0	361.92	0	362.05
20	13	361.79	0	361.92	0	362.05
50	75	361.80	1	361.92	0	362.05
100	231	361.83	3	361.92	1	362.05
200	543	361.88	13	361.92	4	362.05
500	1086	361.98	68	361.93	23	362.06
1000	1320	362.02	162	361.95	74	362.07
2000	1400	362.04	249	361.96	170	362.08
5000	1425	362.04	304	361.97	268	362.10
10K	1428	362.04	351	361.98	297	362.11
20K	1429	362.04	488	362.01	326	362.11
50K	1429	362.04	927	362.09	462	362.14
100K	1429	362.04	1239	362.14	754	362.19
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.137 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10	10	10
Temperature T (K)	323.15	323.15	323.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.00753	0.0100	0.0125
Enhancement factor f_e	1.03049	1.03049	1.03049
Corrections			
Specific heat K_C (ppm)	−592	−606	−619
Virial K_V (ppm)	8247	8183	8113
Simple sound speed W_s (m/s)	360.81	360.95	361.10

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	362.19	0	362.32	0	362.45
10	0	362.19	0	362.32	0	362.45
20	0	362.19	0	362.32	0	362.45
50	0	362.19	0	362.32	0	362.45
100	0	362.19	0	362.32	0	362.45
200	2	362.19	1	362.32	1	362.45
500	11	362.19	6	362.32	4	362.45
1000	40	362.19	24	362.32	16	362.45
2000	114	362.21	78	362.33	55	362.46
5000	237	362.23	205	362.36	174	362.48
10K	282	362.24	267	362.37	252	362.50
20K	303	362.24	293	362.37	286	362.50
50K	357	362.25	325	362.38	311	362.51
100K	507	362.28	407	362.39	361	362.52
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.138 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10	10	10
Temperature T (K)	373.15	373.15	373.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.0206	0.0411
Enhancement factor f_e	1.02853	1.02853	1.02853
Corrections			
Specific heat K_C (ppm)	−2253	−2409	−2562
Virial K_V (ppm)	10156	9649	8972
Simple sound speed W_s (m/s)	387.25	388.54	389.84

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	388.77	0	389.94	0	391.08
10	4	388.77	0	389.94	0	391.08
20	18	388.78	0	389.94	0	391.08
50	104	388.79	0	389.94	0	391.08
100	344	388.84	0	389.94	0	391.08
200	865	388.94	1	389.94	0	391.08
500	1921	389.15	4	389.94	1	391.08
1000	2609	389.28	15	389.94	4	391.09
2000	2914	389.34	57	389.95	15	391.09
5000	3017	389.36	264	389.99	84	391.10
10K	3032	389.36	554	390.04	260	391.14
20K	3036	389.36	765	390.09	542	391.19
50K	3037	389.36	864	390.10	780	391.24
100K	3037	389.36	909	390.11	838	391.25
Uncertainty $\delta W/W$ (%)		0.12		0.12		0.12

TABLE 16.139 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	373.15		373.15		373.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.0617		0.0823		0.103	
Enhancement factor f_e	1.02853		1.02853		1.02853	
Corrections						
Specific heat K_C (ppm)	−2713		−2861		−3008	
Virial K_V (ppm)	8121		7089		5872	
Simple sound speed W_s (m/s)	391.16		392.51		393.87	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	392.22	0	393.33	0	394.43
10	0	392.22	0	393.33	0	394.43
20	0	392.22	0	393.33	0	394.43
50	0	392.22	0	393.33	0	394.43
100	0	392.22	0	393.33	0	394.43
200	0	392.22	0	393.33	0	394.43
500	0	392.22	0	393.33	0	394.43
1000	2	392.22	1	393.33	1	394.43
2000	6	392.22	4	393.33	2	394.43
5000	39	392.22	22	393.33	14	394.43
10K	136	392.24	80	393.35	52	394.44
20K	364	392.29	247	393.38	173	394.46
50K	686	392.35	589	393.45	498	394.52
100K	787	392.37	735	393.48	681	394.56
Uncertainty $\delta W/W$ (%)		0.11		0.12		0.12

TABLE 16.140 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	423.15		423.15		423.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.0967		0.193	
Enhancement factor f_e	1.02879		1.02879		1.02879	
Corrections						
Specific heat K_C (ppm)	−4607		−5514		−6355	
Virial K_V (ppm)	10833		7805		2883	
Simple sound speed W_s (m/s)	412.38		418.99		426.05	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	413.65	0	419.46	0	425.31
10	5	413.65	0	419.46	0	425.31
20	21	413.65	0	419.46	0	425.31
50	128	413.68	0	419.46	0	425.31
100	448	413.74	0	419.46	0	425.31
200	1231	413.90	0	419.46	0	425.31
500	2888	414.25	0	419.46	0	425.31
1000	4224	414.52	1	419.46	0	425.31
2000	5006	414.68	5	419.46	1	425.31
5000	5315	414.75	29	419.47	6	425.31
10K	5363	414.76	110	419.48	25	425.31
20K	5376	414.76	370	419.54	95	425.33
50K	5379	414.76	1093	419.69	444	425.40
100K	5380	414.76	1519	419.78	940	425.51
Uncertainty $\delta W/W$ (%)		0.13		0.12		0.13

TABLE 16.141 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	423.15		423.15		423.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.290		0.387		0.484	
Enhancement factor f_e	1.02879		1.02879		1.02879	
Corrections						
Specific heat K_C (ppm)	−7134		−7858		−8529	
Virial K_V (ppm)	−4043		−13094		−24403	
Simple sound speed W_s (m/s)	433.61		441.70		450.39	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	xxx	xxx	xxx	xxx	xxx	Xxx
10	xxx	xxx	xxx	xxx	xxx	xxx
20	xxx	xxx	xxx	xxx	xxx	xxx
50	xxx	xxx	xxx	xxx	xxx	xxx
100	xxx	xxx	xxx	xxx	xxx	xxx
200	xxx	xxx	xxx	xxx	xxx	xxx
500	xxx	xxx	xxx	xxx	xxx	xxx
1000	xxx	xxx	xxx	xxx	xxx	xxx
2000	xxx	xxx	xxx	xxx	xxx	xxx
5000	xxx	xxx	xxx	xxx	xxx	xxx
10K	xxx	xxx	xxx	xxx	xxx	xxx
20K	xxx	xxx	xxx	xxx	xxx	xxx
50K	xxx	xxx	xxx	xxx	xxx	xxx
100K	xxx	xxx	xxx	xxx	xxx	xxx
Uncertainty $\delta W/W$ (%)		xxx		xxx		xxx

TABLE 16.142 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	473.15		473.15		473.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.318		0.635	
Enhancement factor f_e	1.03008		1.03008		1.03008	
Corrections						
Specific heat K_C (ppm)	−7566		−10829		−13355	
Virial K_V (ppm)	10982		−1427		−25435	
Simple sound speed W_s (m/s)	436.06		460.89		492.15	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	436.79	0	458.06	0	482.59
10	6	436.79	0	458.06	0	482.59
20	24	436.79	0	458.06	0	482.59
50	143	436.82	0	458.06	0	482.59
100	523	436.90	0	458.06	0	482.59
200	1569	437.13	0	458.06	0	482.59
500	3967	437.65	0	458.06	0	482.59
1000	6003	438.10	0	458.06	0	482.59
2000	7511	438.43	0	458.06	0	482.59
5000	8227	438.58	3	458.06	0	482.59
10K	8349	438.61	12	458.06	1	482.59
20K	8380	438.61	46	458.07	6	482.60
50K	8389	438.62	260	458.12	34	482.60
100K	8390	438.62	767	458.24	122	482.62
Uncertainty $\delta W/W$ (%)		0.14		0.17		0.22

TABLE 16.143 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10	10	10
Temperature T (K)	473.15	473.15	473.15
Humidity			
RH, h_r (%)	55	60	62.95
Mole fraction x_h	0.874	0.953	1.000
Enhancement factor f_e	1.03008	1.03008	1.03008
Corrections			
Specific heat K_C (ppm)	−14873	−15318	−15568
Virial K_V (ppm)	−51983	−62618	−69336
Simple sound speed W_s (m/s)	521.41	532.61	539.61

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	503.89	0	511.70	0	516.50
10	0	503.89	0	511.70	0	516.50
20	0	503.89	0	511.70	0	516.50
50	0	503.89	0	511.70	0	516.50
100	0	503.89	0	511.70	0	516.50
200	0	503.89	0	511.70	0	516.50
500	0	503.89	0	511.70	0	516.50
1000	0	503.89	0	511.70	0	516.50
2000	0	503.89	0	511.70	0	516.50
5000	0	503.89	0	511.70	0	516.50
10K	0	503.89	0	511.70	0	516.50
20K	1	503.89	0	511.70	0	516.50
50K	6	503.89	2	511.70	0	516.50
100K	22	503.90	7	511.70	0	516.50
Uncertainty $\delta W/W$ (%)		0.30		0.30		0.33

TABLE 16.144 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	523.15		523.15		523.15	
Humidity						
RH, h_r (%)	0		12		24	
Mole fraction x_h	0		0.495		0.989	
Enhancement factor f_e	1.03181		1.03181		1.03181	
Corrections						
Specific heat K_C (ppm)	−11077		−16426		−19968	
Virial K_V (ppm)	10862		−7283		−41451	
Simple sound speed W_s (m/s)	458.52		501.95		565.69	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	458.45	0	495.99	0	548.29
10	6	458.45	0	495.99	0	548.29
20	25	458.45	0	495.99	0	548.29
50	151	458.48	0	495.99	0	548.29
100	566	458.58	0	495.99	0	548.29
200	1820	458.86	0	495.99	0	548.29
500	5085	459.61	0	495.99	0	548.29
1000	7848	460.24	0	495.99	0	548.29
2000	10207	460.78	0	495.99	0	548.29
5000	11577	461.09	1	495.99	0	548.29
10K	11832	461.15	5	495.99	0	548.29
20K	11899	461.17	18	496.00	0	548.29
50K	11918	461.17	111	496.02	0	548.29
100K	11921	461.17	389	496.09	2	548.29
Uncertainty $\delta W/W$ (%)		0.15		0.37		0.81

TABLE 16.145 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10	10	10
Temperature T (K)	573.15	573.15	573.15
Humidity			
RH, h_r (%)	0	5.4	10.8
Mole fraction x_h	0	0.494	0.988
Enhancement factor f_e	1.03371	1.03371	1.03371
Corrections			
Specific heat K_C (ppm)	−15083	−20828	−24566
Virial K_V (ppm)	10605	−3976	−27265
Simple sound speed W_s (m/s)	479.94	525.31	591.87

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	478.82	0	518.78	0	576.53
10	6	478.82	0	518.78	0	576.53
20	25	478.83	0	518.78	0	576.53
50	152	478.86	0	518.78	0	576.53
100	581	478.96	0	518.78	0	576.53
200	1967	479.29	0	518.78	0	576.53
500	6115	480.28	0	518.78	0	576.53
1000	9690	481.14	0	518.78	0	576.53
2000	12897	481.90	0	518.78	0	576.53
5000	15144	482.43	1	518.78	0	576.53
10K	15613	482.55	6	518.78	0	576.53
20K	15740	482.58	24	518.78	0	576.53
50K	15776	482.58	143	518.81	1	576.53
100K	15781	482.59	506	518.91	3	576.53
Uncertainty $\delta W/W$ (%)		0.15		0.58		1.36

TABLE 16.146 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	10		10		10	
Temperature T (K)	603.15		603.15		603.15	
Humidity						
RH, h_r (%)	0		3.55		7.1	
Mole fraction x_h	0		0.497		0.994	
Enhancement factor f_e	1.03487		1.03487		1.03487	
Corrections						
Specific heat K_C (ppm)	−17700		−23605		−27393	
Virial K_V (ppm)	10416		−2801		−22054	
Simple sound speed W_s (m/s)	492.34		539.24		608.26	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	490.49	0	532.10	0	593.22
10	6	490.50	0	532.10	0	593.22
20	24	490.50	0	532.10	0	593.22
50	151	490.53	0	532.10	0	593.22
100	579	490.64	0	532.10	0	593.22
200	2008	490.99	0	532.10	0	593.22
500	6641	492.12	0	532.10	0	593.22
1000	10759	493.13	0	532.10	0	593.22
2000	14448	494.03	0	532.10	0	593.22
5000	17296	494.72	2	532.10	0	593.22
10K	17938	494.87	7	532.10	0	593.22
20K	18114	494.92	26	532.10	0	593.22
50K	18165	494.93	157	532.14	0	593.22
100K	18172	494.93	563	532.24	1	593.22
Uncertainty $\delta W/W$ (%)		0.15		0.70		1.72

TABLE 16.147 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20	20	20
Temperature T (K)	233.15	233.15	233.15
Humidity			
RH, h_r (%)	0	50	100
Mole fraction x_h	0	0.000005	0.000010
Enhancement factor f_e	1.10729	1.10729	1.10729
Corrections			
Specific heat K_C (ppm)	755	755	755
Virial K_V (ppm)	−3637	−3637	−3637
Simple sound speed W_s (m/s)	306.10	306.10	306.10

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	305.66	0	305.66	0	305.66
10	0	305.66	0	305.66	0	305.66
20	2	305.66	1	305.66	1	305.66
50	9	305.66	8	305.66	8	305.66
100	29	305.67	27	305.67	25	305.67
200	72	305.67	69	305.67	66	305.67
500	133	305.68	131	305.68	129	305.68
1000	153	305.68	152	305.68	151	305.68
2000	158	305.68	158	305.69	158	305.69
5000	160	305.69	160	305.69	160	305.69
10K	160	305.69	160	305.69	160	305.69
20K	160	305.69	160	305.69	160	305.69
50K	160	305.69	160	305.69	160	305.69
100K	160	305.69	160	305.69	160	305.69
Uncertainty $\delta W/W$ (%)		0.23		0.23		0.23

TABLE 16.148 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20	20	20
Temperature T (K)	243.15	243.15	243.15
Humidity			
RH, h_r (%)	0	50	100
Mole fraction x_h	0	0.000014	0.000028
Enhancement factor f_e	1.09710	1.09710	1.09710
Corrections			
Specific heat K_C (ppm)	725	725	725
Virial K_V (ppm)	783	783	782
Simple sound speed W_s (m/s)	312.60	312.60	312.60

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	312.83	0	312.83	0	312.84
10	0	312.83	0	312.83	0	312.84
20	2	312.83	1	312.83	1	312.84
50	10	312.84	8	312.84	7	312.84
100	33	312.84	28	312.84	23	312.84
200	87	312.85	76	312.85	66	312.85
500	176	312.86	167	312.86	157	312.86
1000	208	312.87	205	312.87	201	312.87
2000	218	312.87	217	312.87	216	312.87
5000	221	312.87	221	312.87	221	312.87
10K	222	312.87	222	312.87	222	312.87
20K	222	312.87	222	312.87	222	312.87
50K	222	312.87	222	312.87	222	312.87
100K	222	312.87	222	312.87	222	312.87
Uncertainty $\delta W/W$ (%)		0.21		0.21		0.21

TABLE 16.149 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	253.15		253.15		253.15	
Humidity						
RH, h_r (%)	0		50		100	
Mole fraction x_h	0		0.000034		0.000067	
Enhancement factor f_e	1.08854		1.08854		1.08854	
Corrections						
Specific heat K_C (ppm)	666		666		666	
Virial K_V (ppm)	4439		4439		4439	
Simple sound speed W_s (m/s)	318.96		318.96		318.96	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	319.78	0	319.78	0	319.78
10	0	319.78	0	319.78	0	319.78
20	2	319.78	1	319.78	1	319.78
50	11	319.78	7	319.78	5	319.78
100	37	319.78	25	319.78	17	319.78
200	102	319.79	72	319.79	49	319.79
500	224	319.81	190	319.81	148	319.80
1000	276	319.82	260	319.82	235	319.82
2000	293	319.82	288	319.82	280	319.82
5000	298	319.82	297	319.82	296	319.83
10K	299	319.82	299	319.82	298	319.83
20K	299	319.82	299	319.82	299	319.83
50K	299	319.82	299	319.82	299	319.83
100K	299	319.82	299	319.82	299	319.83
Uncertainty $\delta W/W$ (%)		0.20		0.20		0.20

TABLE 16.150 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	263.15		263.15		263.15	
Humidity						
RH, h_r (%)	0		50		100	
Mole fraction x_h	0		0.000076		0.000153	
Enhancement factor f_e	1.08132		1.08132		1.08132	
Corrections						
Specific heat K_C (ppm)	579		578		578	
Virial K_V (ppm)	7480		7478		7477	
Simple sound speed W_s (m/s)	325.20		325.20		325.21	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	326.51	0	326.51	0	326.52
10	1	326.51	0	326.51	0	326.52
20	2	326.51	1	326.51	0	326.52
50	12	326.51	5	326.51	3	326.52
100	42	326.52	18	326.52	10	326.52
200	118	326.53	53	326.52	29	326.52
500	278	326.55	164	326.54	87	326.53
1000	356	326.57	285	326.56	184	326.55
2000	384	326.57	359	326.57	300	326.57
5000	392	326.57	388	326.58	375	326.58
10K	394	326.57	393	326.58	389	326.58
20K	394	326.57	394	326.58	393	326.58
50K	394	326.57	394	326.58	394	326.58
100K	394	326.57	394	326.58	394	326.58
Uncertainty $\delta W/W$ (%)		0.19		0.19		0.19

TABLE 16.151 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	273.15		273.15		273.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000065		0.000130	
Enhancement factor f_e	1.07520		1.07520		1.07520	
Corrections						
Specific heat K_C (ppm)	462		461		461	
Virial K_V (ppm)	10017		10016		10014	
Simple sound speed W_s (m/s)	331.32		331.33		331.33	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	333.05	0	333.06	0	333.06
10	1	333.05	0	333.06	0	333.06
20	2	333.05	1	333.06	1	333.06
50	14	333.06	7	333.06	4	333.06
100	47	333.06	24	333.06	14	333.06
200	134	333.08	70	333.07	42	333.07
500	337	333.11	214	333.09	127	333.08
1000	449	333.13	368	333.12	258	333.10
2000	492	333.14	463	333.13	402	333.13
5000	506	333.14	500	333.14	487	333.14
10K	508	333.14	506	333.14	503	333.14
20K	508	333.14	508	333.14	507	333.14
50K	508	333.14	508	333.14	508	333.14
100K	508	333.14	508	333.14	508	333.14
Uncertainty $\delta W/W$ (%)		0.17		0.17		0.18

TABLE 16.152 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	273.15		273.15		273.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000194		0.000259		0.000324	
Enhancement factor f_e	1.07520		1.07520		1.07520	
Corrections						
Specific heat K_C (ppm)	461		461		461	
Virial K_V (ppm)	10013		10011		10009	
Simple sound speed W_s (m/s)	331.33		331.34		331.34	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	333.06	0	333.07	0	333.07
10	0	333.06	0	333.07	0	333.07
20	0	333.06	0	333.07	0	333.07
50	3	333.06	2	333.07	1	333.07
100	10	333.07	7	333.07	6	333.07
200	29	333.07	23	333.07	18	333.07
500	85	333.08	64	333.08	54	333.08
1000	172	333.09	121	333.09	94	333.09
2000	319	333.12	239	333.11	179	333.10
5000	461	333.14	422	333.14	371	333.13
10K	496	333.15	483	333.15	464	333.15
20K	505	333.15	502	333.15	496	333.15
50K	508	333.15	507	333.15	506	333.15
100K	508	333.15	508	333.15	508	333.15
Uncertainty $\delta W/W$ (%)		0.17		0.17		0.17

TABLE 16.153 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	283.15		283.15		283.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000130		0.000259	
Enhancement factor f_e	1.07001		1.07001		1.07001	
Corrections						
Specific heat K_C (ppm)	316		315		315	
Virial K_V (ppm)	12142		12138		12135	
Simple sound speed W_s (m/s)	337.33		337.34		337.35	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	339.43	0	339.43	0	339.44
10	1	339.43	0	339.43	0	339.44
20	2	339.43	1	339.43	0	339.44
50	15	339.43	5	339.43	2	339.44
100	53	339.44	17	339.44	9	339.44
200	152	339.45	52	339.44	29	339.45
500	399	339.50	153	339.46	84	339.45
1000	555	339.52	308	339.49	153	339.47
2000	619	339.53	492	339.52	293	339.49
5000	640	339.54	613	339.54	525	339.53
10K	643	339.54	636	339.54	608	339.54
20K	644	339.54	642	339.54	634	339.55
50K	644	339.54	644	339.54	642	339.55
100K	644	339.54	644	339.54	643	339.55
Uncertainty $\delta W/W$ (%)		0.17		0.17		0.17

TABLE 16.154 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	283.15		283.15		283.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000389		0.000518		0.000648	
Enhancement factor f_e	1.07001		1.07001		1.07001	
Corrections						
Specific heat K_C (ppm)	314		314		313	
Virial K_V (ppm)	12131		12127		12123	
Simple sound speed W_s (m/s)	337.35		337.36		337.37	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	339.45	0	339.45	0	339.46
10	0	339.45	0	339.45	0	339.46
20	0	339.45	0	339.45	0	339.46
50	2	339.45	1	339.45	1	339.46
100	6	339.45	4	339.45	3	339.46
200	20	339.45	15	339.46	11	339.46
500	63	339.46	51	339.46	43	339.47
1000	104	339.46	86	339.47	76	339.47
2000	177	339.48	128	339.47	106	339.48
5000	392	339.51	277	339.50	202	339.49
10K	549	339.54	462	339.53	370	339.52
20K	616	339.55	583	339.55	535	339.55
50K	639	339.55	633	339.56	623	339.56
100K	643	339.56	641	339.56	638	339.57
Uncertainty $\delta W/W$ (%)		0.16		0.17		0.17

TABLE 16.155 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20	20	20
Temperature T (K)	293.15	293.15	293.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.000246	0.000492
Enhancement factor f_e	1.06558	1.06558	1.06558
Corrections			
Specific heat K_C (ppm)	142	141	139
Virial K_V (ppm)	13925	13917	13909
Simple sound speed W_s (m/s)	343.24	343.25	343.26

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	345.64	0	345.66	0	345.67
10	1	345.64	0	345.66	0	345.67
20	3	345.64	1	345.66	0	345.67
50	16	345.65	3	345.66	1	345.67
100	58	345.65	12	345.66	6	345.67
200	170	345.67	38	345.66	20	345.67
500	464	345.72	113	345.67	70	345.68
1000	672	345.76	201	345.69	118	345.69
2000	765	345.78	373	345.72	175	345.70
5000	796	345.78	657	345.77	366	345.73
10K	801	345.78	759	345.79	592	345.77
20K	802	345.78	791	345.79	733	345.79
50K	802	345.78	800	345.79	790	345.80
100K	802	345.78	802	345.79	799	345.81
Uncertainty $\delta W/W$ (%)		0.16		0.16		0.16

TABLE 16.156 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	293.15		293.15		293.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000737		0.000983		0.00123	
Enhancement factor f_e	1.06558		1.06558		1.06558	
Corrections						
Specific heat K_C (ppm)	138		137		136	
Virial K_V (ppm)	13901		13893		13885	
Simple sound speed W_s (m/s)	343.28		343.29		343.30	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	345.68	0	345.69	0	345.70
10	0	345.68	0	345.69	0	345.70
20	0	345.68	0	345.69	0	345.70
50	1	345.68	1	345.69	0	345.70
100	3	345.68	2	345.69	2	345.70
200	12	345.68	8	345.69	6	345.70
500	51	345.69	38	345.70	29	345.71
1000	96	345.70	81	345.71	70	345.72
2000	132	345.70	117	345.71	108	345.72
5000	218	345.72	164	345.72	143	345.73
10K	390	345.75	264	345.74	201	345.74
20K	612	345.79	469	345.77	353	345.76
50K	762	345.81	711	345.81	639	345.81
100K	791	345.82	776	345.83	752	345.83
Uncertainty $\delta W/W$ (%)		0.16		0.16		0.16

TABLE 16.157 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	303.15		303.15		303.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000445		0.000889	
Enhancement factor f_e	1.06181		1.06181		1.06181	
Corrections						
Specific heat K_C (ppm)	−61		−63		−65	
Virial K_V (ppm)	15423		15408		15393	
Simple sound speed W_s (m/s)	349.04		349.07		349.09	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	351.71	0	351.74	0	351.76
10	1	351.71	0	351.74	0	351.76
20	3	351.71	0	351.74	0	351.76
50	18	351.72	2	351.74	1	351.76
100	64	351.72	8	351.74	3	351.76
200	189	351.75	28	351.74	12	351.76
500	532	351.81	97	351.75	55	351.77
1000	800	351.85	163	351.76	114	351.78
2000	930	351.88	243	351.78	162	351.79
5000	976	351.88	499	351.82	232	351.80
10K	983	351.89	766	351.87	376	351.82
20K	985	351.89	916	351.90	638	351.87
50K	985	351.89	973	351.91	898	351.91
100K	985	351.89	982	351.91	961	351.93
Uncertainty $\delta W/W$ (%)		0.15		0.15		0.15

TABLE 16.158 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	303.15		303.15		303.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.001334		0.001778		0.002223	
Enhancement factor f_e	1.06181		1.06181		1.06181	
Corrections						
Specific heat K_C (ppm)	−67		−69		−71	
Virial K_V (ppm)	15376		15360		15342	
Simple sound speed W_s (m/s)	349.12		349.14		349.17	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	351.78	0	351.80	0	351.82
10	0	351.78	0	351.80	0	351.82
20	0	351.78	0	351.80	0	351.82
50	0	351.78	0	351.80	0	351.82
100	2	351.78	1	351.80	1	351.82
200	6	351.78	4	351.80	3	351.82
500	34	351.79	23	351.80	16	351.83
1000	86	351.79	65	351.81	50	351.83
2000	140	351.80	123	351.82	108	351.84
5000	184	351.81	169	351.83	161	351.85
10K	240	351.82	199	351.84	183	351.85
20K	394	351.85	279	351.85	229	351.86
50K	741	351.91	568	351.90	434	351.90
100K	906	351.94	815	351.94	704	351.95
Uncertainty $\delta W/W$ (%)		0.15		0.15		0.15

TABLE 16.159 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	313.15		313.15		313.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000771		0.00154	
Enhancement factor f_e	1.05859		1.05859		1.05859	
Corrections						
Specific heat K_C (ppm)	−292		−296		−300	
Virial K_V (ppm)	16683		16655		16626	
Simple sound speed W_s (m/s)	354.75		354.80		354.84	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	357.65	0	357.69	0	357.72
10	1	357.65	0	357.69	0	357.72
20	3	357.65	0	357.69	0	357.72
50	19	357.65	1	357.69	0	357.72
100	69	357.66	5	357.69	2	357.72
200	210	357.68	18	357.69	6	357.73
500	602	357.75	79	357.70	35	357.73
1000	939	357.82	159	357.71	96	357.74
2000	1116	357.85	223	357.73	172	357.76
5000	1181	357.86	331	357.75	231	357.77
10K	1191	357.86	547	357.78	279	357.77
20K	1193	357.86	868	357.84	409	357.80
50K	1194	357.86	1120	357.89	797	357.87
100K	1194	357.86	1174	357.90	1049	357.91
Uncertainty $\delta W/W$ (%)		0.14		0.14		0.14

TABLE 16.160 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	313.15		313.15		313.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.00231		0.00308		0.00385	
Enhancement factor f_e	1.05859		1.05859		1.05859	
Corrections						
Specific heat K_C (ppm)	−304		−308		−311	
Virial K_V (ppm)	16595		16563		16530	
Simple sound speed W_s (m/s)	354.88		354.93		354.97	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	357.76	0	357.80	0	357.84
10	0	357.76	0	357.80	0	357.84
20	0	357.76	0	357.80	0	357.84
50	0	357.76	0	357.80	0	357.84
100	1	357.76	0	357.80	0	357.84
200	3	357.76	2	357.80	1	357.84
500	19	357.77	12	357.80	8	357.84
1000	61	357.77	41	357.81	29	357.84
2000	136	357.79	106	357.82	84	357.85
5000	210	357.80	195	357.84	180	357.87
10K	239	357.81	225	357.84	217	357.88
20K	287	357.81	252	357.85	239	357.88
50K	510	357.85	372	357.87	308	357.89
100K	828	357.91	624	357.91	485	357.92
Uncertainty $\delta W/W$ (%)		0.14		0.14		0.14

TABLE 16.161 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20	20	20
Temperature T (K)	323.15	323.15	323.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.00129	0.00257
Enhancement factor f_e	1.05584	1.05584	1.05584
Corrections			
Specific heat K_C (ppm)	−551	−558	−565
Virial K_V (ppm)	17743	17693	17641
Simple sound speed W_s (m/s)	360.37	360.45	360.52

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	363.46	0	363.52	0	363.58
10	1	363.46	0	363.52	0	363.58
20	3	363.46	0	363.52	0	363.58
50	21	363.46	1	363.52	0	363.58
100	75	363.47	3	363.52	1	363.58
200	231	363.50	10	363.52	3	363.58
500	676	363.58	55	363.53	20	363.59
1000	1086	363.65	143	363.55	66	363.60
2000	1320	363.69	239	363.56	159	363.61
5000	1411	363.71	314	363.58	265	363.63
10K	1425	363.71	396	363.59	302	363.64
20K	1428	363.71	614	363.63	347	363.65
50K	1429	363.71	1098	363.72	554	363.69
100K	1429	363.71	1322	363.76	907	363.75
Uncertainty $\delta W/W$ (%)		0.14		0.14		0.14

TABLE 16.162 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	323.15		323.15		323.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.00386		0.00514		0.00643	
Enhancement factor f_e	1.05584		1.05584		1.05584	
Corrections						
Specific heat K_C (ppm)	−572		−579		−586	
Virial K_V (ppm)	17585		17526		17464	
Simple sound speed W_s (m/s)	360.60		360.67		360.74	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	363.65	0	363.71	0	363.77
10	0	363.65	0	363.71	0	363.77
20	0	363.65	0	363.71	0	363.77
50	0	363.65	0	363.71	0	363.77
100	0	363.65	0	363.71	0	363.77
200	2	363.65	1	363.71	1	363.77
500	10	363.65	6	363.71	4	363.78
1000	36	363.65	22	363.72	15	363.78
2000	105	363.67	72	363.72	51	363.78
5000	232	363.69	199	363.75	169	363.81
10K	282	363.70	267	363.76	251	363.82
20K	309	363.70	296	363.77	288	363.83
50K	390	363.72	340	363.77	319	363.83
100K	595	363.76	453	363.79	387	363.84
Uncertainty $\delta W/W$ (%)		0.14		0.14		0.14

TABLE 16.163 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	373.15		373.15		373.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.0105		0.0209	
Enhancement factor f_e	1.04712		1.04712		1.04712	
Corrections						
Specific heat K_C (ppm)	−2253		−2333		−2412	
Virial K_V (ppm)	20946		20452		19872	
Simple sound speed W_s (m/s)	387.25		387.90		388.56	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	390.84	0	391.39	0	391.93
10	1	390.84	0	391.39	0	391.93
20	4	390.84	0	391.39	0	391.93
50	28	390.85	0	391.39	0	391.93
100	104	390.86	0	391.39	0	391.93
200	344	390.91	1	391.39	0	391.93
500	1092	391.06	4	391.39	1	391.93
1000	1921	391.22	14	391.39	4	391.93
2000	2609	391.35	54	391.40	14	391.93
5000	2957	391.42	254	391.44	83	391.94
10K	3017	391.43	547	391.50	258	391.98
20K	3032	391.44	769	391.54	547	392.04
50K	3037	391.44	877	391.56	800	392.08
100K	3037	391.44	930	391.57	863	392.10
Uncertainty $\delta W/W$ (%)		0.13		0.13		0.13

TABLE 16.164 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	373.15		373.15		373.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.0314		0.0419		0.0524	
Enhancement factor f_e	1.04712		1.04712		1.04712	
Corrections						
Specific heat K_C (ppm)	−2490		−2568		−2645	
Virial K_V (ppm)	19202		18440		17583	
Simple sound speed W_s (m/s)	389.22		389.89		390.56	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	392.45	0	392.96	0	393.46
10	0	392.45	0	392.96	0	393.46
20	0	392.45	0	392.96	0	393.46
50	0	392.45	0	392.96	0	393.46
100	0	392.45	0	392.96	0	393.46
200	0	392.45	0	392.96	0	393.46
500	0	392.45	0	392.96	0	393.46
1000	2	392.45	1	392.96	1	393.46
2000	6	392.45	4	392.96	2	393.46
5000	39	392.46	22	392.97	14	393.46
10K	136	392.48	82	392.98	54	393.47
20K	370	392.52	254	393.01	180	393.49
50K	711	392.59	617	393.08	528	393.56
100K	821	392.61	777	393.11	730	393.60
Uncertainty $\delta W/W$ (%)		0.13		0.13		0.13

TABLE 16.165 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	423.15		423.15		423.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.0490		0.0981	
Enhancement factor f_e	1.04349		1.04349		1.04349	
Corrections						
Specific heat K_C (ppm)	−4607		−5076		−5527	
Virial K_V (ppm)	22108		19440		15815	
Simple sound speed W_s (m/s)	412.38		415.68		419.09	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	415.95	0	418.63	0	421.22
10	1	415.95	0	418.63	0	421.22
20	5	415.95	0	418.63	0	421.22
50	33	415.96	0	418.63	0	421.22
100	128	415.98	0	418.63	0	421.22
200	448	416.04	0	418.63	0	421.22
500	1585	416.28	0	418.63	0	421.22
1000	2888	416.55	1	418.63	0	421.22
2000	4224	416.83	5	418.63	1	421.22
5000	5132	417.02	30	418.64	7	421.22
10K	5315	417.05	114	418.66	28	421.23
20K	5363	417.06	385	418.71	107	421.24
50K	5377	417.07	1157	418.87	505	421.33
100K	5379	417.07	1623	418.97	1079	421.45
Uncertainty $\delta W/W$ (%)		0.14		0.14		0.14

TABLE 16.166 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	423.15		423.15		423.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.147		0.196		0.245	
Enhancement factor f_e	1.04349		1.04349		1.04349	
Corrections						
Specific heat K_C (ppm)	−5960		−6378		−6780	
Virial K_V (ppm)	11183		5486		−1335	
Simple sound speed W_s (m/s)	422.61		426.26		430.03	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	423.70	0	426.06	0	428.29
10	0	423.70	0	426.06	0	428.29
20	0	423.70	0	426.06	0	428.29
50	0	423.70	0	426.06	0	428.29
100	0	423.70	0	426.06	0	428.29
200	0	423.70	0	426.06	0	428.29
500	0	423.70	0	426.06	0	428.29
1000	0	423.70	0	426.06	0	428.29
2000	0	423.70	0	426.06	0	428.29
5000	3	423.70	2	426.06	1	428.29
10K	12	423.70	6	426.06	4	428.29
20K	46	423.71	24	426.07	14	428.29
50K	249	423.75	139	426.09	85	428.31
100K	680	423.85	434	426.16	286	428.35
Uncertainty $\delta W/W$ (%)		0.14		0.14		0.15

TABLE 16.167 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	473.15		473.15		473.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.161		0.322	
Enhancement factor f_e	1.04245		1.04245		1.04245	
Corrections						
Specific heat K_C (ppm)	−7566		−9322		−10863	
Virial K_V (ppm)	22280		12339		−3357	
Simple sound speed W_s (m/s)	436.06		447.94		461.22	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	439.22	0	448.59	0	457.94
10	1	439.22	0	448.59	0	457.94
20	6	439.22	0	448.59	0	457.94
50	37	439.23	0	448.59	0	457.94
100	143	439.25	0	448.59	0	457.94
200	523	439.34	0	448.59	0	457.94
500	2080	439.68	0	448.59	0	457.94
1000	3967	440.09	0	448.59	0	457.94
2000	6003	440.54	1	448.59	0	457.94
5000	7792	440.93	4	448.59	1	457.94
10K	8227	441.03	15	448.60	3	457.94
20K	8349	441.05	59	448.61	11	457.94
50K	8384	441.06	334	448.67	69	457.96
100K	8389	441.06	991	448.82	253	458.00
Uncertainty $\delta W/W$ (%)		0.14		0.15		0.17

TABLE 16.168 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	473.15		473.15		473.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.482		0.643		0.804	
Enhancement factor f_e	1.04245		1.04245		1.04245	
Corrections						
Specific heat K_C (ppm)	−12217		−13408		−14457	
Virial K_V (ppm)	−25445		−54685		−91961	
Simple sound speed W_s (m/s)	476.14		493.00		512.20	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	467.16	0	476.10	0	484.54
10	0	467.16	0	476.10	0	484.54
20	0	467.16	0	476.10	0	484.54
50	0	467.16	0	476.10	0	484.54
100	0	467.16	0	476.10	0	484.54
200	0	467.16	0	476.10	0	484.54
500	0	467.16	0	476.10	0	484.54
1000	0	467.16	0	476.10	0	484.54
2000	0	467.16	0	476.10	0	484.54
5000	0	467.16	0	476.10	0	484.54
10K	1	467.16	0	476.10	0	484.54
20K	4	467.16	1	476.11	0	484.54
50K	22	467.17	8	476.11	3	484.54
100K	86	467.18	32	476.11	11	484.55
Uncertainty $\delta W/W$ (%)		0.23		0.23		0.30

TABLE 16.169 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	523.15		523.15		523.15	
Humidity						
RH, h_r (%)	0		5		10	
Mole fraction x_h	0		0.104		0.208	
Enhancement factor f_e	1.04279		1.04279		1.04279	
Corrections						
Specific heat K_C (ppm)	−11077		−12395		−13603	
Virial K_V (ppm)	21956		16727		10219	
Simple sound speed W_s (m/s)	458.52		466.46		474.98	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	460.96	0	467.42	0	474.15
10	2	460.96	0	467.42	0	474.15
20	6	460.96	0	467.42	0	474.15
50	38	460.97	0	467.42	0	474.15
100	151	460.99	0	467.42	0	474.15
200	566	461.09	0	467.42	0	474.15
500	2487	461.53	0	467.42	0	474.15
1000	5085	462.13	1	467.42	0	474.15
2000	7848	462.76	2	467.42	0	474.15
5000	10720	463.42	14	467.43	3	474.15
10K	11577	463.62	54	467.44	12	474.15
20K	11832	463.68	210	467.47	46	474.16
50K	11907	463.69	1076	467.67	272	474.21
100K	11918	463.70	2617	468.03	911	474.36
Uncertainty $\delta W/W$ (%)		0.16		0.18		0.21

TABLE 16.170 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	523.15		523.15		523.15	
Humidity						
RH, h_r (%)	20		24		48	
Mole fraction x_h	0.417		0.500		1.000	
Enhancement factor f_e	1.04279		1.04279		1.04279	
Corrections						
Specific heat K_C (ppm)	−15722		−16472		−20029	
Virial K_V (ppm)	−6866		−15317		−88323	
Simple sound speed W_s (m/s)	494.03		502.50		567.38	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	488.44	0	494.51	0	536.29
10	0	488.44	0	494.51	0	536.29
20	0	488.44	0	494.51	0	536.29
50	0	488.44	0	494.51	0	536.29
100	0	488.44	0	494.51	0	536.29
200	0	488.44	0	494.51	0	536.29
500	0	488.44	0	494.51	0	536.29
1000	0	488.44	0	494.51	0	536.29
2000	0	488.44	0	494.51	0	536.29
5000	0	488.44	0	494.51	0	536.29
10K	2	488.44	1	494.51	0	536.29
20K	8	488.45	4	494.51	0	536.29
50K	48	488.45	28	494.52	0	536.29
100K	183	488.49	107	494.54	0	536.29
Uncertainty $\delta W/W$ (%)		0.31		0.35		0.75

TABLE 16.171 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	573.15		573.15		573.15	
Humidity						
RH, h_r (%)	0		10.5		21	
Mole fraction x_h	0.000		0.485		0.970	
Enhancement factor f_e	1.04385		1.04385		1.04385	
Corrections						
Specific heat K_C (ppm)	−15083		−20744		−24456	
Virial K_V (ppm)	21385		−7277		−53656	
Simple sound speed W_s (m/s)	479.94		524.33		588.90	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	481.37	0	516.97	0	565.84
10	2	481.37	0	516.97	0	565.84
20	6	481.37	0	516.97	0	565.84
50	39	481.38	0	516.97	0	565.84
100	152	481.41	0	516.97	0	565.84
200	581	481.51	0	516.97	0	565.84
500	2759	482.03	0	516.97	0	565.84
1000	6115	482.84	0	516.97	0	565.84
2000	9690	483.70	0	516.97	0	565.84
5000	13691	484.65	0	516.97	0	565.84
10K	15144	485.00	2	516.97	0	565.84
20K	15613	485.11	6	516.97	0	565.84
50K	15755	485.15	39	516.98	0	565.84
100K	15776	485.15	151	517.01	2	565.84
Uncertainty $\delta W/W$ (%)		0.16		0.52		1.20

TABLE 16.172 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	20		20		20	
Temperature T (K)	603.15		603.15		603.15	
Humidity						
RH, h_r (%)	0		7		14	
Mole fraction x_h	0		0.495		0.990	
Enhancement factor f_e	1.04469		1.04469		1.04469	
Corrections						
Specific heat K_C (ppm)	−17700		−23583		−27365	
Virial K_V (ppm)	20981		−5432		−44386	
Simple sound speed W_s (m/s)	492.34		538.98		607.46	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	493.05	0	531.14	0	585.64
10	2	493.05	0	531.14	0	585.64
20	6	493.05	0	531.14	0	585.64
50	38	493.06	0	531.14	0	585.64
100	151	493.09	0	531.14	0	585.64
200	579	493.20	0	531.14	0	585.64
500	2855	493.76	0	531.14	0	585.64
1000	6641	494.69	0	531.14	0	585.64
2000	10759	495.70	0	531.14	0	585.64
5000	15417	496.84	0	531.14	0	585.64
10K	17296	497.30	2	531.14	0	585.64
20K	17938	497.45	7	531.14	0	585.64
50K	18136	497.50	41	531.15	0	585.64
100K	18165	497.51	160	531.18	1	585.64
Uncertainty $\delta W/W$ (%)		0.16		0.65		1.59

TABLE 16.173 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50	50	50
Temperature T (K)	233.15	233.15	233.15
Humidity			
RH, h_r (%)	0	50	100
Mole fraction x_h	0	0.000002	0.000005
Enhancement factor f_e	1.30279	1.30279	1.30279
Corrections			
Specific heat K_C (ppm)	755	755	755
Virial K_V (ppm)	4797	4797	4797
Simple sound speed W_s (m/s)	306.10	306.10	306.10

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	306.95	0	306.95	0	306.95
10	0	306.95	0	306.95	0	306.95
20	0	306.95	0	306.95	0	306.95
50	2	306.95	1	306.95	1	306.95
100	6	306.95	6	306.95	5	306.95
200	20	306.95	19	306.95	19	306.95
500	72	306.96	71	306.96	69	306.96
1000	122	306.97	121	306.97	120	306.97
2000	148	306.97	148	306.97	148	306.97
5000	158	306.98	158	306.98	158	306.98
10K	160	306.98	160	306.98	160	306.98
20K	160	306.98	160	306.98	160	306.98
50K	160	306.98	160	306.98	160	306.98
100K	160	306.98	160	306.98	160	306.98
Uncertainty $\delta W/W$ (%)		0.54		0.54		0.54

TABLE 16.174 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	243.15		243.15		243.15	
Humidity						
RH, h_r (%)	0		50		100	
Mole fraction x_h	0		0.000006		0.000013	
Enhancement factor f_e	1.27075		1.27075		1.27075	
Corrections						
Specific heat K_C (ppm)	725		725		725	
Virial K_V (ppm)	15006		15006		15005	
Simple sound speed W_s (m/s)	312.60		312.60		312.60	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	315.05	0	315.05	0	315.05
10	0	315.05	0	315.05	0	315.05
20	0	315.05	0	315.05	0	315.05
50	2	315.05	2	315.05	1	315.05
100	6	315.05	6	315.05	5	315.05
200	23	315.05	21	315.05	19	315.05
500	87	315.06	82	315.06	77	315.06
1000	158	315.07	153	315.07	148	315.07
2000	201	315.08	199	315.08	197	315.08
5000	218	315.08	218	315.08	218	315.08
10K	221	315.08	221	315.08	221	315.08
20K	222	315.08	222	315.08	222	315.08
50K	222	315.08	222	315.08	222	315.08
100K	222	315.08	222	315.08	222	315.08
Uncertainty $\delta W/W$ (%)		0.48		0.48		0.48

TABLE 16.175 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	253.15		253.15		253.15	
Humidity						
RH, h_r (%)	0		50		100	
Mole fraction x_h	0		0.000015		0.000031	
Enhancement factor f_e	1.24372		1.24372		1.24372	
Corrections						
Specific heat K_C (ppm)	666		666		666	
Virial K_V (ppm)	23270		23269		23268	
Simple sound speed W_s (m/s)	318.96		318.96		318.96	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	322.76	0	322.76	0	322.76
10	0	322.76	0	322.76	0	322.76
20	0	322.76	0	322.76	0	322.76
50	2	322.76	2	322.76	1	322.76
100	7	322.76	6	322.76	5	322.76
200	26	322.76	21	322.76	18	322.76
500	102	322.78	88	322.77	74	322.77
1000	197	322.79	181	322.79	162	322.79
2000	264	322.80	256	322.80	245	322.80
5000	293	322.81	291	322.81	289	322.81
10K	298	322.81	297	322.81	297	322.81
20K	299	322.81	299	322.81	299	322.81
50K	299	322.81	299	322.81	299	322.81
100K	299	322.81	299	322.81	299	322.81
Uncertainty $\delta W/W$ (%)		0.44		0.44		0.44

TABLE 16.176 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	263.15		263.15		263.15	
Humidity						
RH, h_r (%)	0		50		100	
Mole fraction x_h	0		0.000034		0.000069	
Enhancement factor f_e	1.22076		1.22076		1.22076	
Corrections						
Specific heat K_C (ppm)	579		578		578	
Virial K_V (ppm)	29999		29996		29994	
Simple sound speed W_s (m/s)	325.20		325.20		325.20	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	330.14	0	330.14	0	330.14
10	0	330.14	0	330.14	0	330.14
20	0	330.14	0	330.14	0	330.14
50	2	330.14	1	330.14	1	330.14
100	8	330.14	5	330.14	4	330.14
200	29	330.14	19	330.14	13	330.14
500	118	330.16	82	330.15	57	330.15
1000	240	330.18	188	330.17	138	330.16
2000	338	330.19	305	330.19	259	330.18
5000	384	330.20	376	330.20	362	330.20
10K	391	330.20	389	330.20	386	330.20
20K	393	330.20	393	330.20	392	330.21
50K	394	330.20	394	330.20	394	330.21
100K	394	330.20	394	330.20	394	330.21
Uncertainty $\delta W/W$(%)		0.39		0.39		0.39

TABLE 16.177 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	273.15		273.15		273.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000029		0.000058	
Enhancement factor f_e	1.20111		1.20111		1.20111	
Corrections						
Specific heat K_C (ppm)	462		462		461	
Virial K_V (ppm)	35502		35500		35497	
Simple sound speed W_s (m/s)	331.32		331.32		331.32	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	337.23	0	337.23	0	337.23
10	0	337.23	0	337.23	0	337.23
20	0	337.23	0	337.23	0	337.23
50	2	337.23	2	337.23	1	337.23
100	9	337.23	6	337.23	5	337.23
200	32	337.24	23	337.23	17	337.23
500	134	337.25	100	337.25	75	337.24
1000	286	337.28	230	337.27	179	337.26
2000	422	337.30	383	337.30	333	337.29
5000	492	337.31	482	337.31	467	337.31
10K	504	337.31	502	337.32	497	337.32
20K	507	337.32	507	337.32	506	337.32
50K	508	337.32	508	337.32	508	337.32
100K	508	337.32	508	337.32	508	337.32
Uncertainty $\delta W/W$ (%)		0.36		0.36		0.36

TABLE 16.178 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	273.15		273.15		273.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000087		0.000116		0.000145	
Enhancement factor f_e	1.20111		1.20111		1.20111	
Corrections						
Specific heat K_C (ppm)	461		461		461	
Virial K_V (ppm)	35494		35492		35489	
Simple sound speed W_s (m/s)	331.33		331.33		331.33	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	337.23	0	337.23	0	337.24
10	0	337.23	0	337.23	0	337.24
20	0	337.23	0	337.23	0	337.24
50	1	337.23	1	337.23	1	337.24
100	4	337.23	3	337.23	2	337.24
200	13	337.24	10	337.24	9	337.24
500	57	337.24	46	337.24	38	337.24
1000	138	337.26	109	337.25	89	337.25
2000	280	337.28	230	337.27	188	337.27
5000	445	337.31	417	337.30	383	337.30
10K	491	337.32	481	337.32	469	337.31
20K	504	337.32	501	337.32	498	337.32
50K	508	337.32	507	337.32	507	337.32
100K	508	337.32	508	337.32	508	337.32
Uncertainty $\delta W/W$ (%)		0.36		0.36		0.36

TABLE 16.179 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	283.15		283.15		283.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000057		0.000115	
Enhancement factor f_e	1.18421		1.18421		1.18421	
Corrections						
Specific heat K_C (ppm)	316		316		315	
Virial K_V (ppm)	40018		40012		40007	
Simple sound speed W_s (m/s)	337.33		337.34		337.34	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	344.07	0	344.07	0	344.07
10	0	344.07	0	344.07	0	344.07
20	0	344.07	0	344.07	0	344.07
50	2	344.07	1	344.07	1	344.07
100	10	344.07	5	344.07	3	344.07
200	36	344.08	20	344.08	13	344.08
500	152	344.10	87	344.09	56	344.08
1000	333	344.13	208	344.11	133	344.10
2000	516	344.16	398	344.14	275	344.12
5000	619	344.18	582	344.17	514	344.16
10K	637	344.18	627	344.18	605	344.18
20K	642	344.18	640	344.18	634	344.18
50K	644	344.18	643	344.18	642	344.18
100K	644	344.18	644	344.18	643	344.18
Uncertainty $\delta W/W$ (%)		0.33		0.33		0.33

TABLE 16.180 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	283.15		283.15		283.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000172		0.000229		0.000287	
Enhancement factor f_e	1.18421		1.18421		1.18421	
Corrections						
Specific heat K_C (ppm)	315		315		315	
Virial K_V (ppm)	40001		39995		39990	
Simple sound speed W_s (m/s)	337.34		337.34		337.35	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	344.08	0	344.08	0	344.08
10	0	344.08	0	344.08	0	344.08
20	0	344.08	0	344.08	0	344.08
50	1	344.08	0	344.08	0	344.08
100	2	344.08	2	344.08	1	344.08
200	9	344.08	7	344.08	5	344.08
500	41	344.08	33	344.08	27	344.09
1000	95	344.09	75	344.09	64	344.09
2000	191	344.11	142	344.10	114	344.10
5000	424	344.15	334	344.14	260	344.13
10K	566	344.17	511	344.17	445	344.16
20K	622	344.18	603	344.18	576	344.18
50K	640	344.19	637	344.19	632	344.19
100K	643	344.19	642	344.19	641	344.19
Uncertainty $\delta W/W$ (%)		0.33		0.33		0.33

TABLE 16.181 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	293.15		293.15		293.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000108		0.000216	
Enhancement factor f_e	1.16959		1.16959		1.16959	
Corrections						
Specific heat K_C (ppm)	142		141		141	
Virial K_V (ppm)	43731		43720		43709	
Simple sound speed W_s (m/s)	343.24		343.24		343.25	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	350.69	0	350.69	0	350.69
10	0	350.69	0	350.69	0	350.69
20	0	350.69	0	350.69	0	350.69
50	3	350.69	1	350.69	1	350.70
100	11	350.69	4	350.69	2	350.70
200	39	350.69	16	350.69	9	350.70
500	170	350.72	71	350.70	43	350.70
1000	383	350.75	165	350.72	100	350.71
2000	618	350.80	337	350.75	187	350.73
5000	765	350.82	633	350.80	424	350.77
10K	793	350.83	750	350.82	641	350.81
20K	800	350.83	789	350.83	753	350.83
50K	802	350.83	800	350.83	794	350.83
100K	802	350.83	802	350.83	800	350.84
Uncertainty $\delta W/W$ (%)		0.30		0.30		0.30

TABLE 16.182 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50	50	50
Temperature T (K)	293.15	293.15	293.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.000324	0.000432	0.000540
Enhancement factor f_e	1.16959	1.16959	1.16959
Corrections			
Specific heat K_C (ppm)	140	140	139
Virial K_V (ppm)	43697	43686	43674
Simple sound speed W_s (m/s)	343.25	343.26	343.27

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	350.70	0	350.70	0	350.71
10	0	350.70	0	350.70	0	350.71
20	0	350.70	0	350.70	0	350.71
50	0	350.70	0	350.70	0	350.71
100	2	350.70	1	350.70	1	350.71
200	6	350.70	4	350.70	3	350.71
500	30	350.70	23	350.71	18	350.71
1000	75	350.71	61	350.71	51	350.72
2000	134	350.72	111	350.72	98	350.72
5000	274	350.75	198	350.74	161	350.74
10K	488	350.78	356	350.77	267	350.75
20K	682	350.82	582	350.81	476	350.79
50K	780	350.84	754	350.84	714	350.83
100K	796	350.84	789	350.84	778	350.84
Uncertainty $\delta W/W$ (%)		0.30		0.30		0.30

TABLE 16.183 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	303.15		303.15		303.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000194		0.000388	
Enhancement factor f_e	1.15689		1.15689		1.15689	
Corrections						
Specific heat K_C (ppm)	−61		−62		−63	
Virial K_V (ppm)	46787		46766		46745	
Simple sound speed W_s (m/s)	349.04		349.05		349.06	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	357.10	0	357.11	0	357.12
10	0	357.10	0	357.11	0	357.12
20	0	357.10	0	357.11	0	357.12
50	3	357.10	1	357.11	0	357.12
100	12	357.11	3	357.11	2	357.12
200	43	357.11	12	357.11	6	357.12
500	189	357.14	57	357.12	32	357.12
1000	434	357.18	134	357.13	85	357.13
2000	727	357.23	249	357.16	154	357.15
5000	930	357.27	548	357.21	277	357.17
10K	971	357.28	804	357.25	487	357.21
20K	982	357.28	931	357.28	756	357.25
50K	985	357.28	976	357.29	937	357.29
100K	985	357.28	983	357.29	972	357.29
Uncertainty $\delta W/W$ (%)		0.28		0.28		0.28

TABLE 16.184 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	303.15		303.15		303.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000581		0.000775		0.000969	
Enhancement factor f_e	1.15689		1.15689		1.15689	
Corrections						
Specific heat K_C (ppm)	−64		−65		−66	
Virial K_V (ppm)	46723		46702		46680	
Simple sound speed W_s (m/s)	349.07		349.09		349.10	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	357.13	0	357.13	0	357.14
10	0	357.13	0	357.13	0	357.14
20	0	357.13	0	357.13	0	357.14
50	0	357.13	0	357.13	0	357.14
100	1	357.13	1	357.13	0	357.14
200	4	357.13	2	357.13	2	357.14
500	20	357.13	14	357.14	10	357.14
1000	61	357.14	46	357.14	36	357.15
2000	123	357.15	104	357.15	89	357.16
5000	199	357.16	171	357.16	157	357.17
10K	304	357.18	230	357.17	198	357.18
20K	531	357.22	373	357.20	285	357.19
50K	848	357.28	719	357.26	584	357.24
100K	946	357.29	897	357.29	825	357.29
Uncertainty $\delta W/W$ (%)		0.28		0.28		0.28

TABLE 16.185 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	313.15		313.15		313.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000334		0.000667	
Enhancement factor f_e	1.14582		1.14582		1.14582	
Corrections						
Specific heat K_C (ppm)	−292		−294		−295	
Virial K_V (ppm)	49301		49264		49226	
Simple sound speed W_s (m/s)	354.75		354.77		354.79	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	363.34	0	363.35	0	363.36
10	0	363.34	0	363.35	0	363.36
20	1	363.34	0	363.35	0	363.36
50	3	363.34	1	363.35	0	363.36
100	12	363.34	2	363.35	1	363.36
200	47	363.35	8	363.35	4	363.37
500	210	363.38	44	363.36	21	363.37
1000	487	363.43	117	363.37	67	363.38
2000	843	363.49	212	363.39	146	363.39
5000	1116	363.54	390	363.42	237	363.41
10K	1173	363.55	671	363.47	329	363.42
20K	1189	363.56	974	363.53	544	363.46
50K	1193	363.56	1150	363.56	955	363.54
100K	1194	363.56	1182	363.57	1120	363.57
Uncertainty $\delta W/W$ (%)		0.26		0.26		0.26

TABLE 16.186 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	313.15		313.15		313.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.00100		0.00133		0.00167	
Enhancement factor f_e	1.14582		1.14582		1.14582	
Corrections						
Specific heat K_C (ppm)	−297		−299		−300	
Virial K_V (ppm)	49187		49147		49107	
Simple sound speed W_s (m/s)	354.81		354.83		354.85	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	363.38	0	363.39	0	363.40
10	0	363.38	0	363.39	0	363.40
20	0	363.38	0	363.39	0	363.40
50	0	363.38	0	363.39	0	363.40
100	1	363.38	0	363.39	0	363.40
200	2	363.38	1	363.39	1	363.40
500	12	363.38	8	363.39	6	363.40
1000	43	363.38	29	363.39	21	363.41
2000	110	363.40	85	363.40	66	363.41
5000	204	363.41	183	363.42	166	363.43
10K	253	363.42	229	363.43	215	363.44
20K	347	363.44	279	363.44	251	363.45
50K	681	363.50	486	363.48	375	363.47
100K	980	363.55	800	363.53	632	363.52
Uncertainty $\delta W/W$ (%)		0.26		0.26		0.26

TABLE 16.187 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	323.15		323.15		323.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000553		0.00111	
Enhancement factor f_e	1.13612		1.13612		1.13612	
Corrections						
Specific heat K_C (ppm)	−551		−554		−557	
Virial K_V (ppm)	51366		51302		51236	
Simple sound speed W_s (m/s)	360.37		360.40		360.44	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	369.41	0	369.43	0	369.45
10	0	369.41	0	369.43	0	369.45
20	1	369.41	0	369.43	0	369.45
50	3	369.41	0	369.43	0	369.45
100	13	369.41	1	369.43	1	369.45
200	50	369.42	6	369.43	2	369.45
500	231	369.45	32	369.44	13	369.45
1000	543	369.51	98	369.45	46	369.46
2000	965	369.59	204	369.47	127	369.48
5000	1320	369.65	329	369.49	252	369.50
10K	1400	369.67	478	369.52	311	369.51
20K	1422	369.67	793	369.58	397	369.53
50K	1428	369.67	1236	369.66	729	369.59
100K	1429	369.67	1373	369.68	1102	369.66
Uncertainty $\delta W/W$ (%)		0.24		0.24		0.24

TABLE 16.188 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50	50	50
Temperature T (K)	323.15	323.15	323.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.00166	0.00221	0.00277
Enhancement factor f_e	1.13612	1.13612	1.13612
Corrections			
Specific heat K_C (ppm)	−560	−563	−566
Virial K_V (ppm)	51169	51101	51031
Simple sound speed W_s (m/s)	360.47	360.50	360.53

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	369.47	0	369.49	0	369.51
10	0	369.47	0	369.49	0	369.51
20	0	369.47	0	369.49	0	369.51
50	0	369.47	0	369.49	0	369.51
100	0	369.47	0	369.49	0	369.51
200	1	369.47	1	369.49	0	369.51
500	7	369.47	4	369.49	3	369.51
1000	26	369.48	17	369.50	11	369.51
2000	83	369.49	57	369.50	41	369.52
5000	213	369.51	178	369.53	149	369.54
10K	279	369.52	259	369.54	240	369.56
20K	323	369.53	300	369.55	288	369.57
50K	468	369.56	375	369.56	337	369.57
100K	766	369.61	555	369.60	446	369.59
Uncertainty $\delta W/W$ (%)		0.24		0.24		0.24

TABLE 16.189 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	373.15		373.15		373.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00441		0.00882	
Enhancement factor f_e	1.10244		1.10244		1.10244	
Corrections						
Specific heat K_C (ppm)	−2253		−2287		−2320	
Virial K_V (ppm)	57117		56561		55969	
Simple sound speed W_s (m/s)	387.25		387.52		387.80	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	397.71	0	397.88	0	398.04
10	0	397.71	0	397.88	0	398.04
20	1	397.71	0	397.88	0	398.04
50	4	397.71	0	397.88	0	398.04
100	18	397.71	0	397.88	0	398.04
200	68	397.72	0	397.88	0	398.04
500	344	397.77	3	397.88	1	398.04
1000	865	397.88	11	397.88	3	398.04
2000	1645	398.03	44	397.89	13	398.04
5000	2609	398.23	220	397.92	73	398.06
10K	2914	398.29	506	397.98	234	398.09
20K	3005	398.30	753	398.03	523	398.15
50K	3032	398.31	886	398.05	802	398.20
100K	3036	398.31	961	398.07	877	398.22
Uncertainty $\delta W/W$ (%)		0.21		0.22		0.21

TABLE 16.190 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	373.15		373.15		373.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.0132		0.0176		0.0221	
Enhancement factor f_e	1.10244		1.10244		1.10244	
Corrections						
Specific heat K_C (ppm)	−2354		−2387		−2420	
Virial K_V (ppm)	55339		54669		53959	
Simple sound speed W_s (m/s)	388.08		388.35		388.63	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	398.20	0	398.35	0	398.49
10	0	398.20	0	398.35	0	398.49
20	0	398.20	0	398.35	0	398.49
50	0	398.20	0	398.35	0	398.49
100	0	398.20	0	398.35	0	398.49
200	0	398.20	0	398.35	0	398.49
500	0	398.20	0	398.35	0	398.49
1000	1	398.20	1	398.35	1	398.49
2000	6	398.20	3	398.35	2	398.49
5000	35	398.21	20	398.35	13	398.50
10K	124	398.22	75	398.36	50	398.50
20K	350	398.27	239	398.40	170	398.53
50K	711	398.34	615	398.47	525	398.60
100K	837	398.37	795	398.51	750	398.64
Uncertainty $\delta W/W$ (%)		0.21		0.21		0.21

TABLE 16.191 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	423.15		423.15		423.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.0204		0.0408	
Enhancement factor f_e	1.08391		1.08391		1.08391	
Corrections						
Specific heat K_C (ppm)	−4607		−4804		−4998	
Virial K_V (ppm)	58576		55902		52836	
Simple sound speed W_s (m/s)	412.38		413.74		415.11	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	423.31	0	424.12	0	424.87
10	0	423.31	0	424.12	0	424.87
20	1	423.31	0	424.12	0	424.87
50	5	423.31	0	424.12	0	424.87
100	21	423.31	0	424.12	0	424.87
200	83	423.32	0	424.12	0	424.87
500	448	423.40	0	424.12	0	424.87
1000	1231	423.57	1	424.12	0	424.87
2000	2441	423.82	5	424.12	1	424.87
5000	4224	424.20	28	424.13	7	424.87
10K	5006	424.36	107	424.14	28	424.88
20K	5279	424.42	369	424.20	107	424.90
50K	5363	424.44	1157	424.37	515	424.98
100K	5376	424.44	1667	424.47	1135	425.11
Uncertainty $\delta W/W$ (%)		0.22		0.22		0.21

TABLE 16.192 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	423.15		423.15		423.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.0611		0.0815		0.102	
Enhancement factor f_e	1.08391		1.08391		1.08391	
Corrections						
Specific heat K_C (ppm)	−5188		−5376		−5561	
Virial K_V (ppm)	49358		45445		41072	
Simple sound speed W_s (m/s)	416.51		417.92		419.36	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	425.56	0	426.16	0	426.69
10	0	425.56	0	426.16	0	426.69
20	0	425.56	0	426.16	0	426.69
50	0	425.56	0	426.16	0	426.69
100	0	425.56	0	426.16	0	426.69
200	0	425.56	0	426.16	0	426.69
500	0	425.56	0	426.16	0	426.69
1000	0	425.56	0	426.16	0	426.69
2000	0	425.56	0	426.16	0	426.69
5000	3	425.56	2	426.16	1	426.69
10K	12	425.56	7	426.16	4	426.69
20K	48	425.57	27	426.17	17	426.69
50K	264	425.61	154	426.20	99	426.71
100K	737	425.71	489	426.27	338	426.76
Uncertainty $\delta W/W$ (%)		0.20		0.19		0.19

TABLE 16.193 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50	50	50
Temperature T (K)	473.15	473.15	473.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.0662	0.132
Enhancement factor f_e	1.07348	1.07348	1.07348
Corrections			
Specific heat K_C (ppm)	−7566	−8317	−9029
Virial K_V (ppm)	58066	49103	37863
Simple sound speed W_s (m/s)	436.06	440.80	445.75

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	446.84	0	449.61	0	452.06
10	0	446.84	0	449.61	0	452.06
20	1	446.84	0	449.61	0	452.06
50	6	446.85	0	449.61	0	452.06
100	24	446.85	0	449.61	0	452.06
200	93	446.86	0	449.61	0	452.06
500	523	446.96	0	449.61	0	452.06
1000	1569	447.19	0	449.61	0	452.06
2000	3329	447.59	1	449.61	0	452.06
5000	6003	448.18	4	449.61	1	452.06
10K	7511	448.52	16	449.61	4	452.06
20K	8140	448.66	64	449.63	15	452.06
50K	8349	448.71	364	449.69	90	452.08
100K	8380	448.71	1097	449.86	331	452.14
Uncertainty $\delta W/W$ (%)		0.21		0.20		0.18

TABLE 16.194 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	473.15		473.15		473.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.199		0.265		0.331	
Enhancement factor f_e	1.07348		1.07348		1.07348	
Corrections						
Specific heat K_C (ppm)	−9704		−10343		−10949	
Virial K_V (ppm)	24116		7609		−11931	
Simple sound speed W_s (m/s)	450.94		456.37		462.06	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	454.13	0	455.73	0	456.78
10	0	454.13	0	455.73	0	456.78
20	0	454.13	0	455.73	0	456.78
50	0	454.13	0	455.73	0	456.78
100	0	454.13	0	455.73	0	456.78
200	0	454.13	0	455.73	0	456.78
500	0	454.13	0	455.73	0	456.78
1000	0	454.13	0	455.73	0	456.78
2000	0	454.13	0	455.73	0	456.78
5000	0	454.13	0	455.73	0	456.78
10K	1	454.13	1	455.73	0	456.78
20K	6	454.13	3	455.73	2	456.78
50K	37	454.13	19	455.73	11	456.78
100K	141	454.16	73	455.74	42	456.79
Uncertainty $\delta W/W$ (%)		0.18		0.18		0.20

TABLE 16.195 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50	50	50
Temperature T (K)	523.15	523.15	523.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.171	0.341
Enhancement factor f_e	1.06766	1.06766	1.06766
Corrections			
Specific heat K_C (ppm)	−11077	−13178	−14998
Virial K_V (ppm)	56629	32959	261
Simple sound speed W_s (m/s)	458.52	471.83	486.80

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	468.71	0	476.37	0	483.20
10	0	468.71	0	476.37	0	483.20
20	1	468.71	0	476.37	0	483.20
50	6	468.71	0	476.37	0	483.20
100	25	468.72	0	476.37	0	483.20
200	97	468.73	0	476.37	0	483.20
500	566	468.84	0	476.37	0	483.20
1000	1820	469.14	0	476.37	0	483.20
2000	4204	469.70	0	476.37	0	483.20
5000	7848	470.55	1	476.37	0	483.20
10K	10207	471.10	3	476.37	1	483.20
20K	11398	471.37	12	476.37	2	483.20
50K	11832	471.48	73	476.39	14	483.21
100K	11899	471.49	277	476.44	54	483.22
Uncertainty $\delta W/W$ (%)		0.21		0.21		0.24

TABLE 16.196 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	523.15		523.15		523.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.512		0.682		0.853	
Enhancement factor f_e	1.06766		1.06766		1.06766	
Corrections						
Specific heat K_C (ppm)	−16575		−17944		−19132	
Virial K_V (ppm)	−43229		−99635		−171435	
Simple sound speed W_s (m/s)	503.76		523.09		545.35	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	488.65	0	491.88	0	491.63
10	0	488.65	0	491.88	0	491.63
20	0	488.65	0	491.88	0	491.63
50	0	488.65	0	491.88	0	491.63
100	0	488.65	0	491.88	0	491.63
200	0	488.65	0	491.88	0	491.63
500	0	488.65	0	491.88	0	491.63
1000	0	488.65	0	491.88	0	491.63
2000	0	488.65	0	491.88	0	491.63
5000	0	488.65	0	491.88	0	491.63
10K	0	488.65	0	491.88	0	491.63
20K	1	488.65	0	491.88	0	491.63
50K	4	488.65	1	491.88	0	491.63
100K	17	488.65	6	491.88	2	491.63
Uncertainty $\delta W/W$ (%)		0.37		0.33		0.52

TABLE 16.197 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	573.15		573.15		573.15	
Humidity						
RH, h_r (%)	0		10		20	
Mole fraction x_h	0		0.188		0.377	
Enhancement factor f_e	1.06458		1.06458		1.06458	
Corrections						
Specific heat K_C (ppm)	−15083		−17571		−19680	
Virial K_V (ppm)	54770		31236		1753	
Simple sound speed W_s (m/s)	479.94		495.41		513.05	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	489.17	0	498.65	0	508.42
10	0	489.17	0	498.65	0	508.42
20	1	489.17	0	498.65	0	508.42
50	6	489.17	0	498.65	0	508.42
100	25	489.18	0	498.65	0	508.42
200	98	489.20	0	498.65	0	508.42
500	581	489.31	0	498.65	0	508.42
1000	1967	489.65	0	498.65	0	508.42
2000	4947	490.38	0	498.65	0	508.42
5000	9690	491.54	1	498.65	0	508.42
10K	12897	492.32	3	498.65	1	508.42
20K	14825	492.79	12	498.65	2	508.43
50K	15613	492.98	74	498.67	13	508.43
100K	15740	493.01	288	498.72	53	508.44
Uncertainty $\delta W/W$ (%)		0.20		0.26		0.35

TABLE 16.198 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50	50	50
Temperature T (K)	573.15	573.15	573.15
Humidity			
RH, h_r (%)	30	40	50
Mole fraction x_h	0.565	0.754	0.942
Enhancement factor f_e	1.06458	1.06458	1.06458
Corrections			
Specific heat K_C (ppm)	−21471	−22992	−24283
Virial K_V (ppm)	−34728	−79451	−133847
Simple sound speed W_s (m/s)	533.32	556.83	584.41

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	518.32	0	528.07	0	537.25
10	0	518.32	0	528.07	0	537.25
20	0	518.32	0	528.07	0	537.25
50	0	518.32	0	528.07	0	537.25
100	0	518.32	0	528.07	0	537.25
200	0	518.32	0	528.07	0	537.25
500	0	518.32	0	528.07	0	537.25
1000	0	518.32	0	528.07	0	537.25
2000	0	518.32	0	528.07	0	537.25
5000	0	518.32	0	528.07	0	537.25
10K	0	518.32	0	528.07	0	537.25
20K	1	518.32	0	528.07	0	537.25
50K	4	518.32	1	528.07	0	537.25
100K	15	518.33	4	528.07	1	537.25
Uncertainty $\delta W/W$ (%)		0.52		0.59		0.74

TABLE 16.199 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	50		50		50	
Temperature T (K)	603.15		603.15		603.15	
Humidity						
RH, h_r (%)	0		16		32	
Mole fraction x_h	0		0.461		0.921	
Enhancement factor f_e	1.06360		1.06360		1.06360	
Corrections						
Specific heat K_C (ppm)	−17700		−23254		−26936	
Virial K_V (ppm)	53566		−7821		−99312	
Simple sound speed W_s (m/s)	492.34		535.19		596.14	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	500.86	0	526.86	0	558.09
10	0	500.86	0	526.86	0	558.09
20	1	500.86	0	526.86	0	558.09
50	6	500.86	0	526.86	0	558.09
100	24	500.86	0	526.86	0	558.09
200	97	500.88	0	526.86	0	558.09
500	579	501.00	0	526.86	0	558.09
1000	2008	501.36	0	526.86	0	558.09
2000	5294	502.18	0	526.86	0	558.09
5000	10759	503.55	0	526.86	0	558.09
10K	14448	504.46	0	526.86	0	558.09
20K	16870	505.07	1	526.86	0	558.09
50K	17938	505.33	8	526.86	0	558.09
100K	18114	505.37	33	526.87	1	558.09
Uncertainty $\delta W/W$ (%)		0.20		0.50		1.03

TABLE 16.200 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100	100	100
Temperature T (K)	233.15	233.15	233.15
Humidity			
RH, h_r (%)	0	50	100
Mole fraction x_h	0	0.000002	0.000003
Enhancement factor f_e	1.73305	1.73305	1.73305
Corrections			
Specific heat K_C (ppm)	755	755	755
Virial K_V (ppm)	55894	55894	55894
Simple sound speed W_s (m/s)	306.10	306.10	306.10

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	314.66	0	314.66	0	314.66
10	0	314.66	0	314.66	0	314.66
20	0	314.66	0	314.66	0	314.66
50	0	314.66	0	314.66	0	314.66
100	2	314.66	1	314.66	1	314.66
200	6	314.66	6	314.66	6	314.66
500	29	314.66	28	314.66	28	314.66
1000	72	314.67	71	314.67	70	314.67
2000	122	314.68	121	314.68	120	314.68
5000	153	314.68	152	314.68	152	314.68
10K	158	314.68	158	314.68	158	314.68
20K	160	314.68	160	314.68	160	314.68
50K	160	314.68	160	314.68	160	314.68
100K	160	314.68	160	314.68	160	314.68
Uncertainty $\delta W/W$ (%)		1.32		1.32		1.32

TABLE 16.201 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	243.15		243.15		243.15	
Humidity						
RH, h_r (%)	0		50		100	
Mole fraction x_h	0		0.000004		0.000008	
Enhancement factor f_e	1.64212		1.64212		1.64212	
Corrections						
Specific heat K_C (ppm)	725		725		725	
Virial K_V (ppm)	73510		73509		73508	
Simple sound speed W_s (m/s)	312.60		312.60		312.60	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	324.00	0	324.00	0	324.00
10	0	324.00	0	324.00	0	324.00
20	0	324.00	0	324.00	0	324.00
50	0	324.00	0	324.00	0	324.00
100	2	324.00	2	324.00	2	324.00
200	6	324.00	6	324.00	6	324.00
500	33	324.01	31	324.01	30	324.01
1000	87	324.02	84	324.02	81	324.01
2000	158	324.03	155	324.03	152	324.03
5000	208	324.04	207	324.04	206	324.03
10K	218	324.04	218	324.04	218	324.04
20K	221	324.04	221	324.04	221	324.04
50K	222	324.04	222	324.04	222	324.04
100K	222	324.04	222	324.04	222	324.04
Uncertainty $\delta W/W$ (%)		1.16		1.16		1.16

TABLE 16.202 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100	100	100
Temperature T (K)	253.15	253.15	253.15
Humidity			
RH, h_r (%)	0	50	100
Mole fraction x_h	0	0.000010	0.000019
Enhancement factor f_e	1.56740	1.56740	1.56740
Corrections			
Specific heat K_C (ppm)	666	666	666
Virial K_V (ppm)	87113	87111	87108
Simple sound speed W_s (m/s)	318.96	318.96	318.96

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	332.68	0	332.68	0	332.68
10	0	332.68	0	332.68	0	332.68
20	0	332.68	0	332.68	0	332.68
50	0	332.68	0	332.68	0	332.68
100	2	332.68	2	332.68	1	332.68
200	7	332.68	6	332.68	6	332.68
500	37	332.68	33	332.68	30	332.68
1000	102	332.69	93	332.69	84	332.69
2000	197	332.71	187	332.71	176	332.70
5000	276	332.72	272	332.72	268	332.72
10K	293	332.72	292	332.72	291	332.72
20K	298	332.72	297	332.72	297	332.72
50K	299	332.72	299	332.72	299	332.73
100K	299	332.72	299	332.73	299	332.73
Uncertainty $\delta W/W$ (%)		1.03		1.03		1.03

TABLE 16.203 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100	100	100
Temperature T (K)	263.15	263.15	263.15
Humidity			
RH, h_r (%)	0	50	100
Mole fraction x_h	0	0.000021	0.000043
Enhancement factor f_e	1.50533	1.50533	1.50533
Corrections			
Specific heat K_C (ppm)	579	578	578
Virial K_V (ppm)	97665	97659	97653
Simple sound speed W_s (m/s)	325.20	325.20	325.20

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	340.81	0	340.81	0	340.81
10	0	340.81	0	340.81	0	340.81
20	0	340.81	0	340.81	0	340.81
50	1	340.81	0	340.81	0	340.81
100	2	340.81	2	340.81	1	340.81
200	8	340.81	6	340.81	5	340.81
500	42	340.82	33	340.82	26	340.81
1000	118	340.83	95	340.83	75	340.82
2000	240	340.85	209	340.85	175	340.84
5000	356	340.87	342	340.87	324	340.86
10K	384	340.87	380	340.87	374	340.87
20K	391	340.88	390	340.88	389	340.88
50K	394	340.88	393	340.88	393	340.88
100K	394	340.88	394	340.88	394	340.88
Uncertainty $\delta W/W$ (%)		0.92		0.92		0.92

TABLE 16.204 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	273.15		273.15		273.15	
Humidity						
RH, h_r (%)	0		50		100	
Mole fraction x_h	0		0.000044		0.000088	
Enhancement factor f_e	1.45325		1.45325		1.45325	
Corrections						
Specific heat K_C (ppm)	462		461		461	
Virial K_V (ppm)	105869		105856		105844	
Simple sound speed W_s (m/s)	331.32		331.32		331.33	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	348.50	0	348.50	0	348.50
10	0	348.50	0	348.50	0	348.50
20	0	348.50	0	348.50	0	348.50
50	1	348.50	0	348.50	0	348.50
100	2	348.50	1	348.50	1	348.50
200	9	348.50	5	348.50	4	348.50
500	47	348.51	29	348.50	19	348.50
1000	134	348.52	86	348.51	57	348.51
2000	286	348.55	203	348.54	138	348.52
5000	449	348.58	400	348.57	329	348.56
10K	492	348.59	475	348.58	445	348.58
20K	504	348.59	500	348.59	491	348.59
50K	508	348.59	507	348.59	505	348.59
100K	508	348.59	508	348.59	508	348.59
Uncertainty $\delta W/W$ (%)		0.83		0.83		0.83

TABLE 16.205 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	283.15		283.15		283.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000034		0.000068	
Enhancement factor f_e	1.40920		1.40920		1.40920	
Corrections						
Specific heat K_C (ppm)	316		316		316	
Virial K_V (ppm)	112248		112238		112228	
Simple sound speed W_s (m/s)	337.33		337.33		337.34	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	355.82	0	355.82	0	355.82
10	0	355.82	0	355.82	0	355.82
20	0	355.82	0	355.82	0	355.82
50	1	355.82	0	355.82	0	355.82
100	2	355.82	2	355.82	1	355.82
200	10	355.82	7	355.82	5	355.82
500	53	355.83	37	355.82	27	355.82
1000	152	355.84	108	355.84	79	355.83
2000	333	355.88	254	355.86	190	355.85
5000	555	355.92	502	355.91	435	355.90
10K	619	355.93	601	355.92	572	355.92
20K	637	355.93	632	355.93	624	355.93
50K	643	355.93	642	355.93	641	355.93
100K	644	355.93	644	355.93	643	355.93
Uncertainty $\delta W/W$ (%)		0.75		0.75		0.75

TABLE 16.206 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100	100	100
Temperature T (K)	283.15	283.15	283.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.000102	0.000137	0.000171
Enhancement factor f_e	1.40920	1.40920	1.40920
Corrections			
Specific heat K_C (ppm)	316	315	315
Virial K_V (ppm)	112218	112208	112198
Simple sound speed W_s (m/s)	337.34	337.34	337.34

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	355.82	0	355.82	0	355.82
10	0	355.82	0	355.82	0	355.82
20	0	355.82	0	355.82	0	355.82
50	0	355.82	0	355.82	0	355.82
100	1	355.82	1	355.82	1	355.82
200	4	355.82	3	355.82	2	355.82
500	20	355.82	16	355.82	14	355.82
1000	61	355.83	50	355.83	42	355.83
2000	145	355.84	115	355.84	96	355.84
5000	362	355.88	295	355.87	240	355.86
10K	531	355.91	482	355.90	426	355.89
20K	611	355.93	592	355.92	567	355.92
50K	638	355.93	635	355.93	630	355.93
100K	643	355.93	642	355.93	640	355.93
Uncertainty $\delta W/W$ (%)		0.75		0.75		0.75

TABLE 16.207 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100	100	100
Temperature T (K)	293.15	293.15	293.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.000063	0.000127
Enhancement factor f_e	1.37166	1.37166	1.37166
Corrections			
Specific heat K_C (ppm)	142	141	141
Virial K_V (ppm)	117194	117175	117156
Simple sound speed W_s (m/s)	343.24	343.24	343.24

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	362.82	0	362.82	0	362.82
10	0	362.82	0	362.82	0	362.82
20	0	362.82	0	362.82	0	362.82
50	1	362.82	0	362.82	0	362.82
100	3	362.82	1	362.82	1	362.82
200	11	362.82	6	362.82	4	362.82
500	58	362.83	32	362.82	21	362.82
1000	170	362.85	96	362.84	64	362.83
2000	383	362.89	228	362.86	148	362.85
5000	672	362.94	526	362.91	368	362.89
10K	765	362.96	704	362.95	598	362.93
20K	793	362.96	775	362.96	737	362.95
50K	801	362.96	798	362.96	791	362.96
100K	802	362.96	801	362.96	799	362.96
Uncertainty $\delta W/W$ (%)		0.69		0.69		0.69

TABLE 16.208 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100	100	100
Temperature T (K)	293.15	293.15	293.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.000190	0.000253	0.000316
Enhancement factor f_e	1.37166	1.37166	1.37166
Corrections			
Specific heat K_C (ppm)	141	140	140
Virial K_V (ppm)	117138	117119	117100
Simple sound speed W_s (m/s)	343.25	343.25	343.25

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	362.82	0	362.82	0	362.82
10	0	362.82	0	362.82	0	362.82
20	0	362.82	0	362.82	0	362.82
50	0	362.82	0	362.82	0	362.82
100	1	362.82	0	362.82	0	362.82
200	3	362.82	2	362.82	2	362.82
500	15	362.82	12	362.82	9	362.82
1000	47	362.83	38	362.83	31	362.83
2000	110	362.84	90	362.84	77	362.84
5000	259	362.87	195	362.86	160	362.85
10K	472	362.91	362	362.89	282	362.87
20K	673	362.94	589	362.93	499	362.91
50K	778	362.96	756	362.96	724	362.95
100K	796	362.96	790	362.96	781	362.96
Uncertainty $\delta W/W$ (%)		0.69		0.69		0.69

TABLE 16.209 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	303.15		303.15		303.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.000112		0.000224	
Enhancement factor f_e	1.33945		1.33945		1.33945	
Corrections						
Specific heat K_C (ppm)	−61		−62		−62	
Virial K_V (ppm)	121006		120973		120939	
Simple sound speed W_s (m/s)	349.04		349.05		349.05	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	369.55	0	369.55	0	369.55
10	0	369.55	0	369.55	0	369.55
20	0	369.55	0	369.55	0	369.55
50	1	369.55	0	369.55	0	369.55
100	3	369.55	1	369.55	1	369.55
200	12	369.55	5	369.55	3	369.55
500	64	369.56	26	369.55	16	369.55
1000	189	369.58	82	369.56	51	369.56
2000	434	369.63	191	369.58	122	369.57
5000	800	369.69	465	369.63	267	369.60
10K	930	369.72	742	369.68	484	369.64
20K	971	369.73	907	369.71	755	369.69
50K	983	369.73	972	369.73	937	369.72
100K	985	369.73	982	369.73	972	369.73
Uncertainty $\delta W/W$ (%)		0.63		0.63		0.63

TABLE 16.210 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	303.15		303.15		303.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000337		0.000449		0.000561	
Enhancement factor f_e	1.33945		1.33945		1.33945	
Corrections						
Specific heat K_C (ppm)	−63		−63		−64	
Virial K_V (ppm)	120905		120871		120836	
Simple sound speed W_s (m/s)	349.06		349.07		349.07	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	369.55	0	369.55	0	369.55
10	0	369.55	0	369.55	0	369.55
20	0	369.55	0	369.55	0	369.55
50	0	369.55	0	369.55	0	369.55
100	0	369.55	0	369.55	0	369.55
200	2	369.55	1	369.55	1	369.55
500	11	369.55	8	369.55	6	369.55
1000	36	369.56	27	369.56	21	369.56
2000	93	369.57	76	369.56	63	369.56
5000	193	369.58	162	369.58	145	369.58
10K	320	369.61	241	369.59	203	369.59
20K	563	369.65	412	369.63	316	369.61
50K	866	369.71	762	369.69	643	369.67
100K	951	369.73	914	369.72	860	369.71
Uncertainty $\delta W/W$ (%)		0.63		0.63		0.63

TABLE 16.211 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100	100	100
Temperature T (K)	313.15	313.15	313.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.000191	0.000382
Enhancement factor f_e	1.31167	1.31167	1.31167
Corrections			
Specific heat K_C (ppm)	−292	−293	−294
Virial K_V (ppm)	123913	123856	123798
Simple sound speed W_s (m/s)	354.75	354.76	354.77

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	376.04	0	376.04	0	376.04
10	0	376.04	0	376.04	0	376.04
20	0	376.04	0	376.04	0	376.04
50	1	376.04	0	376.04	0	376.04
100	3	376.04	1	376.04	0	376.04
200	12	376.04	4	376.04	2	376.04
500	69	376.05	21	376.04	11	376.04
1000	210	376.07	69	376.05	39	376.05
2000	487	376.13	165	376.07	107	376.06
5000	939	376.21	364	376.11	226	376.08
10K	1116	376.24	646	376.16	344	376.10
20K	1173	376.26	958	376.22	588	376.15
50K	1191	376.26	1146	376.25	990	376.22
100K	1193	376.26	1181	376.26	1133	376.25
Uncertainty $\delta W/W$ (%)		0.58		0.58		0.58

TABLE 16.212 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	313.15		313.15		313.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.000573		0.000764		0.000955	
Enhancement factor f_e	1.31167		1.31167		1.31167	
Corrections						
Specific heat K_C (ppm)	−295		−296		−297	
Virial K_V (ppm)	123740		123681		123622	
Simple sound speed W_s (m/s)	354.79		354.80		354.81	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	376.04	0	376.04	0	376.04
10	0	376.04	0	376.04	0	376.04
20	0	376.04	0	376.04	0	376.04
50	0	376.04	0	376.04	0	376.04
100	0	376.04	0	376.04	0	376.04
200	1	376.04	1	376.04	1	376.04
500	7	376.04	5	376.04	3	376.04
1000	25	376.05	18	376.05	13	376.05
2000	77	376.05	58	376.05	45	376.05
5000	184	376.07	160	376.07	141	376.07
10K	256	376.09	224	376.08	207	376.08
20K	380	376.11	295	376.10	258	376.09
50K	754	376.18	552	376.15	424	376.12
100K	1026	376.23	874	376.21	716	376.18
Uncertainty $\delta W/W$ (%)		0.58		0.58		0.58

TABLE 16.213 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100	100	100
Temperature T (K)	323.15	323.15	323.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.000314	0.000627
Enhancement factor f_e	1.28758	1.28758	1.28758
Corrections			
Specific heat K_C (ppm)	−551	−553	−554
Virial K_V (ppm)	126094	125999	125904
Simple sound speed W_s (m/s)	360.37	360.39	360.41

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	382.31	0	382.32	0	382.32
10	0	382.31	0	382.32	0	382.32
20	0	382.31	0	382.32	0	382.32
50	1	382.31	0	382.32	0	382.32
100	3	382.31	1	382.32	0	382.32
200	13	382.32	3	382.32	1	382.32
500	75	382.33	16	382.32	7	382.32
1000	231	382.36	56	382.33	28	382.32
2000	543	382.42	149	382.34	87	382.34
5000	1086	382.52	313	382.38	224	382.36
10K	1320	382.57	492	382.41	310	382.38
20K	1400	382.58	828	382.47	428	382.40
50K	1425	382.59	1256	382.56	817	382.47
100K	1428	382.59	1380	382.58	1171	382.54
Uncertainty $\delta W/W$ (%)		0.54		0.54		0.54

TABLE 16.214 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100	100	100
Temperature T (K)	323.15	323.15	323.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.000941	0.00125	0.00157
Enhancement factor f_e	1.28758	1.28758	1.28758
Corrections			
Specific heat K_C (ppm)	−556	−558	−559
Virial K_V (ppm)	125808	125711	125612
Simple sound speed W_s (m/s)	360.43	360.44	360.46

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	382.32	0	382.32	0	382.33
10	0	382.32	0	382.32	0	382.33
20	0	382.32	0	382.32	0	382.33
50	0	382.32	0	382.32	0	382.33
100	0	382.32	0	382.32	0	382.33
200	1	382.32	0	382.32	0	382.33
500	4	382.32	3	382.32	2	382.33
1000	16	382.32	11	382.33	8	382.33
2000	56	382.33	39	382.33	28	382.33
5000	180	382.36	146	382.35	119	382.35
10K	267	382.37	241	382.37	219	382.37
20K	331	382.38	300	382.38	283	382.38
50K	526	382.42	404	382.40	352	382.39
100K	867	382.49	632	382.44	495	382.42
Uncertainty $\delta W/W$ (%)		0.53		0.54		0.53

TABLE 16.215 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	373.15		373.15		373.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.00241		0.00482	
Enhancement factor f_e	1.20546		1.20546		1.20546	
Corrections						
Specific heat K_C (ppm)	−2253		−2272		−2290	
Virial K_V (ppm)	130071		129360		128629	
Simple sound speed W_s (m/s)	387.25		387.40		387.55	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	411.20	0	411.23	0	411.25
10	0	411.20	0	411.23	0	411.25
20	0	411.20	0	411.23	0	411.25
50	1	411.20	0	411.23	0	411.25
100	4	411.20	0	411.23	0	411.25
200	18	411.20	0	411.23	0	411.25
500	104	411.22	2	411.23	1	411.25
1000	344	411.27	8	411.23	2	411.25
2000	865	411.38	33	411.23	10	411.25
5000	1921	411.60	171	411.26	58	411.26
10K	2609	411.74	436	411.32	194	411.29
20K	2914	411.80	713	411.37	470	411.35
50K	3017	411.82	886	411.41	784	411.41
100K	3032	411.82	987	411.43	877	411.43
Uncertainty $\delta W/W$ (%)		0.44		0.44		0.44

TABLE 16.216 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100	100	100
Temperature T (K)	373.15	373.15	373.15
Humidity			
RH, h_r (%)	60	80	100
Mole fraction x_h	0.00723	0.00964	0.0121
Enhancement factor f_e	1.20546	1.20546	1.20546
Corrections			
Specific heat K_C (ppm)	−2308	−2327	−2345
Virial K_V (ppm)	127876	127101	126304
Simple sound speed W_s (m/s)	387.70	387.85	388.00

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	411.27	0	411.28	0	411.29
10	0	411.27	0	411.28	0	411.29
20	0	411.27	0	411.28	0	411.29
50	0	411.27	0	411.28	0	411.29
100	0	411.27	0	411.28	0	411.29
200	0	411.27	0	411.28	0	411.29
500	0	411.27	0	411.28	0	411.29
1000	1	411.27	1	411.28	0	411.29
2000	5	411.27	3	411.28	2	411.29
5000	28	411.27	16	411.29	11	411.30
10K	102	411.29	62	411.30	41	411.30
20K	305	411.33	205	411.32	145	411.32
50K	682	411.41	580	411.40	487	411.39
100K	832	411.44	786	411.44	736	411.44
Uncertainty $\delta W/W$ (%)		0.43		0.43		0.43

TABLE 16.217 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	423.15		423.15		423.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.0109		0.0218	
Enhancement factor f_e	1.16121		1.16121		1.16121	
Corrections						
Specific heat K_C (ppm)	−4607		−4713		−4818	
Virial K_V (ppm)	128176		125068		121756	
Simple sound speed W_s (m/s)	412.38		413.10		413.83	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	437.00	0	437.14	0	437.25
10	0	437.00	0	437.14	0	437.25
20	0	437.00	0	437.14	0	437.25
50	1	437.00	0	437.14	0	437.25
100	5	437.00	0	437.14	0	437.25
200	21	437.01	0	437.14	0	437.25
500	128	437.03	0	437.14	0	437.25
1000	448	437.10	1	437.14	0	437.25
2000	1231	437.27	4	437.14	1	437.25
5000	2888	437.63	24	437.15	6	437.25
10K	4224	437.92	92	437.16	24	437.25
20K	5006	438.09	322	437.21	94	437.27
50K	5315	438.16	1086	437.38	470	437.35
100K	5363	438.17	1643	437.50	1091	437.49
Uncertainty $\delta W/W$ (%)		0.41		0.41		0.40

TABLE 16.218 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	423.15		423.15		423.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.0327		0.0437		0.0546	
Enhancement factor f_e	1.16121		1.16121		1.16121	
Corrections						
Specific heat K_C (ppm)	−4922		−5025		−5127	
Virial K_V (ppm)	118228		114468		110465	
Simple sound speed W_s (m/s)	414.57		415.31		416.06	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	437.31	0	437.33	0	437.31
10	0	437.31	0	437.33	0	437.31
20	0	437.31	0	437.33	0	437.31
50	0	437.31	0	437.33	0	437.31
100	0	437.31	0	437.33	0	437.31
200	0	437.31	0	437.33	0	437.31
500	0	437.31	0	437.33	0	437.31
1000	0	437.31	0	437.33	0	437.31
2000	0	437.31	0	437.33	0	437.31
5000	3	437.31	2	437.33	1	437.31
10K	11	437.31	6	437.34	4	437.31
20K	43	437.32	24	437.34	15	437.31
50K	241	437.36	142	437.36	92	437.33
100K	700	437.46	464	437.44	322	437.38
Uncertainty $\delta W/W$ (%)		0.39		0.38		0.37

TABLE 16.219 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100	100	100
Temperature T (K)	473.15	473.15	473.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.0351	0.0701
Enhancement factor f_e	1.13639	1.13639	1.13639
Corrections			
Specific heat K_C (ppm)	−7566	−7969	−8360
Virial K_V (ppm)	124023	114367	103574
Simple sound speed W_s (m/s)	436.06	438.54	441.08

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	460.56	0	461.09	0	461.42
10	0	460.56	0	461.09	0	461.42
20	0	460.56	0	461.09	0	461.42
50	1	460.56	0	461.09	0	461.42
100	6	460.56	0	461.09	0	461.42
200	24	460.57	0	461.09	0	461.42
500	143	460.59	0	461.09	0	461.42
1000	523	460.68	0	461.09	0	461.42
2000	1569	460.92	1	461.09	0	461.42
5000	3967	461.47	4	461.10	1	461.42
10K	6003	461.94	15	461.10	4	461.42
20K	7511	462.29	59	461.11	14	461.43
50K	8227	462.45	340	461.17	88	461.44
100K	8349	462.48	1052	461.34	327	461.50
Uncertainty $\delta W/W$ (%)		0.39		0.37		0.34

TABLE 16.220 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	473.15		473.15		473.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.105		0.140		0.175	
Enhancement factor f_e	1.13639		1.13639		1.13639	
Corrections						
Specific heat K_C (ppm)	−8740		−9110		−9469	
Virial K_V (ppm)	91517		78062		63069	
Simple sound speed W_s (m/s)	443.69		446.35		449.08	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	461.51	0	461.33	0	460.83
10	0	461.51	0	461.33	0	460.83
20	0	461.51	0	461.33	0	460.83
50	0	461.51	0	461.33	0	460.83
100	0	461.51	0	461.33	0	460.83
200	0	461.51	0	461.33	0	460.83
500	0	461.51	0	461.33	0	460.83
1000	0	461.51	0	461.33	0	460.83
2000	0	461.51	0	461.33	0	460.83
5000	0	461.51	0	461.33	0	460.83
10K	2	461.51	1	461.33	0	460.83
20K	6	461.52	3	461.33	2	460.83
50K	38	461.52	20	461.33	12	460.83
100K	147	461.55	80	461.35	49	460.84
Uncertainty $\delta W/W$ (%)		0.31		0.28		0.26

TABLE 16.221 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	523.15		523.15		523.15	
Humidity						
RH, h_r (%)	0		20		40	
Mole fraction x_h	0		0.090		0.179	
Enhancement factor f_e	1.12240		1.12240		1.12240	
Corrections						
Specific heat K_C (ppm)	−11077		−12219		−13278	
Virial K_V (ppm)	119056		95086		66753	
Simple sound speed W_s (m/s)	458.52		465.32		472.55	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	482.36	0	483.96	0	484.82
10	0	482.36	0	483.96	0	484.82
20	0	482.36	0	483.96	0	484.82
50	2	482.36	0	483.96	0	484.82
100	6	482.36	0	483.96	0	484.82
200	25	482.36	0	483.96	0	484.82
500	151	482.39	0	483.96	0	484.82
1000	566	482.49	0	483.96	0	484.82
2000	1820	482.80	0	483.96	0	484.82
5000	5085	483.58	1	483.96	0	484.82
10K	7848	484.25	3	483.96	1	484.82
20K	10207	484.81	12	483.96	3	484.82
50K	11577	485.14	74	483.98	16	484.82
100K	11832	485.20	285	484.03	65	484.83
Uncertainty $\delta W/W$ (%)		0.37		0.32		0.25

TABLE 16.222 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	523.15		523.15		523.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.269		0.359		0.448	
Enhancement factor f_e	1.12240		1.12240		1.12240	
Corrections						
Specific heat K_C (ppm)	−14259		−15170		−16015	
Virial K_V (ppm)	33177		−6628		−53759	
Simple sound speed W_s (m/s)	480.25		488.44		497.20	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	484.65	0	483.12	0	479.76
10	0	484.65	0	483.12	0	479.76
20	0	484.65	0	483.12	0	479.76
50	0	484.65	0	483.12	0	479.76
100	0	484.65	0	483.12	0	479.76
200	0	484.65	0	483.12	0	479.76
500	0	484.65	0	483.12	0	479.76
1000	0	484.65	0	483.12	0	479.76
2000	0	484.65	0	483.12	0	479.76
5000	0	484.65	0	483.12	0	479.76
10K	0	484.65	0	483.12	0	479.76
20K	1	484.65	0	483.12	0	479.76
50K	6	484.66	3	483.12	2	479.76
100K	25	484.66	12	483.12	6	479.76
Uncertainty $\delta W/W$ (%)		0.27		0.31		0.42

TABLE 16.223 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100	100	100
Temperature T (K)	573.15	573.15	573.15
Humidity			
RH, h_r (%)	0	20	40
Mole fraction x_h	0	0.197	0.395
Enhancement factor f_e	1.11480	1.11480	1.11480
Corrections			
Specific heat K_C (ppm)	−15083	−17679	−19862
Virial K_V (ppm)	113899	62801	−1524
Simple sound speed W_s (m/s)	479.94	496.19	514.85

Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	502.70	0	506.99	0	509.32
10	0	502.70	0	506.99	0	509.32
20	0	502.70	0	506.99	0	509.32
50	2	502.70	0	506.99	0	509.32
100	6	502.70	0	506.99	0	509.32
200	25	502.70	0	506.99	0	509.32
500	152	502.74	0	506.99	0	509.32
1000	581	502.84	0	506.99	0	509.32
2000	1967	503.19	0	506.99	0	509.32
5000	6115	504.23	0	506.99	0	509.32
10K	9690	505.13	1	506.99	0	509.32
20K	12897	505.93	3	506.99	0	509.32
50K	15144	506.49	17	507.00	3	509.32
100K	15613	506.61	67	507.01	12	509.32
Uncertainty $\delta W/W$ (%)		0.35		0.27		0.25

TABLE 16.224 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	573.15		573.15		573.15	
Humidity						
RH, h_r (%)	60		80		100	
Mole fraction x_h	0.592		0.789		0.987	
Enhancement factor f_e	1.11480		1.11480		1.11480	
Corrections						
Specific heat K_C (ppm)	−21702		−23252		−24558	
Virial K_V (ppm)	−83968		−190340		−327364	
Simple sound speed W_s (m/s)	536.43		561.69		591.64	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	507.82	0	499.50	0	479.23
10	0	507.82	0	499.50	0	479.23
20	0	507.82	0	499.50	0	479.23
50	0	507.82	0	499.50	0	479.23
100	0	507.82	0	499.50	0	479.23
200	0	507.82	0	499.50	0	479.23
500	0	507.82	0	499.50	0	479.23
1000	0	507.82	0	499.50	0	479.23
2000	0	507.82	0	499.50	0	479.23
5000	0	507.82	0	499.50	0	479.23
10K	0	507.82	0	499.50	0	479.23
20K	0	507.82	0	499.50	0	479.23
50K	1	507.82	0	499.50	0	479.23
100K	3	507.82	1	499.50	0	479.23
Uncertainty $\delta W/W$ (%)		0.64		1.03		2.53

TABLE 16.225 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	603.15		603.15		603.15	
Humidity						
RH, h_r (%)	0		15		30	
Mole fraction x_h	0		0.226		0.452	
Enhancement factor f_e	1.11223		1.11223		1.11223	
Corrections						
Specific heat K_C (ppm)	−17700		−20708		−23165	
Virial K_V (ppm)	110841		55458		−11810	
Simple sound speed W_s (m/s)	492.34		511.61		534.20	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	514.29	0	520.13	0	524.85
10	0	514.29	0	520.13	0	524.85
20	0	514.29	0	520.13	0	524.85
50	2	514.29	0	520.13	0	524.85
100	6	514.29	0	520.13	0	524.85
200	24	514.30	0	520.13	0	524.85
500	151	514.33	0	520.13	0	524.85
1000	579	514.44	0	520.13	0	524.85
2000	2008	514.81	0	520.13	0	524.85
5000	6641	516.00	0	520.13	0	524.85
10K	10759	517.05	1	520.13	0	524.85
20K	14448	517.99	2	520.13	0	524.85
50K	17296	518.72	14	520.14	2	524.85
100K	17938	518.88	55	520.15	9	524.85
Uncertainty $\delta W/W$ (%)		0.34		0.28		0.32

TABLE 16.226 Predicted Speed of Sound in Air and Uncertainty

Pressure P (atm)	100		100		100	
Temperature T (K)	603.15		603.15		603.15	
Humidity						
RH, h_r (%)	50		60		65	
Mole fraction x_h	0.753		0.903		0.978	
Enhancement factor f_e	1.11223		1.11223		1.11223	
Corrections						
Specific heat K_C (ppm)	−25760		−26818		−27296	
Virial K_V (ppm)	−128397		−202004		−243460	
Simple sound speed W_s (m/s)	571.07		593.27		605.54	
Frequency (Hz)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)	Relaxation correction K_r (ppm)	Real sound speed W (m/s)
0	0	526.23	0	522.81	0	519.46
10	0	526.23	0	522.81	0	519.46
20	0	526.23	0	522.81	0	519.46
50	0	526.23	0	522.81	0	519.46
100	0	526.23	0	522.81	0	519.46
200	0	526.23	0	522.81	0	519.46
500	0	526.23	0	522.81	0	519.46
1000	0	526.23	0	522.81	0	519.46
2000	0	526.23	0	522.81	0	519.46
5000	0	526.23	0	522.81	0	519.46
10K	0	526.23	0	522.81	0	519.46
20K	0	526.23	0	522.81	0	519.46
50K	0	526.23	0	522.81	0	519.46
100K	1	526.24	0	522.81	0	519.46
Uncertainty $\delta W/W$ (%)		0.66		0.96		1.35

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CHAPTER 17

Air Sound Speed Measurements and Computation: A Historical Review

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17.1 INTRODUCTION

The speed of sound has attracted the attention of human curiosity since the dawn of science. In 1636 Mersenne performed one of the earliest quantitative measurements of sound speed in air [1]. He used gunfire and musical instruments as sound sources to estimate the sound speed as 448 m/s. He was the first to utilize cannon flash observations and to note the time arrival of the sound as a means of range finding. Borelli and Viviani [2] and Boyle [3] concluded that Mersenne's sound speed was too high and repeated the measurements, obtaining values of 361 m/s and 366 m/s, respectively. Derham utilized guns fired from various church towers and observed the flashes from distances up to 20.1 km (12.5 miles) and timed the intervals with a pendulum beating half seconds [4]. He reconfirmed the experimental results of 348 m/s obtained by Flamsteed and Halley (see Derham[4]), who measured the time taken to travel a distance of 4.7 km (3 miles). Derham also concluded that favorable winds increased sound speed, and vice versa [4]. None of these investigators measured temperature during their experiments, since the information on the mercury-in-glass thermometer Fahrenheit [5] and the Celsius [6] scales had not been established. Cassini made measurements

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over a distance of approximately 28 km with cannons and pendulum clocks and performed the experiments at night under stable meteorological conditions [7]. With reciprocal firing of the cannons at either end of the baseline to minimize wind effects, he arrived at a sound speed of 337 m/s. Cassini was the first to state that the wind speed had to be added or subtracted from the measured sound speed depending on whether the wind was favorable or against the direction of sound propagation. Bianconi conducted a quantitative study of the influence of temperature [8] on sound speed. He compared sound speeds measured in the winter and in summer and correctly concluded that sound speed increases with temperature. In 1822 a definitive determination of sound speed was commissioned by the Bureau des Longitudes [9]. Reciprocal firing of cannons and accurate chronometers were used to measure sound speed over an accurately surveyed distance of 18.6223 km. The report arrived at a sound speed of 340.9 m/s at approximately 16 °C, or W_o of 331.2 m/s at 0 °C. Other conditions related to sound propagation such as attenuation, refraction due to wind and temperature gradients, scattering and fluctuations due to turbulences, and ground conditions were discussed by Delany [10].

17.2 THEORETICAL CONSIDERATIONS

In order to have a better understanding of sound speed assessment methods it is necessary to consider the theoretical aspects of sound speed in air. According to Laplace's adiabatic assumption for an ideal gas, the sound speed [11–13] is given by

$$W = (\gamma P/\rho)^{1/2} \tag{17.1}$$

where γ, P, and ρ are the specific heat ratio, pressure, and density of the medium, respectively.

From the ideal-gas equation resulting from Boyle's law, Eq. (17.1) is modified to

$$W = (RT\gamma/M)^{1/2} \tag{17.2}$$

where R, T, and M are the universal gas constant, absolute temperature (in degrees Kelvin), and molar mass, respectively. One can see from Eq. (17.2) that γ is an important factor in sound speed computations and measurements.

17.3 SOUND SPEED DETERMINATION METHODS

Beginning in 1800, new techniques for sound speed measurement were developed. The method of coincidences was based on transmitting a tapping sound at regular known intervals and adjusting the distance of the source from a reflecting wall until the reflected sound was delayed by a time interval exactly equal to a multiple of the interval between the pulses, such that the reflected sound was exactly coincident with that from the source. The electronic version of this method [14–16] was used by Lenihan, who arrived at a sound speed of 331.45 m/s [17]. Measurements in pipes were performed by Regnault [18]. Because sound speed in pipes is lower than that in free space, he used pipes of various diameters and extrapolated to the free-air conditions, obtaining a sound speed for dry air W_o of 330.7 m/s.

In recent years, more precise methods for determining thermodynamic properties [19, 20] and sound speed [21–23] in gases have been developed. Sound speed has been measured with a fixed-path-length cavity (a resonator) [21]. The frequency of the oscillator that drives an exciter is adjusted for maximum received amplitude from the receiver, which occurs at cavity resonance with an integral of half-wavelengths in the cavity. The sound speed is computed from the resonance frequencies, the number of halve-wavelengths, and the dimensions of the cavity. For the spherical resonator method, the uncertainty in the measurement of the speed of sound in a gas is estimated as 200 ppm [21], and if the volume of the resonator is known precisely, the uncertainty may approach 5 ppm.

The direct method of sound speed assessment is generally divided into three groups: (a) relatively long distance unbounded (open-air) measurements, (b) short-distance measurements in laboratories, and (c) measurements in tubes or resonating spheres. Indirect methods include derivation of the sound speed from knowledge of γ together with an equation of state [24], and computation based on virial information on the air constituents [25].

Some of the investigators of sound speed are listed in Table 17.1. Due to the improvement of instrumentation with time and the advent of electronics it is reasonable to begin the list with the year 1919 and to discuss in more detail those investigators (marked with an asterisk in the table) who arrived at values of W_o that were relatively close to a previous estimate of $W_o = 331.45$ m/s. Several related investigations are included in the discussion, and some sound speed investigations are excluded due to the relatively large uncertainty in their reported results.*

17.3.1 AIR COMPOSITION AND DISPERSION

The composition of the air supply plays an important part in the determination of sound speed. With the exception of a few, most investigators on sound speed did not give information on the composition of their air supply.

Hebb performed his measurements indoors and gave the percentage volumes of his air constituents following: 97.2 for oxygen and nitrogen, 1.85 for water vapor, and 0.95 for argon. He gave no information on how these percentages were obtained [26].

*Unless otherwise stated, all uncertainty statements are assumed to be one standard deviation given by the respective authors at the time of their publications.

TABLE 17.1 **Some Reported Sound Speed Investigations Since 1919**

Date	Investigator	Sound speed W_o (m/s)	Distance or or length (units as indicated)	Source or Frequency kHz	Method used comments, and notes[a]	Ref.
1919	Esclangon	330.9	1.4–14 km	Cannon	Open air, c1, p, t, h.	65
1919	*Hebb	331.41	80–100 ft	1.3–3.1	Indoor reflector, c2, t.	26
1921	Dixon et al.	331.8	0.16 m	Hammer pulse	Tubes, c1, p, t, h, tb.	72
1921	Grüneisen & Merkel	331.57	0.23–0.95 m	Up to 11	Tubes, c1, tb, p, h, t_0.	73
1921	Angerer and Landenburg	330.78	Approx. 11 km	Explosion	Open air, cl, t, p.	66
1923	McAdie	331.79	Inclined direction	Steam whistle	c1, t, p.	74
1925	Pierce	331.69	Approx. 0.01 m	206	Interferometer, 84% RH, c1, p.	45
1928	*Shilling and Partington	331.4	Approx. 1 m	Approx. 3	Tube, t, c2, R.	27
1928	*Cornish and Eastman	331.41	1.68 m	Approx. 0.1	Tube, c2, R, tb	29
1930	Reid	331.60	0.45 m	40–216	Interferometer in chamber, c2, p.	75
1933	Kaye and Sherratt	331.6	0.6 m	0.79–7.9	Tubes, c2, p, t, tb.	76
1933	Grabau	331.68	0.55 m	20–70	Indoor interferometer, c2, p.	43
1935	Norton	331.78	10–40 λ	5–120	Tubes, c2, p, h, tb.	62
1937	*Miller	331.36	7243–20 312 ft	Cannon	Open air, c1, t, R.	30
1937	Warner	330.3 to 331.6	Approx. 0.08 m	38.6–104.5	Tube, c1, p, h, tb.	77
1938	Colwell et al.	331.54	5–6 m	Pulses, 0.06	Indoor interferometer, c1, p, t, h.	78
1938	Kukkamäki	330.8	1–1.3 km	Explosion	Open air, c1, p, t.	79

1939	*Pielemeier	331.4 to 331.6	0.08 m estimated	Up to 1080	Interferometer, CO_2, and H_2O were variables, c2, R, t.	44
1942	*Hardy et al.	331.44	0.07–0.08 m	300–1100	Interferometer in chamber, c2, p, R, t_0.	31
1944	Itterbeek and Vandoninck	331.9	0.1 m estimated	523.78	Interferometer, c2, tb, R.	51
1946	Stewart	331.7	1 mm	3885	Interferometer, c2, p, t.	80
1948	*Abbey and Barlow	331.4	1.0 m	1.0	Tube, c2, p, t, tb.	32
1952	*Lenihan	331.45	Approx. 1.5 m	13.5	Indoor, c2, p, R.	17
1952	Ener et al.	331.52	1 mm	Approx. 2000	Interferometer, c2, p.	47
1953	*Smith	331.45	Approx. 0.17 m	1.0	Tube, c2, p, tb, R.	37
1954	*Harlow	331.45	1.85 m	1–1.5	Tube, c2, p.	42
1956	Bancroft	331.7 and 331.87	9-in.-diam sphere	2.12 and 3.65	Radial oscillator; air saturated with water vapor, c1, p, t, t_0.	81
1956	Itterbeek and Rop	330.92 to 331.65	0.1 m	Approx. 525	Interferometer, c2.	55
1957	*Lee	331.46	Approx. 1.6 m	0.11–1.0	Tube, c2, p.	41
1959	Steel	331.49	Approx. 1.7 m	0.45–1.2	Tube, c2.	61
1959	Hovi	331.15 to 331.65	Approx. 2 m	1.25–2	Tube, c2, p, tb.	48
1960	*Smith and Wintle	331.45	1.75 m	0.08–1.5	Tube, c2, p, t, tb.	38
1963	Lestz	331.49	<30 in.	2.5 and 4.3	Tube, c2, p, t.	39
1963	*Smith and Harlow	331.45	1.85 m	0.09–1.5	Tube, c2, p.	40

(continues)

TABLE 17.1 (*continued*)

Date	Investigator	Sound speed W_o (m/s)	Distance or or length (units as indicated)	Source or Frequency kHz	Method used comments, and notes[a]	Ref.
1985	Wong	331.29	Indirect method, based on the equation of state and known γ and M for the standard atmosphere			24
1993	*Cramer	331.46	Indirect method based on viral coefficients for the constituents of air.			25

[a]*Notes*: Unless otherwise stated, W_o represents sound speed for 0 °C dry air, at a pressure of 101.325 kPa. Investigator names marked with an asterisk reported their W_o that were relatively close to the previous value of 331.45 m/s; and some of their possible uncertainties were discussed in the text. Part of this table was reproduced from J. Acoust. Soc. Am. 79(5) (1986).

c1: Air composition not considered.
c2: Nonstandard air composition; with CO_2 removed, or with a relatively large uncertainty in composition.
p: Pressure was not measured, or without uncertainty specification.
t: Temperature uncertainty $\geq$ 0.1 °C, or without uncertainty specification.
h: No humidity measurement, or without specification on humidity.
tb: Uncertainty in tube correction, or without uncertainty specification.
R: Calculation or correction based on constants with old numerical values.
RH: Relative humidity.
t_0: W_o is obtained from sound speed determined at 0 °C without temperature reduction.

Shilling and Partington [27] performed their measurements in tubes, but they did not elaborate on the composition of their air supply, except that the authors in a description of their apparatus called their dry CO_2-free air "pure air" [28]; their sound speed, quoted in Table 17.1, was meant for CO_2-free air. It can be shown [24] that a correction of 0.032 m/s should be subtracted from their quoted W_o in order to compensate for the lack of CO_2.

Cornish and Eastman also performed their experiments in tubes, and their air supply was stored in cylinders with a compressor system. Again, their sound speed, quoted in Table 17.1, is applicable to air with CO_2 removed [29].

Miller performed his experiments over relatively longer ranges in an artillery proving ground [30]. He made relatively complete meteorological observations during his experiments and assumed his air composition to contain 300 ppm of CO_2 [30]. After correcting for environmental conditions, he obtained a value of $W_o = 331.36 \pm 0.08$ m/s [30].

Some of the previous sound speed corrections for W_o had relied mainly on the data of Hardy et al., whose air supply for their experiments was from "a light breeze of fresh outdoor air from a nearby window" [31]. The authors pointed out that the oxygen–nitrogen composition variation alone might cause deviations in the measured sound speed of 170 ppm [31], and this was not included in the uncertainty of the ± 150 ppm quoted for their sound speed W_o. In the same investigation the authors confirmed that an increase in atmospheric pressure could result in a reduction of the air density. Their explanation was that when a high-pressure area came in, it brought with it air from higher altitudes, which was richer in the lighter nitrogen components [31]. By examining their experimental results, one can observe that their measured sound speeds were relatively higher and lower when the barometric pressure was rising and falling, respectively [31]. The authors removed CO_2 from their air supply and subtracted 0.018 m/s from the sound speed to correct for the lack of CO_2 [31]. It can be shown [24] that the correction should be 0.032 m/s. The difference in the authors' CO_2 corrections alone resulted in a higher sound speed by approximately 40 ppm.

Abbey and Barlow [32] mentioned the discrepancy in sound speed due to the variation of composition and repeated the citation on composition and corrections originated by Hardy et al. [31]. The authors removed CO_2 and H_2 from their air supply [32] but did not confirm whether their results were corrected for the deviation of the air supply from the standard air [33–36] composition (see Table 17.2).

Lenihan experimented indoors [17]. The CO_2 content of his air was measured to be 0.035%, and he assumed his atmospheric percentage composition to be 78.04 nitrogen, 20.99 oxygen, 0.94 argon, and 0.03 CO_2 [17].

Smith used "compressed out-of door air" in a cylinder for his experiments [37]. He removed the water vapor and measured the CO_2 content. His measured sound

TABLE 17.2 The Constituents of the Standard Atmosphere As Indicated in ISO 2522-1975 (E), for Dry Clean Air Composition Near Sea Level[a]

Constituent	Concentration	Molar mass (kg/kmol)
Nitrogen (N_2)	78.084%	28.013 4
Oxygen (O_2)	20.947 6%	31.998 8
Argon (Ar)	0.934%	39.948
Carbon dioxide (CO_2)	314 ppm	44.009 95
Neon (Ne)	18.18 ppm	20.183
Krypton (Kr)	1.14 ppm	83.80
Methane (CH_4)	2 ppm	16.043 03
Helium (He)	5.24 ppm	4.002 6
Nitrogen monoxide (N_2O)	0.27 ppm	44.0128
Xenon (Xe)	0.087 ppm	131.30
Carbon monoxide (CO)	0.19 ppm	28.01
Hydrogen (H_2)	0.5 ppm	2.015 94
The following constituents may undergo significant variations from time to time or from place to place.		
Sulfur dioxide (SO_2)	up to 1 ppm	64.062 8
Ozone (O_3) in summer	up to 0.07 ppm	47.998 2
in winter	up to 0.02 ppm	47.998 2
Nitrogen dioxide (NO_2)	up to 0.02 ppm	46.005 5
Iodine (I_2)	up to 0.01 ppm	253.808 8

Source: Reproduced here with permission from the International Organization of Standards (ISO), Geneva, Switzerland.
[a]See Refs. 33 and 34.

speed was corrected for the difference between the measured CO_2 content and his standard volumetric amount of 0.03% [37]. The author did not indicate the measured value of his CO_2 content, but he applied other environmental corrections to his sound speed based on calculations similar to those used by Hardy et al. [31]. The latter, as pointed out earlier, applied too small a correction for CO_2 content, which resulted in a higher sound speed. In the same investigation, Smith did not elaborate on his air composition, except with the statement: ''their usual proportion at sea level'' [37].

The air supply used by Smith and Wintle was taken from their laboratory and was treated to remove carbon dioxide and moisture [38]. The authors did not discuss the composition of their air supply [38].

Similarly, Lestz gave no information on the constituents of the air supply, except that the air was dried out and the CO_2 removed [39].

The air used by Smith and Harlow [40], Lee [41] and Harlow [42] was drawn from outside the building, cleaned, deprived of CO_2, and dried; however, no information was given on the constituents.

A sample of Grabau's air taken in a closed room was confirmed to contain 0.25% CO_2, and he found it necessary to add 0.27 m/s to his sound speed [43]. It can be shown [24] that his CO_2 correction should have been 0.22 m/s.

Pielemeier pointed out that for laboratory methods of sound speed measurements, the CO_2 content might approach 1% and the dispersion (frequency dependence of sound speed) due to CO_2 content plus small changes in H_2O concentration might be responsible for some of the apparent discordant sound speed values at high frequencies. The failure to remove all the water vapor could yield a W_o that is too high, even if there were no dispersion [44].

Pierce [45] reported dispersion at high frequencies for air; the sound speed increased with frequency up to 50 kHz and then decreased to a minimum at approximately 200 kHz (author's Fig. 13); however, for dry air Bömmel observed no dispersion at three frequencies: 951, 2853, and 4755 kHz [46], and Ener et al. observed that for CO_2 free dry air, dispersion began at 30 MHz/atm [47].

Hovi observed that with dry CO_2-free air used in his tube method, the sound speed increased slightly with increasing frequency. At a temperature of 1.9 °C, he obtained sound speeds of 332.3 m/s ($W_o = 331.15$ m/s) and 332.8 m/s ($W_o = 331.65$ m/s) at frequencies of 1250 Hz and 2000 Hz, respectively. The uncertainty of the sound speed measured with the author's apparatus was given as 1000 ppm [48], which could account for the difference of 0.5 m/s at these frequencies.

Several sound speed investigations employed liquid air traps and phosphorous pentoxide to remove water vapor and carbon dioxide from their air supplies. Lee pointed out that the air supply after treatment appeared to be slightly deficient in oxygen, and as a precaution, the phosphorus pentoxide was later replaced with silica gel [41]. Similarly, Cornish and Eastman confirmed that air purified by a liquid air trap had a greater concentration of nitrogen [29]. Because sound travels faster in nitrogen than in oxygen, it would appear that the measured sound speed for air would be higher at a greater concentration of nitrogen. Some of those investigators marked with an asterisk in Table 17.1 who used phosphorous pentoxide in their air purifying system were Abbey and Barlow [32]; Smith and Wintle [38]; Harlow [42]; and Hardy et al. [31]. The latter investigators also employed a liquid air trap.

In general, the percentage volumes of the major constituents in outdoor air remained relatively constant over the years [49, 50]. Glueckauf confirmed that for dry air the uncertainties of the major constituents, nitrogen, oxygen, and argon, were ±0.004, ±0.002, and ±0.001% by volume, respectively [50, 49], and he did not indicate whether the atmospheric pressure conditions were steady when the air samples were taken; however, one must realize that the percentage of the constituents varies significantly with the content of water vapor [35, 36] and CO_2. For example, Humphreys quoted the annual average values (in percent) of the major constituents at the equator as 75.99 nitrogen, 20.44 oxygen, 0.92 argon, 2.63 water vapor, and 0.02 carbon dioxide [51]. Paneth stated that even in open air, the CO_2 content varied between the limits 0.021% and 0.044% [52].

17.3.2 Barometric Pressure and Length Units

The barometric pressure P is usually measured as a function of the height z of a column of mercury, which has a density ρ, as follows:

$$P = \rho g z \tag{17.3}$$

where g is the acceleration due to gravity. One has to assume that the upper surface of the column is subjected to a vacuum. The present standard atmospheric pressure, $P_o = 101.325$ kPa, is derived from $z = 0.76$ m, $\rho = 13\,595.1$ kg/m^3, and the standard value for $g = 9.806\,65$ m/s^2; however, the latter varies with the latitude of the location and with time. For example, in 1926 the values of g at Washington and at Paris were 9.800 95 and 9.809 43 m/s^2, respectively; the difference was approximately 865 ppm [53]. In 1971, the corresponding values were 9.801 042 9 and 9.809 259 7 m/s^2, respectively; the difference was approximately 838 ppm [54].

The observed day-to-day variation of P can be up to several kilopascals. Humphreys gave an example: even for the same day, the pressure readings could vary between 101.5 and 101.3 kPa (761.3 and 759.8 mm) at a Washington location [51].

Most of the authors on direct sound speed measurements (listed in Table 17.1) did not mention explicitly that barometric pressures were measured during their experiments. For example, Hovi cited that the air pressure during the investigations was ''very near to one atmosphere'' [48]; however, there were two exceptions: Miller [30] and Hardy et al. [31] discussed the variation of g with the latitudes of their respective locations, and they cited the resolution of their pressure measurements as 0.1 and 1 mm of mercury, respectively.

Van Itterbeek and Rop, and Hodge confirmed experimentally that at room temperatures the sound speed increased with pressure at a rate of approximately 0.001 m/s per kilopascal [55, 56]. (In both cases, the rate was deducted from the slopes of the curves.) However, at relatively low temperatures, Van Itterbeek and Vandoninck showed that at temperatures from 90.1 K to 79.15 K the sound speed decreased with the increase in air pressure at a rate of approximately 0.03 m/s per kilopascal [57].

The International Critical Tables in 1926 pointed out that the British atmosphere was based on 30 in. instead of 760 mm of mercury [53]. Before the adoption of the international units [58], the conversion relationships among the English-speaking countries were: 1 in. (United States) = 25.400 050 8 mm, 1 in. (Britain) = 25.399 956 mm, and 1 in. (Canada) = 25.4 mm (exactly) [59]. Before the present accepted conversion relationship of 1 in. = 25.4 mm, the

British atmosphere was 2 mm of mercury higher, which was equivalent to approximately 2600 ppm in pressure.

Lenihan gave a conversion unit of 1 in. = 25.400 1 mm [17]. In view of the fact that the actual conversion units were not given by the investigators, it was decided to quote, in Table 17.1, the length units given by the corresponding investigators.

The uncertainties in length conversion units and in pressure measurements account for some of the discordance in previous sound speed assessments.

17.3.3 Temperature

The absolute temperature T_0 in degrees Kelvin is one of the major factors that determines W_o [see Eq. (17.2)]. A temperature uncertainty of 0.1 °C is equivalent to an uncertainty of approximately 180 ppm in sound speed. The International Practical Temperature Scale (IPTS) was redefined in 1927, 1948, and 1968, corresponding to t_{27}, (IPTS-27); t_{48} (IPTS-48); and t_{68} (IPTS-68), respectively. At a temperature range between 20 °C and 30 °C, a relatively popular temperature range for sound speed experiments, there was no numerical difference between t_{27} and t_{48}; however, there was a difference of −0.007 °C for $t_{68}-t_{48}$ (Ref. 60, Table 7) for the temperature range 20–30 °C, and temperature measurements obtained before 1968 were 0.007 °C higher than those obtained after that date, which could result in a slightly higher value for W_o measured.

In 1926 the recommended "ice point" cited by the International Critical Tables was $T_0 = 273.1$ K, with uncertainties of +0.15 K and −0.05 K [53]. Hardy et al. used two different absolute temperatures: (a) in their calculation of their gas correction functions, they employed a value of $T_0 = 273.13$ K; and (b) in their calculation of the specific heat at constant volume C_V, they adopted a value of $T_0 = 273.16$ K [31].

Miller documented the meteorological conditions for sound speed measurements, and the resolution of his temperature reading was 0.1 °C. This might imply an uncertainty of approximately 180 ppm in W_o due to temperature alone [30].

Most of the authors of direct sound speed investigations listed in Table 17.1 had a resolution, or an uncertainty, of 0.1 °C in their temperature assessments, except two groups of authors: (a) Smith and (b) Cornish and Eastman, and Smith and Harlow, who indicated their temperature resolutions as 0.001 °C [37], and 0.01 °C [29, 40], respectively.

17.3.4 Computation and Correction Methods

Most investigators obtained their sound speed with the direct methods and then derived theoretical corrections (which included gas imperfections) for deviations of the environment and air composition from the standard conditions (Table 17.2, and 0 °C).

Hardy et al. calculated their sound speed (for sound speed reduction) with an equation [31] that required the knowledge of the gas correction functions and the air specific heat C_V. These gas correction functions were calculated with older accepted constants (such as R), and C_V for air was based on the specific heats of the constituents obtained by statistical mechanical calculations from spectroscopic data. The referenced equation was the basis of their environmental corrections for sound speed computation [31], and the authors did not supply information on the uncertainty of their C_V. One may conclude that Hardy et al. made the assumption that their relatively complicated basic equation had no uncertainty, and the uncertainty on the sound speed was the result of the uncertainty of measurements only.

Abbey and Barlow measured the sound speed in a tube, and they did not provide any reliable information on the uncertainties of their Helmholtz–Kirchhoff tube corrections [32].

Smith also measured the sound speed in a tube. He recognized the uncertainty involved with the tube corrections, and ''it was decided to use the Helmholtz–Kirchhoff correction formula with the constant increased by 5%; at the same time an uncertainty of 5% of the correction was allowed for in the computation of the probable accuracy'' [37]. He did not elaborate on how he arrived at these decisions.

Smith and Wintle mentioned the corrections for their sound speed measurements with the Helmholtz–Kirchhoff formula without substantiation of the uncertainties of these corrections [38].

Lestz [39] also ignored the uncertainties of his Helmholtz–Kirchhoff tube corrections, and he gave no numerical information on C_V and γ, which were essential for the computation of these corrections [39].

The investigation by Smith and Harlow in a tube was somewhat different [40]. They measured the impedance of the terminated tube with a resonance method. Based on the distance between the peaks and valleys of the plotted impedance curve, the authors constructed a vector locus diagram, which enabled them to deduce the sound speed (p. 103). The authors did not elaborate on the uncertainties of their graphical method and their determination of the peak and valley locations of the impedance curve. Lee [41], Steel [61], and Harlow [42] used similar graphical methods.

It is important to note that the gas correction functions and sound speed environmental corrections developed by Hardy et al. [31] were adopted by Abbey and Barlow [32] and Lenihan [17], and a similar correction was used by Smith [37] to reduce their data to arrive at W_o.

Norton investigated high-frequency sound speed in relatively small tubes [62]. He concluded that for an individual determination of tube velocity, the total probable uncertainty is about 500 ppm, and the uncertainty of the ‘‘free-space velocity’’ is 250 ppm (p. 25).

Miller [30] obtained his sound speed correction data from the investigation by Stevens [63] and from various acoustics handbooks dated from 1909 to 1927 [30], and he did not state the uncertainties of his corrections.

17.4 GENERAL OBSERVATIONS

It was observed by Foley that from 1738 to 1919 there seemed to be a progressive decrease in the numerical value of sound speed recorded with the cannon-flash open-air method, and he suggested that it might be due to a slight change in the constitution of the atmosphere, either in the percentage volumes of the nitrogen and oxygen content, or in the CO_2 content, or with other impurities [64]. From Table 17.1, the sound speeds given by Esclangon [65] and Angerer and Ladenburg [66] may be considered as confirmation of Foley’s observation. It is unlikely that the decrease in the measured sound speed was due to a change in the content of the major constituents; however, one must not rule out the possibility of an increase in the CO_2 content, or a change in the correction methods adopted by the investigators to reduce the measured data to standard conditions.

Miller pointed out that the sound speed obtained with the direct method of measurement over long ranges was less than when measured in a laboratory, and the sound speed obtained with the tube methods was the highest [30]. These differences are most likely due to the tube correction methods or to the sound speed corrections such as the CO_2 correction discussed previously.

One may add that the sound speed obtained by investigators who utilize similar equations and correction factors are nearly identical, as is supported by the results of Hardy et al. [31], Abbey and Barlow [32], Lenihan [17], and Smith [37], shown in Table 17.1. From the preceding discussion it is reasonable to assume that the maximum possible uncertainties on the sound speeds presented by these authors are higher than their cited values of 150 ppm [31], 330–660 ppm [32], 120 ppm [17], and 150 ppm [37], respectively. Due to the CO_2 corrections adopted by some authors, the resulting sound speeds were shown to be higher; however, one cannot substantiate the effects of other corrections on previous sound speed investigations, such as the uncertainty due to ignoring the constituents of the air supply and the barometric pressure corrections. The latter may result in an increase or a decrease in the final W_o values. In view of the lack of detailed information, no attempt is made here to apply corrections to the sound speeds (shown in Table 17.1) given by previous investigators, except the reduction of sound speed values to those at 0 °C.

Contrary to the beliefs of some investigators, the outdoor environment can offer a relatively constant standard air composition [49, 50]. On a calm day over long distances, the enormous averaging effects on the environmental conditions are some of the advantages in free-air sound speed measurements. Nonetheless, proper corrections for the environmental conditions must be applied in order to arrive at a correct sound speed under the standard conditions.

17.5 UNCERTAINTIES

The uncertainty of a computation should be based on the uncertainties of the parameters used for the computation. For sound speed computation that relied on known uncertainties in the universal gas constant R, the absolute temperature T_0, the specific heat ratio γ, and the molar mass M of the air, Wong showed that the uncertainty in the computed sound speed $W_o = 331.29$ m/s was approximately 200 ppm, which corresponds to a sound speed ranging from 331.224 to 331.356 m/s [24]. Wong used the specific heat ratios of the constituents of air with documented uncertainties provided by Touloukian and Makita [67]. Therefore, it is reasonable to assume that the aforementioned uncertainty estimate is reliable.

Cramer [25] computed his sound speed $W_o = 331.46$ m/s (see Table 17.1) with virial coefficients computed from constants given by Kaye and Laby [68], Dymond and Smith [69], and the *Physics Handbook* [70]. He claimed an uncertainty of less than 300 ppm, he did not take into account the uncertainties on the computation of the virial coefficients, and he ignored the warning provided by the handbook: ‘‘It is much harder to assess the absolute accuracy of the tables in any general way. Where data from many sources are available for one substance, as in the case of most of the noble gases and for nitrogen, one usually finds discrepancies up to 1.5 cm^3/mol in B and up to 30% in C between the data from different laboratories.’’ [70], where B and C refers to the second and the third virial coefficient, respectively. A comprehensive analysis [71] concluded that Cramer’s [25] W_o sound speed has an uncertainty of at least 545 ppm, which corresponds to a sound speed ranging from 331.279 to 331.641 m/s.

In general, as discussed previously, most of the sound speed investigators listed in Table 17.1 ignored uncertainties in their air compositions, barometric pressures, length conversion units, temperatures, applied corrections, and computation methods. In spite of this, most of the investigators, including Cramer [25] arrived at sound speeds W_o that are very close to 331.45 m/s.

It is interesting to summarize, in Table 17.3, an updated list of pre-1919 sound speed measurements. Part of the data is based on a table prepared by Lenihan [17].

TABLE 17.3 **This Table is an Updated List Originally Prepared by Lenihan, Acustica, 2, 205–212 (1952)**

Date	Investigator	Place or country	Baseline (m)	Sound speed (m/s)	Temperature °C	Humidity	Method and comments
1636	Mersenne [82]	Paris	158	316			Echo method
1636	Mersenne [1]	Paris	Various	447			
1667	Accademia del Cimento [83]	Florence	1806	361			
1698	Walker [16]	Oxford	100	398			Echo method
1700	Cassini [84]	Paris	2495	356			
1708	Derham [4]	Essex	3219–20012	348			
1708	Flamsteed and Halle [85]	Greenwich	4828	358			
1738	Cassini [7]	Paris	3421–11276	334	0*		
1739	Cassini [86]	Nimes	26492–43992	338			
1744	Bianconi [87]	Bologna	25813	331	0*		
1745	Condamine [88]	Cayenne	39428	358			
1745	Condamine [89]	Quito	?	337			
1778	Kästner and Mayer [90]	Göttingen	536–1045	332	0*		
1791	Müller [91]	Göttingen	2670	338			
1810	Benzenberg [92]	Düsseldorf	4626–9072	334.0	0		
1812	Benzenberg [93]	Düsseldorf	9069	331.2	0*		
1817	Espinosa and Bauza [94]	Chile	4496–14082	354.5	0*		
1822	Arago [9]	Paris	18602	331.2	0*		
1823	Goldingham [95]	Madras	4247–9006	329.1	0	0	
1824	Moll and van Beek [96]	Utrecht	17669	332.0	0	0	

(*continues*)

TABLE 17.3 (*continued*)

Date	Investigator	Place or country	Baseline (m)	Sound speed (m/s)	Temperature °C	Humidity	Method and comments
1824	Gregory [97]	Woolwich	640–1881	330.1	0*		
1825	Parry et al. [98]	Canada	878–2636	327.3	0*		
1826	Parry and Foster [99]	Canada	3957	333.7	0*		
1828	Kendall [100]	Canada	805–1873	340.6	0*		
1845	Bravais and Martens [101]	Switzerland	9560	332.4	0	0	
1868	Regnault [102]	Paris	1447–4891	330.6	0	0	
1872	Stone [103]	Cape Town	4873	332.4	0	0	
1877	Szathmari [104]	Hungary	C	331.6	0	0	Coincidence method
1890	Greeley [105]	Canada	1279	333.3	0*		
1895	Violle [106]	France	3000	331.36	0*	0	3-m-diameter pipe
1898	Frot [107]	France	5565	330.7	0		
1905	Hebb [108]	Chicago	—	331.9	0	0	Stationary wave method

Notes:

1. Measurements were made in the open, or in laboratory under conditions approximating those of free air.
2. Most of the experiments were made by timing the sound of gunfire over a known distance; where a different method was used, this is indicated in the table.
3. The results have been recalculated, where necessary, to obtain the velocity in meters per second in dry air at °C. Where the conversion has been made from information contained in the original account of the experiment, the temperature is indicated as 0*. Where the information provided in the published account has been insufficient to allow for this recalculation, the temperature or humidity columns have been left blank.
4. In compiling the table, an accuracy of ±1 m/s was assumed for results obtained before 1800, and of ±0.1 m/s for later experiments.

17.6 CONCLUSIONS

A historical review of the computation and measurement of sound speed in air is discussed. Sound speed determination methods together with the uncertainties in the key parameters such as temperature, barometric pressure, and virial coefficients could be responsible for some of the discordance in previous sound speed assessments, and could result in much higher numbers than their stated uncertainties.

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LIST OF SYMBOLS

The equation or section where the symbol first appears or is defined is indicated in parentheses.

a_d, a_h	constant, virial *B*-coefficient of dry air, water vapor (16.31a,b)
a_{dh}	constant, virial *B*-interaction coefficient of dry air, water vapor (16.32)
$a_e(\,)$	coefficient, enhancement factor (16.13a)
$a_X(\,)$	coefficient, relaxation frequency of oxygen (16.45)
$a_N(\,)$	coefficient, relaxation frequency of nitrogen (16.47)
$a_0 \ldots a_3$	constant, ideal specific heat at constant pressure (16.25)
B	second virial coefficient of atmospheric air (16.30)
B_{dd}, B_{hh}	second virial coefficient of dry air, water vapor (16.30)
B_{dh}	second virial interaction coefficient of dry air, water vapor (16.30)
$B_{\infty d}$	high-temperature limit of B_{dd} (16.38)
b_d, b_h	constant, virial *B*-coefficient of dry air, water vapor (16.31a,b)
b_{dh}	constant, virial *B*–interaction coefficient of dry air, water vapor (16.32)
b_v	constant, virial *B*-coefficient of atmospheric air (16.59)
C	third virial coefficient of atmospheric air (16.36)
C_{ddd}, C_{hhh}	third virial coefficient of dry air, water vapor (16.36)
C_{ddh}, C_{dhh}	third virial interaction coefficient of dry air, water vapor (16.36)
C_i	specific heat of relaxing degree of freedom (Section 16.4.5; also 5.42)
C_N	vibrational specific heat of nitrogen (16.49)
Cx	vibrational specific heat of oxygen (16.49)
C_P^o	ideal specific heat of atmospheric air at constant pressure (16.25)
C_P^∞	high-frequency limiting specific heat at constant pressure (16.49)

C^o_{Pd}, C^o_{Ph}	ideal specific heat of dry air, water vapor at constant pressure (16.26)
C^o_{Pi}	ideal specific heat of ith constituent at constant pressure (16.29)
$C_{\infty d}$, $C_{\infty h}$	high-temperature limit of C_{ddd}, C_{hhh} (16.37a,b)
c_d, c_h	constant, virial B-coefficient of dry air, water vapor (16.31a,b)
c_{dh}	constant, virial B–interaction coefficient of dry air, water vapor (16.32)
c_v	constant, virial B-coefficient of atmospheric air (16.59)
d_d, d_h	constant, virial C-coefficient of dry air, water vapor (16.37a,b)
e_d, e_h	constant, virial C-coefficient of dry air, water vapor (16.37a,b)
F	second acoustical virial pressure coefficient (16.35)
f	acoustic frequency (16.51)
f_d, f_h	constant, virial C-coefficient of dry air, water vapor (16.37a,b)
f_e	enhancement factor (16.8)
f_{ro}	rotational relaxation time (16.52)
f_N	vibrational relaxation time of nitrogen (16.47)
f_X	vibrational relaxation time of oxygen (16.45)
f_v	constant, virial C-coefficient of atmospheric air (16.59)
G	third acoustical virial pressure coefficient (16.41)
g	acceleration due to gravity (17.3)
g_d, g_h	constant, virial C-coefficient of dry air, water vapor (16.37a,b)
h_r	relative humidity (16.7)
K	second acoustical virial density coefficient (16.33)
K_c	specific heat correction to the speed of sound (16.28)
K_{dd}, K_{hh}	second acoustical virial density coefficient of dry air and water vapor (16.34a,b)
K_{dh}	second acoustical virial interaction coefficient (16.33)
K_r	relaxation correction to the speed of sound (16.51)
K_v	virial correction to the speed of sound (16.42)
L	third acoustical virial density coefficient (16.33)
L_{BBd}, L_{BBh}	constant, third acoustical virial density coefficient of dry air and water vapor, virial B component (16.39)
L_{Cd}, L_{Ch}	constant, third acoustical virial density coefficient of dry air and water vapor, virial C component (16.39)
L_{cr}	length of cylindrical resonator (Section 16.6.4; also 8.11)
M	molar mass of atmospheric air (16.24)
M_c	molar mass of carbon dioxide (16.22)
M_{cf}	molar mass of carbon dioxide–free dry air (16.22)
M_d	molar mass of dry (standard) air (16.21)
M'_d	molar mass of dry air having carbon dioxide content of year 1999 (16.23)
M_h	molar mass of water (16.24)

M_i	molar mass of *i*th constituent of air (16.21)
n	molar density of mixture (16.1)
n_a	molar density of added or removed constituent (16.3)
n_i	molar density of *i*th constituent ((16.1)
P	pressure (16.8)
P_1, P_2	specific values of pressure (16.14)
P_{sat}	saturation vapor pressure (16.8)
P_0^*	reference pressure for relaxation frequencies, 1 atm (16.45)
R	universal gas constant (16.25)
S_d	diffraction parameter (Section 16.6.5; also 8.17)
T	temperature (16.8)
T_d	dew point temperature (16.9)
T_F	zero-crossing temperature of second acoustical virial coefficient (Section 16.4.4)
T_G	zero-crossing temperature of third acoustical virial coefficient (Section 16.4.4)
T_0	reference temperature for relaxation frequencies, 293.15 K (16.47)
$U_v(\,)$	coefficient, uncertainty of the virial correction (16.58)
W	sound speed of atmospheric (real) air (16.53)
W_c	speed of sound at zero frequency referred to 314 ppm carbon dioxide (16.62)
W_s	simple sound speed of air (16.54)
W_{std}, W_o	sound speed of atmospheric air under standard conditions (16.63a, Section 17.3)
x_a	mole fraction of added or removed constituent (16.4)
x_c, x_c'	mole fraction of carbon dioxide in standard air and 1999 air (16.23)
x_d	mole fraction of dry air (16.26)
x_h	mole fraction of water vapor (16.7)
x_i, x_i'	mole fraction of *i*th constituent before and after removal of another constituent (16.1,3)
x_{sat}	mole fraction of water vapor on saturation line (16.7)
x_N, x_X	mole fraction of nitrogen, oxygen (16.49)
x_1, x_2	mole fraction of constituents in a binary mixture (16.17)
Y	any property of a mixture (16.16)
Y_i	property of *i*th constituent (16.16)
Y_1, Y_2	property of constituents in a binary mixture (16.17)
$Y_{11} \ldots Y_{22}$	constants, property scaled to square of constituent mole fractions (16.18)
$Y_{111} \ldots Y_{222}$	constants, property scaled to third power of constituent mole fractions (16.19)
z	height of column of mercury for barometric measurement (17.3)

γ	real specific heat ratio (Section 16.5.5)
γ_m	measured ideal specific heat ratio (16.63a)
γ_o	ideal specific heat ratio of atmospheric air (16.27)
γ_{od}	ideal specific heat ratio of dry air (16.34a)
γ_{oh}	ideal specific heat ratio of water vapor (16.34b)
γ_s	simple specific heat ratio of atmospheric air (16.27)
γ_{std}	ideal specific heat ratio of dry air under standard conditions (16.63a)
δY	uncertainty of any property Y (Section 16.5.5)
ε	relaxation strength (Section 16.4.5)
ε_N	relaxation strength of nitrogen (16.50b)
ε_X	relaxation strength of oxygen (16.50a)
θ_{vb}	characteristic vibrational temperature (Section 16.4.5)
μ_a	absolute viscosity (16.52)
ρ	density (17.3)
ρ_m	density under conditions of sound speed measurement (16.63a)
ρ_{std}	density under standard conditions (16.63a)
ψ	symbol for P/RT (16.58)

INDEX