A Reference Equation of State for the Thermodynamic Properties of Nitrogen for Temperatures from 63.151 to 1000 K and Pressures to 2200 MPa

Roland Span, Eric W. Lemmon, Richard T Jacobsen, Wolfgang Wagner, and Akimichi Yokozeki

Citation: Journal of Physical and Chemical Reference Data **29**, 1361 (2000); doi: 10.1063/1.1349047
View online: http://dx.doi.org/10.1063/1.1349047
View Table of Contents: http://scitation.aip.org/content/aip/journal/jpcrd/29/6?ver=pdfcov
Published by the AIP Publishing

A Reference Equation of State for the Thermodynamic Properties of Nitrogen for Temperatures from 63.151 to 1000 K and Pressures to 2200 MPa

Roland Span[a), d)]
Lehrstuhl für Thermodynamik, Ruhr-Universität Bochum, D-44780 Bochum, Germany

Eric W. Lemmon[b)]
Physical and Chemical Properties Division, National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305-3328

Richard T Jacobsen[c)]
Center for Applied Thermodynamic Studies, College of Engineering, University of Idaho, Moscow, Idaho 83844-1011

Wolfgang Wagner
Lehrstuhl für Thermodynamik, Ruhr-Universität Bochum, D-44780 Bochum, Germany

Akimichi Yokozeki
DuPont FluoroProducts Laboratory, Chestnut Run Plaza 711, Wilmington, Delaware 19880

Received December 10, 1999; revised manuscript received November 20, 2000

A new formulation for the thermodynamic properties of nitrogen has been developed. Many new data sets have become available, including high accuracy data from single and dual-sinker apparatuses which improve the accuracy of the representation of the $p\rho T$ surface of gaseous, liquid, and supercritical nitrogen, including the saturation states. New measurements of the speed of sound from spherical resonators yield accurate information on caloric properties in gaseous and supercritical nitrogen. Isochoric heat capacity and enthalpy data have also been published. Sophisticated procedures for the optimization of the mathematical structure of equations of state and special functional forms for an improved representation of data in the critical region were used. Constraints regarding the structure of the equation ensure reasonable results up to extreme conditions of temperature and pressure. For calibration applications, the new reference equation is supplemented by a simple but also accurate formulation, valid only for supercritical nitrogen between 250 and 350 K at pressures up to 30 MPa. The uncertainty in density of the new reference equation of state ranges from 0.02% at pressures less than 30 MPa up to 0.6% at very high pressures, except in the range from 270 to 350 K at pressures less than 12 MPa where the uncertainty in density is 0.01%. The equation is valid from the triple point temperature to temperatures of 1000 K and up to pressures of 2200 MPa. From 1000 to 1800 K, the equation was validated with data of limited accuracy. The extrapolation behavior beyond 1800 K is reasonable up to the limits of chemical stability of nitrogen, as indicated by comparison to experimental shock tube data.

Key words: caloric properties; density; equation of state; fundamental equation; nitrogen; thermodynamic properties.

a)Electronic mail: Roland.Span@power.alstom.com
b)Electronic mail: ericl@boulder.nist.gov
c)Current Address: Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho 83415-3790.
d)Current address: ALSTOM Power Technology Ltd., Segelhof 1, CH-5405 Baden-Dättwil, Switzerland.

Contents

List of Tables

List of Figures

Nomenclature

Symbol	Physical quantity	Units used in this work
a	Helmholtz energy	J/mol
B	Second virial coefficient	dm^3/mol
B_e	Rotational constant	cm^{-1}
C	Third virial coefficient	$(dm^3/mol)^2$
c	Speed of light	m/s
c_p	Isobaric heat capacity	J/(mol K)
c_v	Isochoric heat capacity	J/(mol K)
c_σ	Saturation heat capacity	J/(mol K)
D_e	Centrifugal distortion constant	cm^{-1}
E_{evj}	Quantum state energy	J
E	Electronic term value	
F	Vibration–rotation term	
g	Gibbs energy	J/mol
g_e, g_{nj}	Weight factor from nuclear spin	
G	Vibrational term	
h	Enthalpy	J/mol
Δh_v	Heat of vaporization	J/mol
j	Quantum number	
k	Boltzmann constant	J/K
M	Molar mass	g/mol

p	Pressure	MPa
q	Molecular partition function	
R	Molar gas constant	J/(mol K)
s	Entropy	J/(mol K)
T	Temperature	K
u	Internal energy	J/mol
v	Molar volume	dm^3/mol
w	Speed of sound	m/s
Z	Compressibility factor ($Z=p/\rho RT$)	
α	Reduced Helmholtz energy ($\alpha=a/RT$)	
α_e, β_e	Vibration–rotation interaction constant	cm^{-1}
δ	Reduced density ($\delta=\rho/\rho_c$)	
γ	Heat capacity ratio ($\gamma=c_p/c_v$)	
μ_J	Joule–Thomson coefficient	K/MPa
ρ	Density	mol/dm^3
τ	Reduced temperature ($\tau=T_c/T$)	
ω_e	Vibrational frequency in wavenumber units	cm^{-1}
$\omega_e x_e$	First order anharmonicity constant	cm^{-1}
$\omega_e y_e$	Second order anharmonicity constant	cm^{-1}
$\omega_e z_e$	Third order anharmonicity constant	cm^{-1}

Superscripts

0	Ideal gas property
r	Residual
$'$	Saturated liquid state
$''$	Saturated vapor state

Subscripts

0	Reference state property
c	Critical point property
σ	Property along the saturation line
tp	Triple point property
tpv	Triple point property of the vapor
tpl	Triple point property of the liquid
calc	Calculated using an equation
data	Experimental value
nbp	Normal boiling point property
t	translational contribution
r	rotational contribution
v	vibrational contribution
anc	anharmonicity correction

Physical Constants and Characteristic Properties of Nitrogen

Symbol	Quantity	Value
R	Molar gas constant	8.314 510 J/(mol K)
M	Molar mass	28.013 48 g/mol
T_c	Critical temperature	126.192 K
p_c	Critical pressure	3.3958 MPa
ρ_c	Critical density	11.1839 mol/dm^3
T_{tp}	Triple point temperature	63.151 K
p_{tp}	Triple point pressure	12.523 kPa
ρ_{tpv}	Triple point density (vapor)	0.024 07 mol/dm^3
ρ_{tpl}	Triple point density (liquid)	30.9573 mol/dm^3
T_{nbp}	Normal boiling point temperature	77.355 K
ρ_{nbpv}	Normal boiling density (vapor)	0.164 64 mol/dm^3
ρ_{nbpl}	Normal boiling density (liquid)	28.7749 mol/dm^3

T_0	Reference temperature	298.15 K
p_0	Reference pressure	0.101 325 MPa
h_0^0	Reference enthalpy at T_0	8670 J/mol
s_0^0	Reference entropy at T_0 and p_0	191.5 J/(mol K)

1. Introduction

Nitrogen has been one of the most important reference fluids both for tests of physical models and for the calibration of experimental equipment. The high demands on the availability and accuracy of thermophysical data resulting from this special role have led to the development of several reference equations of state which were based on state-of-the-art data sets and correlation techniques available at the time. During the last ten years, major improvements have taken place in both experimental and correlation methods.

More than 14 000 experimental data for many types of thermodynamic properties are available in the fluid region of nitrogen. Together with water (Pruss and Wagner, 2000), argon (Tegeler *et al.*, 1999), methane (Setzmann and Wagner, 1991), ethylene (Smukala *et al.*, 2000), and carbon dioxide (Span and Wagner, 1996), nitrogen belongs to the group of substances possessing the most extensive published data sets. Among the thermodynamic properties for which experimental data exist, the data sets for $p\rho T$ data in the single-phase region, for the vapor pressure (p_σ), for the saturated liquid density (ρ'), and for the speed of sound (w) are the most extensive.

A property formulation is the set of equations used to calculate properties of a fluid at specified thermodynamic states defined by an appropriate number of independent variables. The term ''fundamental equation'' is often used in the literature to refer to empirical descriptions of one of four fundamental relations: internal energy as a function of volume and entropy, enthalpy as a function of pressure and entropy, Gibbs energy as a function of pressure and temperature, and Helmholtz energy as a function of density and temperature. Recent practical formulations for fluid properties are usually explicit in the Helmholtz energy. All thermodynamic properties may be calculated from such formulations directly without additional ancillary equations. Saturation properties can be calculated through the use of the Maxwell criterion (equal pressures and Gibbs energies at constant temperature during phase changes). In this work, the general term ''equation of state'' is used to refer to the empirical models developed for calculating fluid properties.

1.1. Prior Correlations of Nitrogen Properties

The equations of state presented by Jacobsen *et al.* (1986) and Sychev *et al.* (1987) are the most recent reference equations for the properties of nitrogen. The equation of Jacobsen *et al.* was accepted as a standard formulation for many applications. The equation of state developed in that work was explicit in the Helmholtz energy. A comprehensive evaluation of the experimental data available up to 1986 was reported by Jacobsen *et al.* and Sychev *et al.* The work of Jacobsen *et al.* superseded the pressure explicit 32 term modified Benedict–Webb–Rubin (BWR) equation of state published by Jacobsen and Stewart (1973), and the IUPAC international tables of properties for nitrogen published by Angus *et al.* (1979). Correlations for nitrogen prior to 1973 are reported by Jacobsen and Stewart. The equations of Jacobsen *et al.* and of Jacobsen and Stewart were reported on the International Practical Temperature Scale of 1968 (IPTS-68). The new equation presented here is given on the International Temperature Scale of 1990 (ITS-90). The property formulation presented here supersedes that of Jacobsen *et al.*, particularly for applications where high accuracy is desired.

1.2. The Equation of State for Nitrogen

A short description of the equation of state for nitrogen presented here was published in the International Journal of Thermophysics by Span *et al.* (1998). This article presented the coefficients of the equation of state and gave several comparisons to selected data used in the regression analysis of the equation. All information given in that paper is repeated here for completeness.

Many new data sets have become available since the publication of the 1986 correlation by Jacobsen *et al.* (1986). The new nitrogen equation of state presented here is compared to all available data including the new measurements. The new data include the $p\rho T$ measurements of Nowak *et al.* (1997a), Klimeck *et al.* (1998), Fenghour *et al.* (1993), Pieperbeck *et al.* (1991), Jaeschke and Hinze (1991), Duschek *et al.* (1988), and Achtermann *et al.* (1986), the isochoric heat capacity data of Magee (1991), the speed of sound data of Costa Gomes and Trusler (1998), Boyes (1992), Ewing and Trusler (1992), and Kortbeek *et al.* (1988), and the enthalpy data of Grini and Owren (1997). New values of the critical parameters as well as the vapor pressures and coexisting densities were reported by Nowak *et al.* (1997b). In order to represent the available accurate data within their uncertainty, while minimizing the number of coefficients, the new equation was developed using state of the art optimization and multiproperty fitting algorithms. The equation of state developed in this work is explicit in the reduced Helmholtz energy. Other thermodynamic properties are derived from the equation of state by differentiation.

The range of validity of the equation of state for nitrogen is from the freezing line to 1000 K at pressures to 2200 MPa. The equation was compared with experimental data (Antanovich and Plotnikov, 1976; Malbrunot, 1970) up to 1800 K. However, these data were not used in the development of the equation of state. The equation presented here represents all the selected experimental data to within the estimated experimental uncertainties. The equation extrapolates reasonably up to the limits of chemical stability of nitrogen (see Secs. 4.1.1 and 5.4.2), at least with respect to basic properties such as pressure, fugacity, and enthalpy.

In addition to the equation of state, ancillary functions are given for the vapor pressure, the densities of the saturated liquid and saturated vapor, the ideal gas heat capacity, and the melting pressure. Summaries of the available data for the properties of nitrogen are given, and the ranges of these data are tabulated.

The equation of state presented in this paper is intended as a highly accurate reference equation for the thermodynamic properties of pure nitrogen, as needed, for example, for the validation of physical models or new experimental techniques, for calibrations of secondary measurement devices, or for calculations of property tables. Nevertheless, the numerical capabilities of recent computers make it possible to use this formulation with the same scientific standard for calculating property values for technical applications, e.g., systems analysis or pure component contributions in state-of-the-art mixture approaches.

Throughout this paper, when tables are given which describe experimental data including temperature and pressure ranges, a column is included which describes the average absolute deviation (AAD) of the data set from values calculated using the equation of state for nitrogen. Details of the property calculations and the statistical parameters will be given later. These values are included to provide the reader with a reliable assessment of the relative uncertainty of both the data sets and the new equation of state.

2. Vapor–Liquid and Solid–Liquid Coexistence Properties

2.1. Critical Point

Critical parameters for nitrogen have been reported by various authors. A discussion of previously measured critical points is given by Jacobsen *et al.* (1986), Angus *et al.* (1979), and Sychev *et al.* (1987). More recently, the critical point has been measured by Pestak and Chan (1984) and by Nowak *et al.* (1997b). Values of the critical temperature, pressure, and density of nitrogen are listed in Table 1. The given temperatures were converted to ITS-90 where necessary.

The considerable differences between the results summarized in Table 1 result from experimental difficulties in the critical region as well as from theoretical problems in determining critical parameters. Different approaches may lead to significantly different results. The critical pressure is usually not measured directly but results from an extrapolation of measured vapor pressures to the assumed critical temperature. Thus the value determined for the critical pressure is usually directly related to the assumed critical temperature. With optical techniques, which are mostly based on an observation of the critical opalescence, critical temperatures can be measured directly. The critical density, which cannot be determined directly due to the infinite compressibility at the critical point, can then be determined using rectilinear diameters by extrapolating saturated densities to the critical point. However, different assumptions have been made regarding the curvature of the rectilinear diameter close to the critical point, and optical measurements of the critical temperature are often questionable due to problems related to the experimental procedure and to the evaluation of the corresponding observations. Therefore the critical temperature is more often determined together with the critical density from fitting power laws to saturated liquid and vapor densities. In this case, it is essential to rely on accurate data as close to the critical point as possible, since simple power law approaches applied to data further away from the critical point lead to systematic shifts, especially in the critical temperature. Overly optimistic uncertainties given by some authors usually result from not considering systematic errors of the chosen approach.

TABLE 1. Summary of critical point measurements

Author	Critical temp. (K)	Critical pressure (MPa)	Critical density (mol/dm^3)
Mathias *et al.* (1914)	126.0199		11.1004
Crommelin (1924)	126.0199	3.393 37	
Claitor and Crawford (1949)	125.9999	3.394 39	
Friedman and White (1950)	126.1453	3.362 06	
White *et al.* (1951)	126.2599	3.398 44	
Hirschfelder *et al.* (1958)	126.0999	3.394 39	11.1111
Kessel'man and Gorykdn (1965)	126.1999	3.394	11.1018
Coleman (1970)	126.1999	3.400 47	10.9
Cheng (1972)	126.2135	3.4	11.1
Wagner (1973)	126.2135	3.4002	
Holleran *et al.* (1975)	126.2135	3.394 39	
Zozulya and Blagoi (1975)	126.2059	3.397 81	11.1768
Haynes *et al.* (1976)	126.2135		11.21
Levelt Sengers *et al.* (1976)	126.2535	3.398	11.2053
Pestak and Chan (1984)	126.2278		
Nowak *et al.* (1997b)[a]	126.1920	3.3958	11.1839

[a]Values selected in this work.

The critical parameters used in this work are those reported by Nowak *et al.* (1997b). These values were determined from fitting the power law

$$\frac{\rho}{\rho_c}-1=N_1\left(1-\frac{T}{T_c}\right)\pm N_2\left(1-\frac{T}{T_c}\right)^{\beta} \tag{1}$$

to accurate experimental results for saturated vapor and liquid densities. In Eq. (1), ρ_c, T_c, N_1,N_2, and β were determined from a nonlinear fit to coexisting densities which reach up to temperatures of $T_c-T\approx 22\,\mathrm{mK}$. The critical density was checked using an extrapolation of the rectilinear diameter. The critical pressure was extrapolated from the vapor pressure measurements by Nowak *et al.*, which also reach up to $T_c-T\approx 22\,\mathrm{mK}$. The reported critical values are

$$T_c=126.192\pm 0.010\ \ \mathrm{K},$$

$$p_c=3.3958\pm 0.0017\ \ \mathrm{MPa},\ \ \text{and} \tag{2}$$

$$\rho_c=313.3\pm 0.4\ \ \mathrm{kg/m^3}\quad (=11.1839\pm 0.014\ \ \mathrm{mol/dm^3}).$$

2.2. Triple Point

The published results for the triple point of nitrogen are summarized in Table 2. The temperature of the nitrogen triple point was a secondary reference point of the International Practical Temperature Scale of 1968 (IPTS-68) and was therefore measured by numerous authors. The most accurate measurements were published by Pavese *et al.* (1984) as a result of a round-robin test in which four specialized laboratories measured the triple point temperature of nitrogen. Converted to the International Temperature Scale of 1990 (ITS-90), these measurements yield triple point temperatures which range from 63.1502 to 63.1508 K. These results agree well with those of Nowak *et al.* (1997b) who reported the values

$$T_{\mathrm{tr}}=63.151\pm0.003\ \mathrm{K}\ \text{and}$$
$$p_{\mathrm{tr}}=12.523\pm0.010\ \mathrm{kPa} \tag{3}$$

measured on the ITS-90 temperature scale. For this work, we adopted the values of Nowak *et al.* for the triple point temperature and pressure.

2.3. Vapor Pressure

From the triple point to the critical point, accurate data for the vapor pressure of nitrogen have been available since 1970 (Weber, 1970; Wagner, 1973). The new data of Nowak *et al.* (1997b) describe the vapor pressure of nitrogen with a lower uncertainty, typically less than 0.015% in vapor pressure. At temperatures below about 100 K, enlarged relative uncertainties result from an absolute contribution of 30 Pa to the uncertainty of measured pressures. At the triple point, the relative uncertainty of the measured vapor pressure is 0.075%. However, the low temperature data of Nowak *et al.* are still substantially more accurate than the other data for which similar effects are also encountered. Table 3 summarizes the available vapor pressure data for nitrogen.

TABLE 2. Summary of triple point measurements

Author	Triple point temp. (K)	Triple point pressure (MPa)
Cath (1918)	63.2401	0.012 858
Justi (1931)	63.1	0.012 520
Verschoyle (1931)	63.2101	0.012 479
Giauque and Clayton (1933)	63.146	0.012 534
Henning and Otto (1936)	63.15	0.012 612
Keesom and Bijl (1937)	63.191	0.012 534
Kirshenbaum and Urey (1942)	63.155	0.012 514
Clusius and Schleich (1958)	63.15	0.012 534
Goodwin and Weber (1963)	63.156	0.012 564
Moussa *et al.* (1966)	63.1484	0.012 520
Coleman (1970)	63.158	0.012 532
Wagner (1973)	63.1524	0.012 520
Preston–Thomas (1976)	63.1504	
Pavese *et al.* (1984)	63.1502–63.1508	
Nowak *et al.* (1997b)[a]	63.151	0.012 523

[a]Values selected in this work.

TABLE 3. Summary of vapor pressure data

Author	No. of points	Temp. range (K)	AAD
Baly (1900)	29	77–91	3.990
Siemens (1913)	9	63–80	0.698
Crommelin (1914)	9	81–124	1.696
Holst and Hamburger (1916)	4	69–81	1.163
Cath (1918)	20	65–84	0.252
Crommelin (1924)	6	77–126	0.882
Henning (1926)	13	65–79	0.641
Porter and Perry (1926)	12	90–121	0.795
Dodge and Davis (1927)	30	76–122	0.502
Giauque and Clayton (1933)	10	65–78	0.184
Henning and Otto (1936)	25	66–78	0.254
Kritschewsky and Torotscheschnikow (1936)	4	100–125	1.244
Keesom and Bijl (1937)	18	64–78	0.525
Friedman and White (1950)	19	78–126	0.210
Michels *et al.* (1953)	10	97–125	0.288
Armstrong (1954)	74	64–78	0.275
Jones (1961)	5	119–124	0.148
Moussa *et al.* (1966)	32	63–78	0.097
Weber (1970)	47	65–126	0.039
Wagner (1973)	68	63–126	0.023
Singh and Miller (1979)	4	91–115	0.063
Baidakov (1994)	10	95–121	0.079
Nowak *et al.* (1997b)	58	63–126	0.003
Overall	516	63–126	

2.4. Saturation Densities

Table 4 summarizes the saturated liquid and vapor density data for nitrogen. For the density of the saturated liquid, the data of Orrit and Lauprete (1978) and Straty and Diller (1980) describe regions of the saturated liquid line within 0.1% in density. However, no reliable data were available for the density of the saturated vapor until Nowak *et al.* (1997b) published a comprehensive set of saturated liquid and vapor densities describing the phase boundaries from the triple point to the critical point with typical uncertainties of 0.012% in saturated liquid density and 0.025% in saturated vapor density. None of the older data sets have comparably small uncertainties. Thus the saturated density data of Nowak *et al.* (1997b) were used to develop the equation of state presented here. Since the uncertainty of measured saturated vapor densities increases as the temperature decreases, Nowak *et al.* (1997b) calculated saturated vapor densities below 83 K from a virial equation (truncated after the third virial coefficient) along the vapor pressure line of nitrogen. The virial equation was developed using the data of Nowak *et al.* (1997a) and Ewing and Trusler (1992) in the range from 64 to 373 K at densities up to 1 mol/dm^3.

2.5. Melting Pressure

Table 5 summarizes the melting pressure data for nitrogen. The data of Grilly and Mills (1957), Mills (1976), and Cheng *et al.* (1975) were used in the development of the equation for the melting pressure given in the next section. The data of Mills (1976) cover the pressure range up to 355 MPa, with

TABLE 4. Summary of saturated liquid and vapor density data

Author	No. of points	Temp. range (K)	AAD
Saturated liquid density data			
Mathias *et al.* (1914)	11	65–125	0.763
Crommelin (1924)	7	65–125	0.480
Van Itterbeek and Verbeke (1960)	9	63–91	0.486
Streett and Staveley (1967)	8	77–120	0.338
Cockett *et al.* (1968)	10	80–125	0.220
Goldman and Scrase (1969)	30	79–126	0.233
Terry *et al.* (1969)	8	78–91	0.296
Weber (1970)	4	77–123	0.159
Brauns (1973)	78	66–111	0.060
Zozulya and Blagoi (1975)	14	120–126	0.201
Haynes *et al.* (1976)	19	95–120	0.108
Orrit and Laupretre (1978)	19	79–111	0.064
Singh and Miller (1979)	4	91–115	0.127
Albuquerque *et al.* (1980)	5	94–120	0.548
Straty and Diller (1980)		80–120	0.077
Baidakov (1994)	10	95–121	0.038
Nowak *et al.* (1997b)	52	64–126	0.003
Overall	297	63–126	
Saturated vapor density data			
Mathias *et al.* (1914)	6	99–125	3.000
Crommelin (1924)	7	65–125	2.081
Zozulya and Blagoi (1975)	14	120–126	0.340
Nowak *et al.* (1997b)[a]	51	63–126	0.005
Overall	78	63–126	

[a]At low temperatures, 11 values for the saturated vapor density were determined from a virial equation of state and the measured vapor pressure.

several additional points around 1672 and 2040 MPa. The data of Cheng *et al.* (1975) cover the pressure range up to 1020 MPa. Apart from the data points near the triple point, the average difference among these three data sets is within 0.3% in melting pressure.

2.6. Ancillary Equations

The vapor pressure equation and equations for the density of the saturated liquid and the saturated vapor as functions of temperature used in this work were reported by Nowak *et al.* (1997b) based on their recent measurements. The equations represent the experimental values well within their uncertainties along the entire coexistence curve. These equations are repeated here for completeness. The vapor pressure equation is

$$\ln\left(\frac{p_\sigma}{p_c}\right)=\left(\frac{T_c}{T}\right)[N_1\theta+N_2\theta^{1.5}+N_3\theta^{2.5}+N_4\theta^5], \quad (4)$$

where

$$N_1=-6.124\,452\,84,$$

$$N_2=1.263\,272\,20,$$

$$N_3=-0.765\,910\,082,$$

$$N_4=-1.775\,705\,64,$$

and where $\theta=(1-T/T_c)$, p_σ is the vapor pressure, p_c is the critical pressure, and T_c is the critical temperature. The values of the critical parameters were given in Sec. 2.1. Comparisons of values calculated using this equation to the vapor pressure data are given in Fig. 1.

The equation for the saturated liquid density is

$$\ln\left(\frac{\rho'}{\rho_c}\right)=[N_1\theta^{0.3294}+N_2\theta^{2/3}+N_3\theta^{8/3}+N_4\theta^{35/6}], \quad (5)$$

where

$$N_1=1.486\,542\,37,$$

$$N_2=-0.280\,476\,066,$$

$$N_3=0.089\,414\,308\,5,$$

$$N_4=-0.119\,879\,866,$$

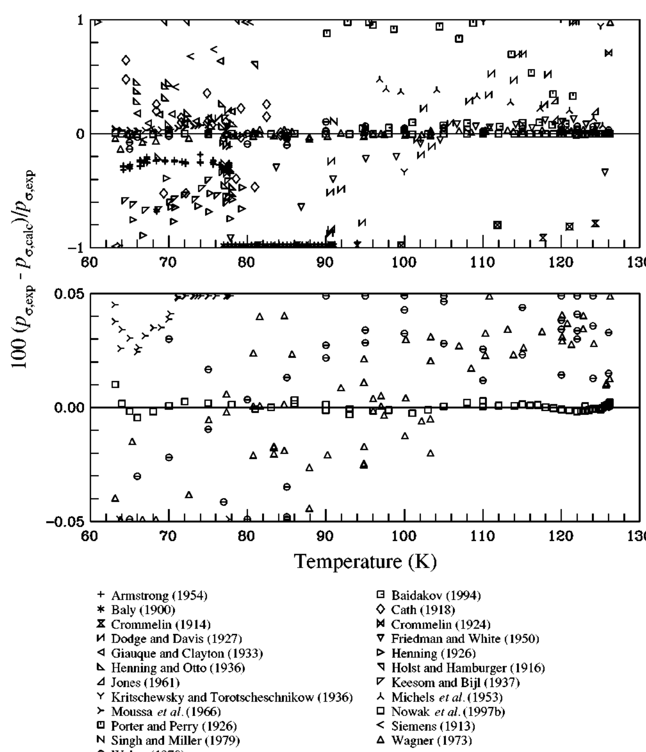

FIG. 1. Comparisons of vapor pressures calculated with the ancillary equations to experimental data.

TABLE 5. Summary of melting pressure data

Author	No. of points	Temp. range (K)	AAD
Simon *et al.* (1930)	22	71–131	6.921
Verschoyle (1931)	5	63–68	1.223[a]
Giauque and Clayton (1933)	7	63–63	[a]
Bridgman (1935)	7	63–149	0.451
Keesom and Lisman (1934)	15	64–66	4.032
Benedict (1937b)	3	98–148	0.807
Robinson (1954)	12	63–190	5.878[a]
Grilly and Mills (1957)	11	63–120	0.270[a]
Cheng *et al.* (1975)	8	87–193	0.218
Mills (1976)	39	64–273	0.591
Overall	129	63–273	

[a]Deviations for temperatures between 63.11 and 63.21 K were not included in the comparisons.

and where ρ' is the saturated liquid density and ρ_c is the critical density. Deviations of saturated liquid density values calculated using this equation from data values are given in Fig. 2. This equation describes the saturated liquid densities of nitrogen with an uncertainty ten times less than that of Jacobsen *et al.* (1986) at the lowest temperatures based upon new experimental data published after 1986.

The equation for the saturated vapor density is

$$\ln\left(\frac{\rho''}{\rho_c}\right)=\frac{T_c}{T}[N_1\theta^{0.34}+N_2\theta^{5/6}+N_3\theta^{7/6}+N_4\theta^{13/6}+N_5\theta^{14/3}], \tag{6}$$

where

$$N_1=-1.701\,271\,64,$$

$$N_2=-3.704\,026\,49,$$

$$N_3=1.298\,593\,83,$$

$$N_4=-0.561\,424\,977,$$

$$N_5=-2.685\,053\,81,$$

and where ρ'' is the saturated vapor density. Deviations of saturated vapor density values calculated using this equation from data values are given in Fig. 3.

The parameters of the Simon equation were fitted to experimental values for the melting pressure, resulting in

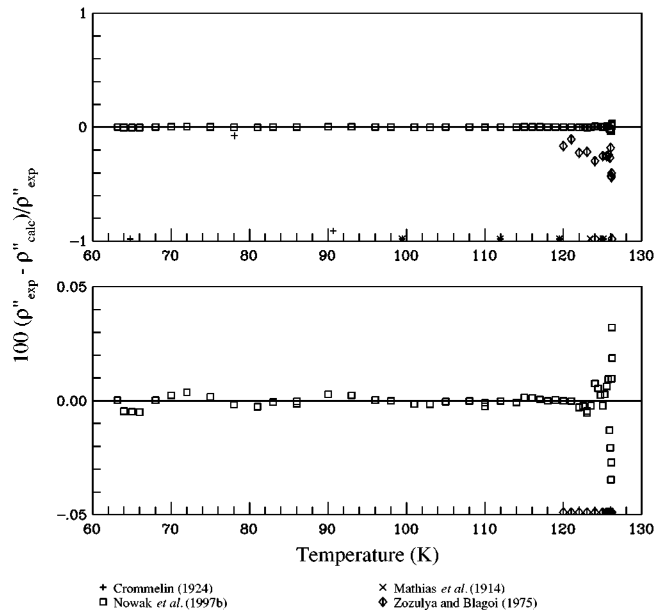

FIG. 3. Comparisons of saturated vapor densities calculated with the ancillary equations to experimental data.

$$\frac{p_{\mathrm{m}}}{p_{\mathrm{tr}}}-1=12\,798.61\left[\left(\frac{T}{T_{\mathrm{tr}}}\right)^{1.789\,63}-1\right], \tag{7}$$

where p_{tr} and T_{tr} are the triple point pressure and temperature given in Sec. 2.2. Comparisons of values calculated using this equation to the melting pressure data are given in Fig. 4.

Equations (4)–(6) are not required for computing vapor–liquid equilibrium properties from the equation of state, but they were used to generate linearized Maxwell data (see Sec.

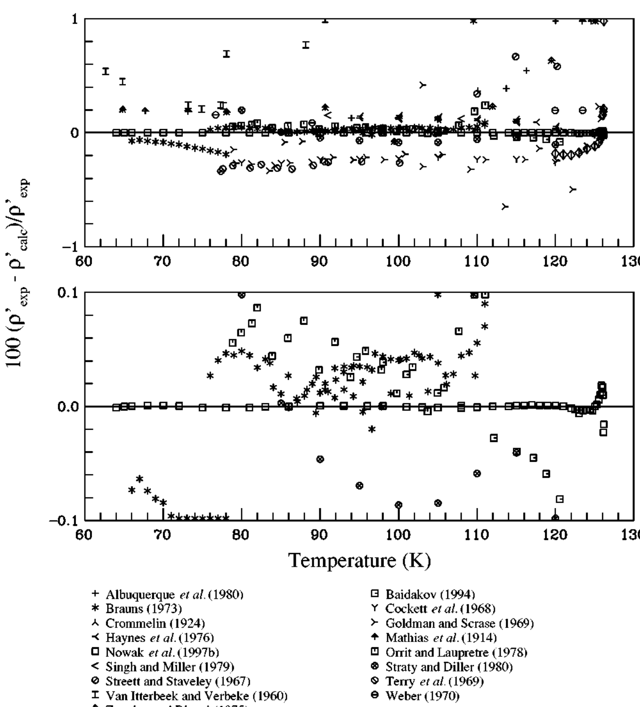

FIG. 2. Comparisons of saturated liquid densities calculated with the ancillary equations to experimental data.

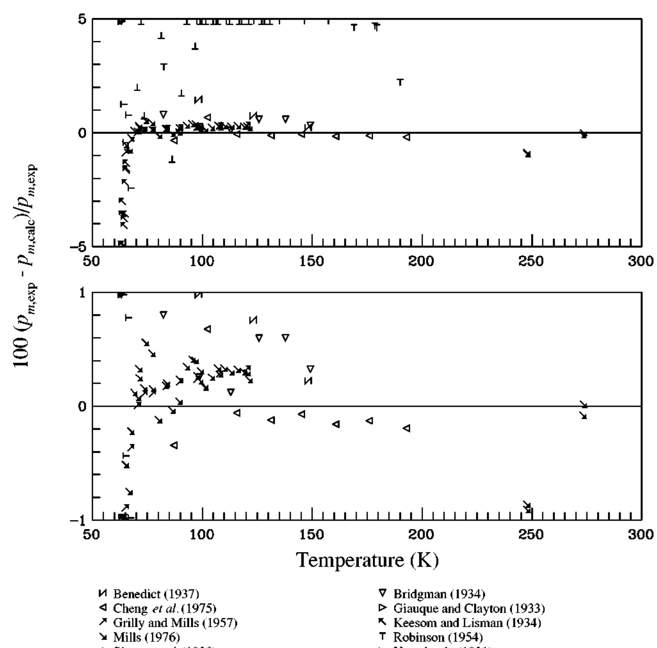

FIG. 4. Comparisons of melting pressures calculated with the ancillary equation to experimental data.

4.2.1) for fitting. They can also be used to determine starting values for iterative procedures using the Maxwell criterion to determine the saturation properties. The melting line equation, Eq. (7), is commonly used to determine the liquid pressure at the solid–liquid equilibrium, and thus the upper limit in pressure at a given temperature for which properties can be calculated from the equation of state.

3. Experimental Data for the Single-Phase Region

The available experimental data for the single-phase region of nitrogen are summarized in the following sections. Additional details covering earlier work can be found in Jacobsen *et al.* (1986) or Sychev *et al.* (1987). Selected data were used as a basis for the development of the new thermodynamic property formulation reported here. Comparisons were made to all available experimental data, including those not used in the development of the equation of state. The data for the coexistence states (liquid–vapor and solid–liquid) are discussed and summarized in Sec. 2.

3.1. $p\rho T$ Data and Virial Coefficients

The experimental $p\rho T$ data for nitrogen are summarized in Table 6. The table summarizes those data used in the development of the equation of state separately from those

TABLE 6. Summary of $p\rho T$ data

Source	No. of points	Temp. range (K)	Pressure range (MPa)	Density range (mol/dm^3)	AAD
Data sets used in developing the equation of state					
Michels *et al.* (1934)	56	273–423	1.93–8.58	0.85–2.37	0.016
Otto *et al.* (1934)	63	273–423	4.62–42.0	2.06–9.59	0.020
Michels *et al.* (1936)	147	273–423	19.5–300.0	8.33–25.8	0.017
Wiebe and Gaddy (1938)	45	273–573	2.53–101.0	0.81–21.6	0.118
Saurel (1958)	87	423–1074	1.01–91.2	0.11–11.3	0.099
Robertson and Babb (1969)	170	308–673	164.0–1011.0	21.0–38.9	0.056
Liebenberg (1975)	533	248–321	69.2–2039.0	17.6–46.8	0.310
Mills *et al.* (1975)	72	248–321	300.0–2200.0	28.3–47.1	0.460
Rivkin (1975)	43	273–473	0.40–9.63	0.18–3.25	0.029
Liebenberg *et al.* (1976)	9	273–273	300.0–1800.0	29.7–45.5	0.359
Straty and Diller (1980)	287	80–300	0.83–34.8	11.2–28.4	0.025
Morris and Wylie (1983)	48	253–308	198.0–559.0	26.0–34.0	0.034
Achtermann *et al.* (1986)	35	323	1.07–28.7	0.40–9.37	0.019
Duschek *et al.* (1988)	127	273–323	0.50–8.01	0.19–3.59	0.004
Jaeschke and Hinze (1991)	643	269–353	0.22–30.2	0.09–11.7	0.011
Pieperbeck *et al.* (1991)	124	273–323	0.10–12.1	0.04–5.37	0.003
Fenghour *et al.* (1993)	50	290–680	3.54–37.0	1.43–5.71	0.077
Nowak *et al.* (1997a)	920	66–340	0.10–12.0	0.07–31.3	0.004[a]
Nowak *et al.* (1997b)	172	125–126	3.20–3.39	7.25–14.9	0.030[a]
Klimeck *et al.* (1998)	197	240–520	1.11–30.1	0.46–13.6	0.001
Data sets not used in developing the equation of state					
Amagat (1993)	76	273–317	0.10–304.0	0.04–29.8	0.101
Holborn and Otto (1922)	32	273–373	1.95–10.1	0.63–4.50	0.074
Smith and Taylor (1923)	40	273–473	3.46–32.4	1.55–7.14	0.977
Bridgman (1924)	14	341	245.0–1471.0	26.3–39.3	3.528
Holborn and Otto (1924a)	66	273–674	1.96–10.0	0.47–4.47	0.052
Holborn and Otto (1924b)	24	143–273	2.00–10.1	1.11–12.9	0.427
Kamerlingh Onnes and Van Urk (1924)	143	125–293	2.32–6.43	1.45–15.6	0.832
Verschoyle (1926)	36	273–293	2.51–20.8	1.04–8.83	0.110
Bartlett (1927)	9	273	0.10–101.0	0.04–21.6	0.161
Bartlett *et al.* (1928)	52	273–673	0.10–101.0	0.02–21.6	0.251
Heuse and Otto (1929)	8	273–273	0.04–0.12	0.02–0.05	0.033
Bartlett *et al.* (1930)	46	203–293	0.10–101.0	0.04–25.1	0.095
Bridgman (1935)	20	133–297	294.0–588.0	28.8–37.9	1.737
Benedict (1937a)	20	90–173	10.1–127.0	9.89–33.4	0.424
Benedict (1937b)	124	98–473	99.4–591.0	18.4–38.0	0.190
Maron and Turnbull (1942)	8	273–273	10.1–101.0	4.46–21.7	0.447
Friedman (1950)	200	80–300	0.02–20.3	0.03–19.8	0.262
Tsiklis (1951)	45	323–423	304.0–1013.0	26.1–39.0	0.581
Townsend (1956)	34	298–323	0.27–14.0	0.10–5.32	0.033
Grilly and Mills (1957)	10	65–120	7.75–349.0	31.1–36.5	0.196
Luft (1957)	26	573	0.41–10.1	0.08–2.14	2.248
Miller *et al.* (1960)	10	294	0.90–26.7	0.37–9.90	0.211

TABLE 6. Summary of $p\rho T$ data—Continued

Source	No. of points	Temp. range (K)	Pressure range (MPa)	Density range (mol/dm^3)	AAD
Van Itterbeek and Verbeke (1960)	67	66–91	1.35–14.6	26.9–31.4	0.273
Date *et al.* (1961)	88	273–373	2.81–109.0	0.90–22.2	0.123
Miller *et al.* (1961)	10	294	0.90–26.7	0.37–9.88	0.191
Van Itterbeek and Verbeke (1961)	13	77–90	8.04–82.6	28.2–32.2	0.696
Canfield *et al.* (1962)	9	143–273	5.07–40.5	2.26–17.2	0.092
Canfield *et al.* (1965)	152	133–273	0.20–54.8	0.11–26.6	0.051
Golubev and Dobrovol'skii (1965)	59	77–133	5.01–49.1	19.7–31.7	0.226
Crain and Sonntag (1966)	90	143–273	0.20–51.3	0.10–23.3	0.027
Ku and Dodge (1967)	29	312–373	0.38–28.4	0.13–9.65	0.172
Streett and Staveley (1967)	107	77–120	0.44–69.0	19.7–32.5	0.224
Cockett *et al.* (1968)	63	85–120	2.53–20.3	18.7–29.3	0.149
Tsiklis and Polyakov (1968)	69	295–673	152.0–1013.0	15.2–35.6	0.395
Gibbons (1969)	17	72–78	2.13–12.7	28.9–30.5	0.176
Malbrunot and Vodar (1969)	62	473–1274	101.0–405.0	7.18–27.6	2.210
Mamedov (1969)	23	78–133	5.01–49.1	19.7–31.6	0.239
Hall and Canfield (1970)	14	103–113	0.28–1.66	0.34–2.49	0.380
Malbrunot (1970)	191	473–1274	80.0–500.0	5.87–28.2	1.195
Weber (1970)	76	80–140	1.42–27.0	9.43–28.8	0.112
Cheng (1972)	393	87–309	37.3–1062.0	13.9–41.3	0.269
Liu and Miller (1972)	5	91–100	0.40–0.80	24.5–26.3	0.315
Roe (1972)	103	156–291	0.23–10.4	0.12–7.14	0.008
Timrot *et al.* (1972)	145	80–200	0.11–37.6	0.10–30.5	3.278
Rodosevich and Miller (1973)	4	91–115	0.40–1.97	20.7–26.4	0.057
Zozulya and Blagoi (1975)	515	120–150	2.37–7.56	3.65–18.9	1.650
Antanovich and Plotnikov (1976)	44	400–1800	100.0–800.0	5.46–26.6	1.400
Nunes da Ponte *et al.* (1978)	101	110–120	1.90–138.0	19.2–32.4	0.172
Kosov and Brovanov (1979)	6	290	15.0–60.0	6.10–16.6	0.259
Palavra (1979)	72	94–106	0.70–29.9	23.3–28.9	0.098
Younglove and McCarty (1980)	237	80–350	0.03–1.51	0.01–2.21	0.053
Kimura *et al.* (1987)	10	295	394.0–2220.0	31.5–47.5	1.171
Blanke *et al.* (1988)	104	280–360	1.02–12.7	0.44–4.08	0.006
Kortbeek *et al.* (1988)	17	298	200–1000	25.9–38.9	0.122
Brugge *et al.* (1989)	40	300–320	0.11–10.4	0.04–3.83	0.011
Sharif and Groves (1989)	53	273–298	1.14–31.9	0.47–12.0	0.614
Jaeschke and Humphreys (1990)	94	279–308	3.74–6.67	1.47–2.86	0.053
Jiang *et al.* (1990)	12	293–293	0.60–6.99	0.25–2.88	0.013
Ricardo *et al.* (1992)	26	119	2.59–151.0	19.2–32.1	0.164
Baidakov (1994)	186	94–126	0.22–5.29	18.4–25.7	0.057
Overall	8187	65–1800	0.02–2200	0.01–58.5	

[a]Excluding the region 126.12–126.4 K and 9–13 mol/dm^3.

not used. The uncertainties and sample purities for most of the data shown in this table up to 1986 are given by Jacobsen *et al.* (1986). The corresponding values are given in Table 7 for data published since 1986. Figure 5 shows all available $p\rho T$ data for nitrogen. For clarity, data between 250 and 300 K are also shown in Fig. 6, and data in the critical region are shown in Fig. 7. Further discussion of the data selection is given in Sec. 5. Table 8 summarizes the sources for the second virial coefficients for nitrogen.

The importance of the recent data of Nowak *et al.* (1997a, 1997b) and of Klimeck *et al.* (1998), measured with two- and single-sinker densimeters, respectively, should be emphasized. For temperatures up to 340 K and pressures up to 12 MPa, $p\rho T$ properties in the single-phase region are represented by the data of Nowak *et al.* (1997a). These data also yield the most reliable information on the thermal properties of nitrogen in the critical region. The data of Nowak *et al.* (1997b) not only describe the liquid–vapor phase boundary from the triple point to the critical point with previously unattained accuracy (see Secs. 2.3 and 2.4), but they also cover the homogeneous states close to the phase boundary in the critical region. The data of Klimeck *et al.* (1998) extend the region covered by accurate $p\rho T$ data to temperatures up to 520 K and pressures up to 30 MPa. Together, these three data sets describe the thermal properties of nitrogen in the technically and scientifically most important regions with the highest accuracy that can be realized in state-of-the-art experiments today.

3.2. Caloric Data

Table 9 summarizes the ideal gas heat capacity data for nitrogen. These data are generally calculated from statistical models based on spectroscopic information, with the excep-

TABLE 7. Uncertainties of experimental data published since 1986 as claimed by the authors of the data

Source	Uncertainty in temperature	Uncertainty in pressure	Uncertainty in density	Total uncertainty in density[a]	Purity
pρT					
Achtermann *et al.* (1986)		0.005%			0.999 995
Baidakov (1994)	15 mK	0.005 MPa	0.05%		0.999 96
Blanke *et al.* (1988)	1 mK	$p<0.2$ MPa: 0.01%; $p>0.2$ MPa: 0.005%	0.03%	0.03%	0.999 999
Brugge *et al.* (1989)	5 mK	$p<4$ MPa: 0.015%; $p>4$ MPa: 0.005%			0.999 995
Duschek *et al.* (1988)	3 mK	larger of 0.007% or 30 Pa	larger of 0.02% or 0.002 kg/m^3		0.999 995
Fenghour *et al.* (1993)	10 mK	0.04%	0.04% to 0.1%		0.9999
Jaeschke and Hinze (1991) (Burnett)	20 mK	0.01%		0.06% to 0.1%	0.999 99
Jaeschke and Hinze (1991) (Interferometer)	20 mK	0.015%		0.07% to 0.11%	0.999 99
Jaeschke and Humphreys (1990)	20 mK	0.01%		0.06% to 0.1%	
Jiang *et al.* (1990)	50 mK				
Kimura *et al.* (1987)	300 mK				0.9999
Klimeck *et al.* (1998)	4–10 mK	0.006%	0.012%		0.999 999
Kortbeek *et al.* (1988)	1 mK	0.05% + 0.2 MPa	0.08%		0.999 995
Sharif and Groves (1989)				0.3% to 0.6%	0.999 99
Pieperbeck *et al.* (1991)	5 mK	greater of 0.007% or 30 Pa	greater of 0.0003 kg/m^3 or 0.015%	0.02% (0.04% under standard conditions)	0.999 995
Ricardo *et al.* (1992)	10 mK	0.01 MPa		0.1%	0.999 98
Nowak *et al.* (1997a, b)	250–340 K: 1.5 mK, 60–250 K: 3 mK	greater of $4\times10^{-5}\,p$ or 30 Pa	greater of $1\times10^{-4}\,\rho$ or 1.5×10^{-3} kg/m^3	0.01% to 0.015%	0.999 999
Source	**Uncertainty in temperature**	**Uncertainty in pressure**	**Uncertainty in sound speed**	**Total uncertainty in sound speed**	**Purity**
Sound Speed					
Kimura *et al.* (1987)	300 mK				0.9999
Kortbeek *et al.* (1988)	10 mK	0.05% + 0.2 MPa	0.02%		0.999 995
Sharif and Groves (1989)				0.73%	0.999 99
Boyes (1992)					0.999 99
Ewing and Trusler (1992)	3 mK	0.02%	0.001%		0.999 98
Costa Gomes and Trusler (1998)	3 mK	4 kPa	0.001% to 0.01%		0.999 999
Source	**Uncertainty in temperature**	**Uncertainty in density**	**Uncertainty in heat capacity**	**Total uncertainty in heat capacity**	**Purity**
Isochoric Heat Capacity					
Magee (1991)	30 mK	0.2%		liquid: 0.5%; vapor: 2%	
Source	**Uncertainty in temperature**	**Uncertainty in pressure**	**Uncertainty in heat capacity**	**Total uncertainty in heat capacity**	**Purity**
Isobaric Heat Capacity					
Perkins *et al.* (1991)[b]				10%	0.999 99
Source	**Uncertainty in temperature**	**Uncertainty in pressure**	**Uncertainty in density**	**Total uncertainty in pressure or density**	**Purity**
Vapor Pressure					
Baidakov (1994)	15 mK	0.005 MPa			0.999 96
Nowak *et al.* (1997b)	[c]	[c]		0.015%	0.999 999
Saturated Liquid Density					
Baidakov (1994)	15 mK		0.05%		0.999 96
Nowak *et al.* (1997b)	[c]		[c]	0.012%	0.999 999
Saturated Vapor Density					
Nowak *et al.* (1997b)	[c]		[c]	0.025%	0.999 999

[a]Except for data in the critical region.
[b]Derived from measurements of the thermal conductivity.
[c]Same as given for Nowak *et al.* (1997) in $p\rho T$ section.

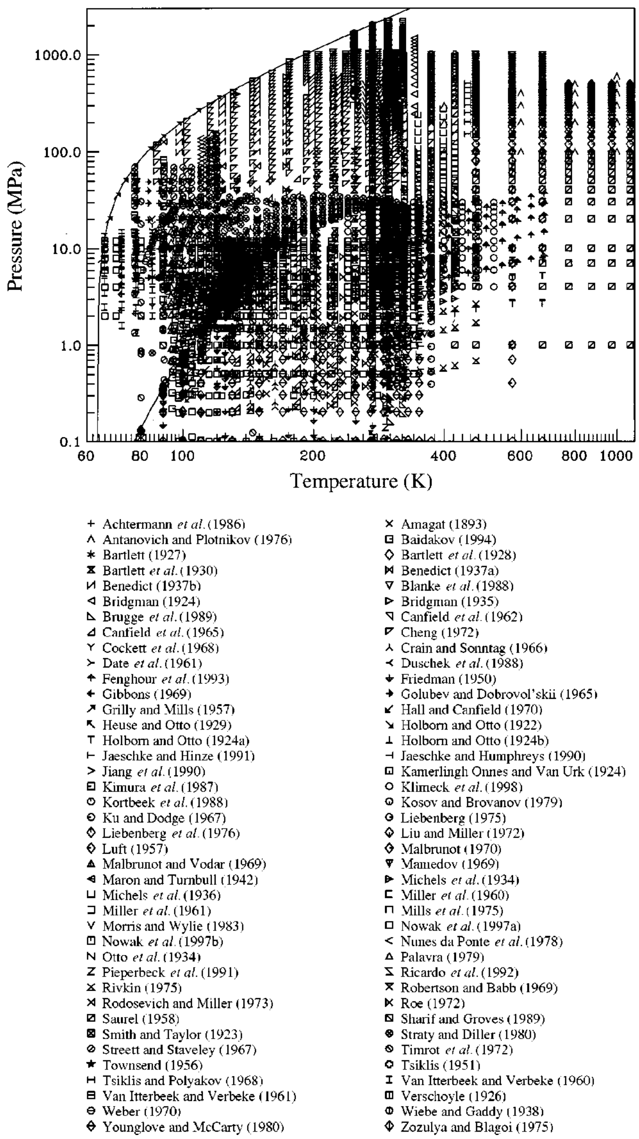

FIG. 5. $p\rho T$ data.

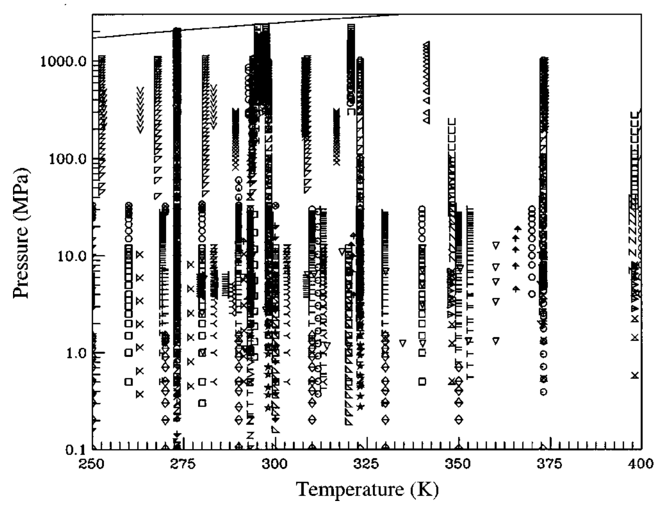

FIG. 6. $p\rho T$ data between 250 and 400 K. (Author labels are given in Fig. 5.)

sity region from temperatures close to the triple point temperature up to 373 K. The other data sets extend this region to higher pressures and densities. These data reach up to pressures of 30 MPa for temperatures from 250 to 350 K. For the highest pressures, the density of the fluid exceeds the critical density, and these data provide important information for the region of intermediate densities, which is very important for the development of equations of state. Until recently, it was not possible to measure reliable data with spherical resonators operating under such conditions. The effects of the long vibrational relaxation time for nitrogen are discussed in Sec. 4.1.2.

In the liquid region, no speed of sound data of comparable accuracy are available. However, the data of Kortbeek *et al.* (1988) verified older results (Liebenberg, 1975; Mills *et al.*, 1975; and Liebenberg *et al.*, 1976) for the speed of sound at very high pressures within the mutually claimed uncertainty of those of Boyes (1992), Ewing and Trusler (1992), and Costa Gomes and Trusler (1998), which are based on information derived from speed of sound measurements.

Extensive measurements for the speed of sound have been reported, especially in the vapor region. The sources of these data are summarized in Table 10. Figure 8 shows the distribution of these data in the *p*-*T* space. The reported measurements of the isochoric heat capacity, isobaric heat capacity, and the heat capacity of the saturated liquid for nitrogen are summarized in Tables 11 and 12 and illustrated in Fig. 9. The sources of enthalpy data, heat of vaporization data, and Joule–Thomson coefficient data are summarized in Table 13.

For the speed of sound in nitrogen, three data sets (Ewing and Trusler, 1992; Boyes, 1992; and Costa Gomes and Trusler, 1998) are available which were measured with spherical resonators, the most accurate experimental technique currently available for vapor phase sound speed measurements. The data of Ewing and Trusler (1992) describe the low den-

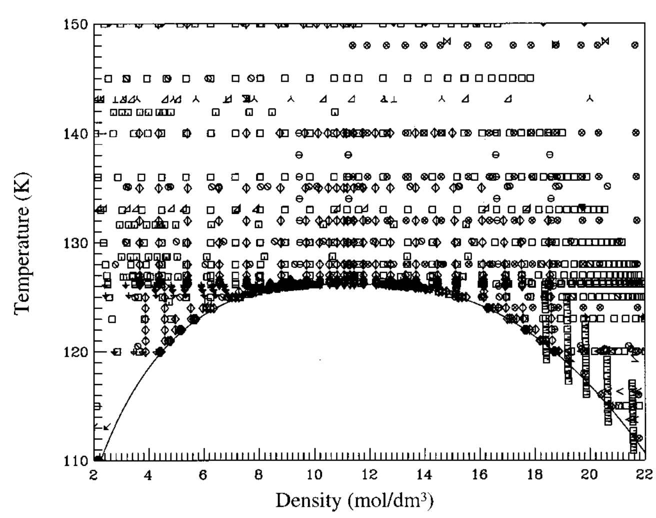

FIG. 7. Critical region $p\rho T$ data. (Author labels are given in Fig. 5.)

TABLE 8. Summary of second virial coefficients

Author	No. of points	Temp. range (K)	AAD[a]
Cath and Kamerlingh Onnes (1922)	21	73–273	2.329
Holborn and Otto (1922)	3	273–373	1.244
Holborn and Otto (1924a)	7	273–673	4.184
Holborn and Otto (1924b)	3	143–223	17.1
Verschoyle (1926)	2	273–293	0.601
Otto *et al.* (1934)	7	273–423	0.231
Claitor and Crawford (1949)	16	127–323	0.468
Bird *et al.* (1950)	7	273–423	0.350
Friedman (1950)	12	80–300	3.659
Van Itterbeek *et al.* (1955)	9	70–150	2.172
Kramer and Miller (1957)	2	303	2.312
Thomas (1957)	4	273–423	0.233
Saurel (1958)	8	423–1074	0.496
Canfield *et al.* (1962)	6	133–273	0.325
Pool *et al.* (1962)	1	90	5.664
Witonsky and Miller (1963)	5	448–748	0.469
Hoover *et al.* (1964)	6	133–273	0.253
Huang (1965)	2	273–373	0.115
Skripka (1965)	17	70–150	2.021
Crain and Sonntag (1966)	4	143–273	0.179
Brewer and Vaughn (1969)	9	123–323	0.621
Hall and Canfield (1970)	2	103–113	5.657
Levelt Sengers *et al.* (1972)	50	100–1400	0.349
Roe (1972)	13	156–291	0.074
Pocock and Wormald (1975)	23	75–700	5.082
Powles and Gubbins (1976)	6	75–500	0.861
Barkan (1978)	8	80–130	4.073
Duschek *et al.* (1988)	6	273–323	0.032
Boyes (1992)	6	250–325	0.065
Ewing and Trusler (1992)	14	75–700	0.195
Nowak *et al.* (1997a)	29	98–340	0.086
Overall	308	70–1400	

[a]Average absolute difference in the second virial coefficient (cm^3/mol) from values calculated using the equation of state of this work.

ties and extended the temperature range for which such experimental information was available.

Available data for the heat capacities of nitrogen include the isochoric heat capacity (c_v) data of Magee (1991) over a wide range of single-phase states, the saturation heat capacities (c_σ) of Magee (1991), the isochoric heat capacities (c_v) of Weber (1981) in the single-phase region at supercritical densities, and the enthalpy difference data of Grini and Owren (1997) in the supercritical fluid region. Most of the data for the other caloric properties have substantially higher uncertainties.

4. The Equation of State for Nitrogen

The equation of state for nitrogen has been formulated using the Helmholtz energy as the fundamental property with independent variables of density and temperature. The equation of state in dimensional form is given by

$$a(\rho,T)=a^0(\rho,T)+a^r(\rho,T), \tag{8}$$

where a is the Helmholtz energy, $a^0(\rho,T)$ is the ideal gas contribution to the Helmholtz energy, and $a^r(\rho,T)$ is the residual Helmholtz energy which corresponds to the influence of intermolecular forces. All thermodynamic properties can be calculated as derivatives of the Helmholtz energy. For example, the pressure derived from this expression is

$$p=\rho^2\left(\frac{\partial a}{\partial \rho}\right)_T. \tag{9}$$

TABLE 9. Summary of ideal gas heat capacity data

Author	No. of points	Temp. range (K)	AAD
Experimental Data			
Boyes (1992)	6	250–325	0.053[a]
Ewing and Trusler (1992)	9	80–373	0.041[a]
Costa Gomes and Trusler (1998)	4	250–350	0.068[a]
Overall	19	80–373	0.051
Calculated Values from Statistical Mechanics			
Johnston and Davis (1934)	21	50–5000	0.739
Justi and Luder (1935)	30	100–3000	2.259
Goff and Gratch (1950)	66	100–5000	0.071
Hilsenrath (1955)	164	10–5000	0.005
Barieau and Tully (1967)	51	50–550	0.003
Baehr *et al.* (1968)	180	10–6000	0.329

[a]0.009%, 0.003%, and 0.002%, respectively, when correcting for the influence of nonexcited vibrational modes, see Sec. 4.1.2.

The general functional form of the new equation for nitrogen, which is formulated in terms of the dimensionless Helmholtz energy (α) with the reduced density (δ) and temperature (τ) as independent variables, reads

$$\frac{a(\rho,T)}{RT}=\alpha(\delta,\tau)=\alpha^0(\delta,\tau)+\alpha^r(\delta,\tau), \tag{10}$$

where $\delta=\rho/\rho_c$, $\tau=T_c/T$, the critical temperature (T_c) is 126.192 K, and the critical density (ρ_c) is 11.1839 mol/dm^3. The equation for the ideal gas Helmholtz energy is given in Sec. 4.1.3 and the equation for the residual Helmholtz energy is given in Sec. 4.2.3.

4.1. Properties of the Ideal Gas

The Helmholtz energy for the ideal gas is given by

$$a^0=h^0-RT-Ts^0, \tag{11}$$

where the ideal gas enthalpy is given by

$$h^0=h_0^0+\int_{T_0}^{T}c_p^0 dT, \tag{12}$$

and where $h_0^0=8670$ J/mol is the value at $T_0=298.15$ K, based upon a zero reference point at absolute zero temperature (Cox *et al.*, 1989) and c_p^0 is the ideal gas heat capacity given in Sec. 4.1.1. The ideal gas entropy is given by

$$s^0=s_0^0+\int_{T_0}^{T}\frac{c_p^0}{T}dT-R\ln\left(\frac{\rho T}{\rho_0 T_0}\right), \tag{13}$$

where $s_0^0=191.5$ J/(mol K) is the value for entropy at $T_0=298.15$ K and $p_0=0.101\,325$ MPa (Cox *et al.*, 1989). Combining these equations results in the following Helmholtz energy equation for the ideal gas,

TABLE 10. Summary of speed of sound data

Author	No. of points	Temp. range (K)	Pressure range (MPa)	AAD
Data sets used in developing the equation of state				
Hodge (1937)	11	300	0.10–10.1	0.129
Dobbs and Finegold (1960)	30	77–90	0.29–13.6	0.113
Van Itterbeek and Van Dael (1961)	44	77–90	0.44–19.7	0.221
Van Itterbeek and Van Dael (1962)	91	64–91	0.11–97.0	0.322
El-Hakeem (1965)	11	273–294	0.10–7.09	0.024
Vasserman and Selevanyuk (1967)	127	150–1001	0.10–100.0	0.362
Mills *et al.* (1975)	72	248–321	300.0–2200.0	0.380
Nishitake and Hanayama (1975a)	15	298	122.0–1471.0	0.981
Nishitake and Hanayama (1975b)	16	298	193.0–1765.0	1.187
Younglove and McCarty (1980)	237	80–350	0.03–1.51	0.064
Kortbeek *et al.* (1988)	134	123–298	85.0–1000.0	0.402
Sharif and Groves (1989)	53	273–298	1.14–31.9	0.230
Boyes (1992)	112	250–325	0.05–6.64	0.011
Ewing and Trusler (1992)	100	80–373	0.00–0.58	0.001
Costa Gomes and Trusler (1998)	68	250–350	0.10–30.1	0.003
Saturated Liquid				
Van Itterbeek and Van Dael (1962)	13	69–91		0.453
Van Dael *et al.* (1966)	37	65–126		0.324
Data sets not used in developing the equation of state				
Dixon *et al.* (1921)	11	273–1273	0.10	0.896
Shilling and Partington (1928)	11	290–1273	0.10	0.908
Keesom and Van Lammeren (1932)	42	72–273	0.01–0.10	0.063
Benedict (1937b)	8	303	0.10–608.0	0.874
Van Itterbeek and Mariens (1937)	4	90	0.01–0.10	0.029
Colwell and Gibson (1941)	7	273	0.00–0.02	0.230
Abbey and Barlow (1948)	7	293	0.00–0.10	0.112
Boyer (1951)	11	273	0.00–0.11	2.358
Verhaegen (1952)	12	65–78	0.02–0.10	2.201
Lacam (1953)	57	298–312	8.05–115.0	0.508
Lacam and Noury (1953)	11	298	1.26–14.0	0.107
Lacam (1956)	98	298–473	8.00–122.0	0.348
Van Itterbeek *et al.* (1957)	122	228–299	0.12–5.93	0.220
Van Itterbeek and Van Dael (1958)	29	77–90	0.42–6.76	1.079
Volarovich and Balashov (1961)	12	293	0.10–490.0	0.694
Lestz (1963)	15	273–304	0.10–1.21	0.011
Blagoi *et al.* (1967)	13	77–112	0.10–1.65	0.765
Singer and Lunsford (1967)	31	74–114	0.16–13.9	0.743
Voronov *et al.* (1969)	113	298–448	20.3–405.0	0.520
Liebenberg (1975)	533	248–321	69.2–2039.0	0.561
Liebenberg *et al.* (1976)	9	273	300.0–1800.0	0.602
Kimura *et al.* (1987)	8	295	291.0–2291.0	0.606
Saturated Liquid				
Liepmann (1939)	12	69–77		0.704
Van Itterbeek *et al.* (1949)	8	65–78		2.363
Blagoi *et al.* (1967)	8	77–110		0.650
Pine (1969)	17	63–77		0.240
Saturated Vapor				
Van Itterbeek *et al.* (1958)	9	77–79		2.585
Overall	2389	63–1273	0.00–2291.0	

$$a^0 = h_0^0 + \int_{T_0}^{T} c_p^0 dT - RT - T\left[s_0^0 + \int_{T_0}^{T} \frac{c_p^0}{T} dT - R \ln\left(\frac{\rho T}{\rho_0 T_0}\right)\right], \tag{14}$$

or, given in reduced variables, the ideal gas Helmholtz energy is

$$\alpha^0 = \frac{h_0^0 \tau}{RT_c} - \frac{s_0^0}{R} - 1 + \ln\frac{\delta\tau_0}{\delta_0\tau} - \frac{\tau}{R}\int_{\tau_0}^{\tau} \frac{c_p^0}{\tau^2} d\tau + \frac{1}{R}\int_{\tau_0}^{\tau} \frac{c_p^0}{\tau} d\tau, \tag{15}$$

where $\delta_0 = \rho_0/\rho_c$, $\tau_0 = T_c/T_0$, and ρ_0 is the ideal gas density at $T_0 = 298.15$ K and $p_0 = 0.101\,325$ MPa.

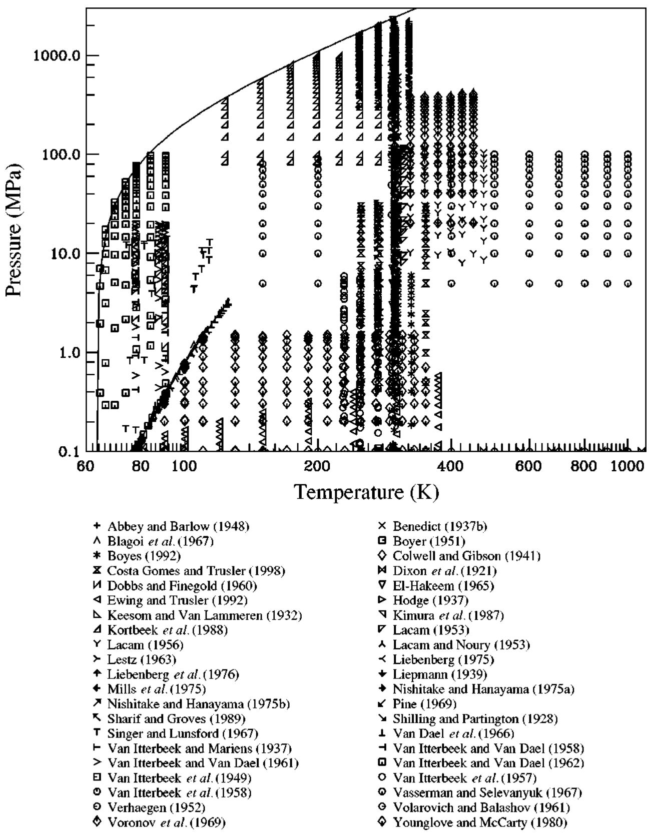

FIG. 8. Speed of sound data.

4.1.1. Ideal Gas Heat Capacity

In the calculation of the thermodynamic properties of nitrogen using an equation of state explicit in Helmholtz energy, a separate equation for the ideal gas heat capacity, $c_p^0(T)$, is used to establish a correlation for the Helmholtz energy of the ideal gas. The values of c_p^0 must be known to high accuracy because errors in the ideal gas heat capacity directly affect the accuracy of caloric properties calculated from the equation of state. Specifically, errors in c_p^0 will cause errors in the real fluid values of isochoric and isobaric heat capacity, internal energy, enthalpy, entropy, and the speed of sound.

There are several methods for determining c_p^0 from experimental or theoretical techniques. One method requires analysis of speed of sound data extrapolated to the limit of zero density. Measurements of speed of sound are taken at finite audio frequencies, and the data contain the effects of the heat capacity of the real fluid. The correction for the vibrational relaxation time to heat capacity values calculated from acoustic measurements is discussed further in Sec. 4.1.2.

The most widely used method of determining c_p^0 depends upon the availability of spectroscopic data to support the

TABLE 11. Summary of experimental isochoric heat capacity data

Author	No. of points	Temp. range (K)	Density range (mol/dm^3)	AAD
Benedict (1937b)	7	303	20.3–34.7	1.09
Chashkin *et al.* (1966)	33	122–129	11.1–11.1	42.0
Voronel *et al.* (1966)	69	106–167	11.2–11.2	33.0
Blagoi *et al.* (1967)[a]	8	77–110		18.0
Weber (1981)	61	91–242	10.7–27.5	0.404
Magee (1991)	173	66–307	6.09–31.0	0.626
Overall	351	66–307	6.09–34.7	

[a]Isochoric heat capacity data along the saturated vapor line.

TABLE 12. Summary of experimental isobaric and saturation heat capacity data

Author	No. of points	Temp. range (K)	Pressure range (MPa)	AAD
Shilling and Partington (1928)	11	290–1273	0.10	5.50
MacKey and Krase (1930)	45	303–423	0.10–81.1	1.12
Keesom and Van Lammeren (1932)	9	83–273	0.00–0.10	0.55
Benedict (1937b)	8	303	0.10–608.0	1.28
Van Itterbeek *et al.* (1957)	79	229–299	0.12–5.88	1.18
Jones (1961)	20	172–273	1.01–13.8	0.47
Lestz (1963)	15	273–304	0.10–1.21	0.18
Mage *et al.* (1963)	36	118–274	1.01–13.8	6.71
Singer and Lunsford (1967)	31	74–114	0.16–13.9	2.12
Mamedov (1969)	106	75–100	0.50–50.0	5.35
Van Kasteren and Zeldenrust (1979)	33	100–270	5.07–5.07	1.58
Perkins *et al.* (1991)	377	81–303	0.33–71.1	7.22
Isobaric Heat Capacity of the Saturated Liquid (c_p)				
Eucken (1916)	5	65–73		1.57
Keesom and Kamerlingh Onnes (1916)	5	64–77		1.76
Clusius (1929)	5	67–74		1.00
Giauque and Clayton (1933)	7	65–78		0.25
Goodwin and Weber (1963)	5	65–73		1.57
Blagoi *et al.* (1967)	8	77–110		1.67
Saturated Liquid Heat Capacity (c_σ)				
Magee (1991)	102	65–121		0.316
Overall	907	64–1273	0.00–608.0	

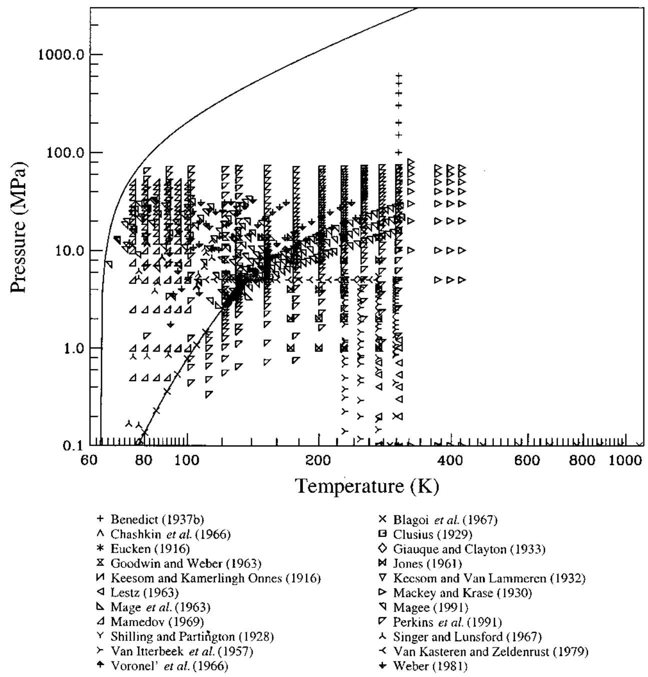

FIG. 9. Isobaric and isochoric heat capacity data.

calculation of values using statistical mechanical models. This method produces reasonably accurate results if the model parameters are known to a high degree of accuracy. The models generally treat the contributions from electronic, rotational, and vibrational modes of energy transfer as the relevant internal modes, and the translational contribution as the important external mode. The internal energies are associated with nuclear spin states, electron spin and angular momentum states, molecular rotational and vibrational states, and excited electronic states as well as their mutual interaction states. Different kinds of energy states usually have very different characteristic energy scales (or characteristic temperatures). The contribution of each energy state to the heat capacity at a given temperature depends upon the relative magnitude of the characteristic temperature.

Accurate isobaric ideal heat capacities of naturally occurring nitrogen molecules (the isotopic mixture) can be calculated in the temperature range from 0 to 5000 K with an uncertainty of less than 0.01%. This level of accuracy is possible because the nitrogen molecule is a simple diatomic molecule with well-established spectroscopic data, and thus the direct quantum-level summation can be made for the molecular partition function to calculate the heat capacity. For temperatures of practical interest (i.e., between 20 and 500 K), the heat capacity can be calculated as a classical rigid-rotor and harmonic oscillator with an uncertainty of 0.01%, assuming it is pure $^{14}N_2$. Below about 15 K, the quantum effects on the heat capacity of nitrogen isotopes become profound because nitrogen molecules have a low rotational characteristic temperature (around 2.8 K). At high temperatures (above 2000 K), additional contributions occur from the high vibrational characteristic temperature (about 3400 K) as well as from a high electronic characteristic temperature of about 72 000 K for the first excited electronic state.

Thus for typical temperature ranges, the translational and rotational contributions to the heat capacity are the number of degrees of freedom of motion times half the gas constant, $R/2$ (Landau and Lifshitz, 1980), and the molecule may be regarded as a classical rigid-rotor and harmonic oscillator (RRHO). In such a case, c_p^0 is given by the well-known formula (Landau and Lifshitz, 1980; Herzberg, 1950),

$$\frac{c_p^0}{R}=\frac{7}{2}+\frac{u^2\exp(u)}{[\exp(u)-1]^2}, \tag{16}$$

where $u=hcv/kT$, hcv/k is the vibrational characteristic temperature, h is Planck's constant, k is Boltzmann's constant, c is the speed of light, and $v=\omega_e-2\omega_e x_e$ is the fundamental frequency. Values of the parameters ω_e and $\omega_e x_e$ are given in Eqs. (29) and (30) below.

TABLE 13. Summary of enthalpy, heat of vaporization, and Joule–Thomson coefficient data

Author	No. of points	Temp. range (K)	Pressure range (MPa)	AAD
Enthalpy difference data				
Roebuck and Osterberg (1935)	394	75–574	0.06–22.4	40.0
Sahgal *et al.* (1964)	12	127–319	0.81–10.1	0.936
Wiener (1966)	16	139–449	1.79–6.83	6.122
Dawe and Snowdon (1973)	4	273	0.00–10.1	0.247
Van Kasteren and Zeldenrust (1979)	32	100–270	5.07	2.418
Grini and Owren (1997)	19	160–270	0.29–15.0	0.128
Overall	477	75–574	0.00–22.4	
Heat of vaporization data				
Furukawa and McCoskey (1953)	9	68–78		0.189
Mage *et al.* (1963)	5	119–124		1.063
Overall	14	68–124		
Joule–Thomson coefficient data				
Roebuck and Osterberg (1935)	164	93–573	0.10–20.3	10.0

When temperatures are very low (<15 K), or very high (>500 K), the accuracy of this model decreases substantially. In the low temperature region, the rotational motion cannot be treated as a classical rigid rotor, but must be treated as a quantum rigid rotor. Furthermore, the most abundant nitrogen molecule ($^{14}N_2$) is a homonuclear diatomic molecule where the rotational state is no longer independent of the nuclear-spin state according to quantum mechanics, and the proper nuclear spin factors (weight) must be applied to each rotational state (Landau and Lifshitz, 1980; Herzberg, 1950). This makes the situation complicated since nitrogen atoms have two isotopes: ^{14}N (99.635%) with nuclear spin $I=1$ and ^{15}N (0.365%) with $I=\frac{1}{2}$; the calculation must be made separately for $^{14}N_2$, $^{14}N^{15}N$, and $^{15}N_2$ in order to obtain c_p^0 of the naturally abundant nitrogen molecules. On the other hand, when the temperature is very high, the anharmonicity in vibrational states becomes important, and vibration and rotation states are not independent. At even higher temperatures, contributions from electronically excited states result.

Therefore in order to calculate c_p^0 accurately (within about 0.01%) for a wide temperature range (from 0 to 5000 K), rather detailed analyses for the various contributions must be made. According to statistical thermodynamics (Landau and Lifshitz, 1980), the heat capacity c_p^0 is calculated from the molecular partition function, q, and its temperature derivatives,

$$\frac{c_p^0}{R}=\frac{5}{2}+\frac{d}{dT}\left(T^2\frac{d\ln q}{dT}\right)$$
$$=\frac{5}{2}+\frac{2T}{q}\frac{dq}{dT}-\left(\frac{T}{q}\frac{dq}{dT}\right)^2+\frac{T^2}{q}\frac{d^2q}{dT^2}. \quad (17)$$

The first term (5/2) comes from the translational motion and the ideal gas equation of state. The rest of the terms are for the molecular internal states. A general partition function (per molecule) and its derivatives, including electronic (e), vibrational (v), and rotational (j) states, can be modeled using the equations:

$$q=\sum_e\sum_v\sum_j g_e g_{nj}(2j+1)\exp\left(\frac{-E_{evj}}{kT}\right) \quad (18)$$

$$\frac{dq}{dT}=\sum_e\sum_v\sum_j g_e g_{nj}(2j+1)\left(\frac{E_{evj}}{kT^2}\right)\exp\left(-\frac{E_{evj}}{kT}\right) \quad (19)$$

$$\frac{d^2q}{dT^2}=\sum_e\sum_v\sum_j g_e g_{nj}(2j+1)$$
$$\times\left(\frac{E_{evj}}{kT^3}\right)\left(\frac{E_{evj}}{kT}-2\right)\exp\left(\frac{-E_{evj}}{kT}\right) \quad (20)$$

The summations of e, v, and j run over the electronic (with the degeneracy factor g_e), vibrational, and rotational quantum states, respectively, and g_{nj} is the weight factor due to the nuclear spin factor, depending on j. The factor $(2j+1)$ is the degeneracy of the rotational quantum number j. E_{evj} is the energy of a given (e,v,j) quantum state and can be written with the conventional notation for constants (in wave number units) (Herzberg, 1950):

$$E_{evj}/hc=E(e)+G(v)-G(0)+F(v,j) \quad (21)$$

$$G(v)=\omega_e(v+\tfrac{1}{2})-\omega_e x_e(v+\tfrac{1}{2})^2+\omega_e y_e(v+\tfrac{1}{2})^3$$
$$+\omega_e z_e(v+\tfrac{1}{2})^4+\cdots \quad (22)$$

$$F(v,j)=[B_e-\alpha_e(v+\tfrac{1}{2})+\cdots]j(j+1)$$
$$-[D_e+\beta_e(v+\tfrac{1}{2})+\cdots]j^2(j+1)^2+\cdots \quad (23)$$

$E(e)$ is an electronic state energy term which is zero for the ground electronic state ($e=0$), and assumed to be separable from (v,j) states. Here, the constants in $G(v)$ and $F(v,j)$ are assumed to have specific values for each electronic e state.

With the proper molecular constants in Eqs. (21)–(23), the partition function and its derivatives, Eqs. (18)–(20), can be calculated by the direct quantum summations, and c_p^0 can be obtained through Eq. (17). Although the direct quantum summation is the preferred method for N_2 molecules with sufficient spectroscopic data, the summations require special attention to nuclear spin (g_{nj} factor) at low temperatures and the summation limits at high temperatures. The ground electronic state (spectroscopic notation, $X\,^1\Sigma_g^+$) is a symmetric state with $g_e=1$. In this state, the following statistical weights must be applied (Herzberg, 1950):

For $^{14}N^{14}N$:

$$g_{nj}=6 \quad \text{for} \quad j=0,2,4,... \ (\text{even } j) \quad (\text{ortho modification}) \quad (24)$$

$$g_{nj}=3 \quad \text{for} \quad j=1,3,5,... \ (\text{odd } j) \quad (\text{para modification}) \quad (25)$$

For $^{15}N^{15}N$:

$$g_{nj}=1 \quad \text{for} \quad j=0,2,4,... \ (\text{even } j) \quad (\text{para modification}) \quad (26)$$

$$g_{nj}=3 \quad \text{for} \quad j=1,3,5,... \ (\text{odd } j) \quad (\text{ortho modification}) \quad (27)$$

For $^{14}N^{15}N$:

$$g_{nj}=1 \quad \text{for} \quad j=0,1,2,3,... \ (\text{all } j) \quad (28)$$

This rule applies only to the equilibrium mixture for each isotope of the nitrogen molecule, and is appropriate for high temperatures above about 15 K, as shown in Fig. 10. For low temperatures, however, the ortho-para conversion (equilibrium) cannot be attained within the ordinary experimental condition (Herzberg, 1950). It is better to treat the ortho and para nitrogen molecules as completely different species in order to meet the practical situation and as a ''normal'' mixture of 2/3 (ortho $^{14}N_2$) + 1/3 (para $^{14}N_2$) for $^{14}N_2$, or similarly, 3/4 (ortho $^{15}N_2$) + 1/4 (para $^{15}N_2$) for $^{15}N_2$. For the heteronuclear diatomic $^{14}N^{15}N$, there is neither such complication nor requirement.

The calculations must first be made for pure ortho $^{14}N_2$ and $^{15}N_2$, pure para $^{14}N_2$ and $^{15}N_2$, and $^{14}N^{15}N$ separately,

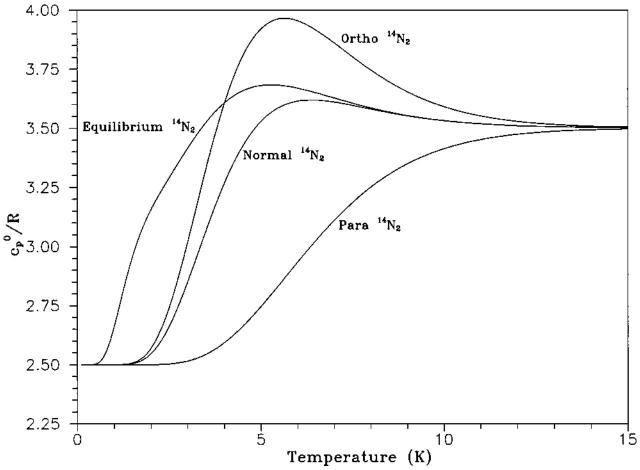

FIG. 10. Low temperature ideal gas heat capacity of $^{14}N_2$. The curves for normal $^{14}N_2$ and naturally occurring nitrogen are nearly identical.

and then c_p^0 for the above ''normal'' mixtures are calculated. Furthermore, c_p^0 for naturally abundant nitrogen (the isotopic mixture) must be calculated for each natural abundance: 99.271% $^{14}N_2$, 0.727% $^{14}N^{15}N$, and 0.002% $^{15}N_2$. The results are summarized in Figs. 10 and 11. Differences between normal $^{14}N_2$ and naturally occurring nitrogen are small, where the maximum difference is -0.3% at 1.9 K, and the difference is less than 0.02% between 5 and 20 K and much less than 0.01% between 20 and 5000 K.

In the present calculations, the following molecular constants for $^{14}N_2$ in Eqs. (22) and (23) have been adopted (Herzberg, 1950; Huber and Herzberg, 1979; Laher and Gilmore, 1991):

$$\omega_e = 2358.57\ \mathrm{cm}^{-1} \tag{29}$$

$$\omega_e x_e = 14.324\ \mathrm{cm}^{-1} \tag{30}$$

$$B_e = 1.998\,24\ \mathrm{cm}^{-1} \tag{31}$$

$$\alpha_e = 0.017\,318\ \mathrm{cm}^{-1} \tag{32}$$

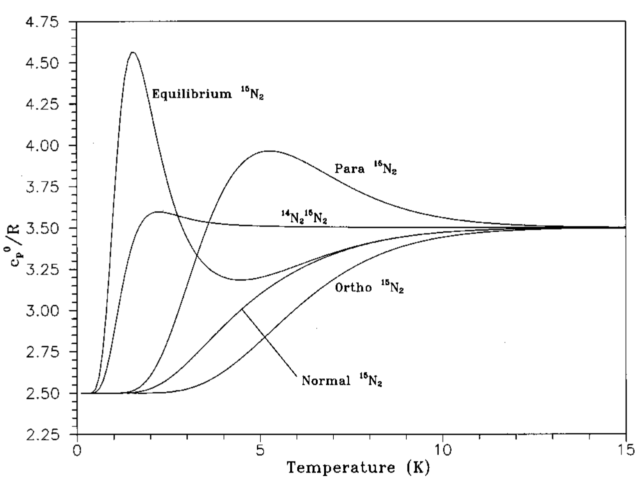

FIG. 11. Low temperature ideal gas heat capacity of $^{15}N_2$ and $^{14}N^{15}N$.

$$D_e = \frac{4B_e^3}{\omega_e^2} \tag{33}$$

$$\beta_e = D_e\left(\frac{8\omega_e x_e}{\omega_e} - \frac{5\alpha_e}{B_e} - \frac{\alpha_e^2\omega_e}{24B_e^3}\right) \tag{34}$$

The higher term coefficients, $\omega_e y_e$ and $\omega_e z_e$ in Eq. (22), can be ignored here because the contribution to the heat capacity from these terms has been found to be less than 0.01% for the entire range of interest (0–5000 K). For the other isotopes, the following formulas are applied (Herzberg, 1950):

$$\omega_e(\text{isotope}) = m\,\omega_e \tag{35}$$

$$\omega_e x_e(\text{isotope}) = m^2\omega_e x_e \tag{36}$$

$$B_e(\text{isotope}) = m^2 B_e \tag{37}$$

$$\alpha_e(\text{isotope}) = m^3\alpha_e \tag{38}$$

$$D_e(\text{isotope}) = m^4 D_e \tag{39}$$

$$\beta_e(\text{isotope}) = m^5\beta_e \tag{40}$$

The value of m is the square root of the reduced mass of $^{14}N_2$ divided by the reduced mass of the other isotope; $m = 0.983\,192$ for $^{14}N^{15}N$ and $m = 0.966\,092$ for $^{15}N_2$. These effects become unimportant above about 15 K.

At higher temperatures, vibrational excitations with vibrational anharmonicity result in dominant contributions to the heat capacity, and the rotational contribution is nearly constant at the value of the classical rigid rotor $(3R/2)$. The contributions from excited electronic states are still minor even in the region from 4000 to 5000 K (less than 0.001% at 4000 K, and less than 0.02% at 5000 K), but they are included in the present calculation in order to obtain an accuracy of less than 0.01% in the entire temperature range. Only the first excited state (spectroscopic notation, $A\,^3\Sigma_u^+$) is sufficient for the present purpose. This state has the degeneracy factor $g_e = 3$, and it is an antisymmetric electronic state (Herzberg, 1950; Steinfeld, 1974). This means that the nuclear spin statistics on the rotational energy levels are in the reverse order given in Eqs. (24) and (25), (i.e., for $^{14}N^{14}N$, $g_{nj} = 3$ for even j, $g_{nj} = 6$ for odd j, etc.), although at high temperatures these effects are minor. In this work, the interactions between the ground and electronically excited states have been neglected, and similarly, the couplings of electronic motion/spin and molecular rotation have not been considered, since the contribution of electronically excited states are minor even at 5000 K as stated above. The following molecular constants are used for the excited electronic state (Herzberg, 1950):

$$E(e=1) = 50\,203.0\ \mathrm{cm}^{-1} \tag{41}$$

$$\omega_e = 1460.37\ \mathrm{cm}^{-1} \tag{42}$$

$$\omega_e x_e = 13.891\ \mathrm{cm}^{-1} \tag{43}$$

$$B_e = 1.440\ \mathrm{cm}^{-1} \tag{44}$$

$$\alpha_e = 0.013\ \mathrm{cm}^{-1} \tag{45}$$

The other necessary constants in Eqs. (22) and (23) are derived from Eqs. (33) to (40).

Finally, the complete summations in Eqs. (18)–(20) have been done for the temperature range between 0.1 and 5000 K for naturally abundant nitrogen molecules (the natural isotopic mixture). The vibrational summations have been made from $v=0$ to $v=27$ (up to the observed maximum vibration quanta of the X ground state) and from $v=0$ to $v=15$ (up to the observed maximum vibration quanta of the A electronic state), while the rotational j number ranges from 0 to 200; this upper limit is sufficient since the upper limit of 500 gives the same result as that of 200. Concerning the errors due to vibrational-sum limits, we have examined the effect with v up to 40 (above the dissociation limits). The error was less than 0.003% in c_p^0 at 5000 K, and at 4000 K it was less than 0.000 01%. Numerical data for c_p^0/R are listed in the Appendix. Figure 12 illustrates the ideal gas heat capacity of naturally occurring nitrogen, Eq. (17), and the simple RRHO model for nitrogen, Eq. (16). Differences between these two models are 0.08% at 500 K, 0.26% at 1000 K, 0.73% at 2000 K, and 2.2% at 5000 K.

The method outlined in the NIST-JANAF tables (Chase, 1998) compares well with calculations from Eq. (17) at temperatures above 15 K. This method includes a correction to the rotational contribution and an anharmonicity correction to the RRHO model [Eq. (16)],

$$\frac{c_{p,\mathrm{rot}}^0}{R}=\left[\frac{hc}{kT}(B_e-\alpha_e/2)\right]^2\Big/45 \tag{46}$$

and

$$\frac{c_{p,\mathrm{anh}}^0}{R}=\frac{16\gamma}{u}-\frac{\delta u^2e^u}{(e^u-1)^2}+\frac{u^2e^u(2\,\delta e^u-4Xu-8X)}{(e^u-1)^3}+\frac{12Xu^3e^{2u}}{(e^u-1)^4}, \tag{47}$$

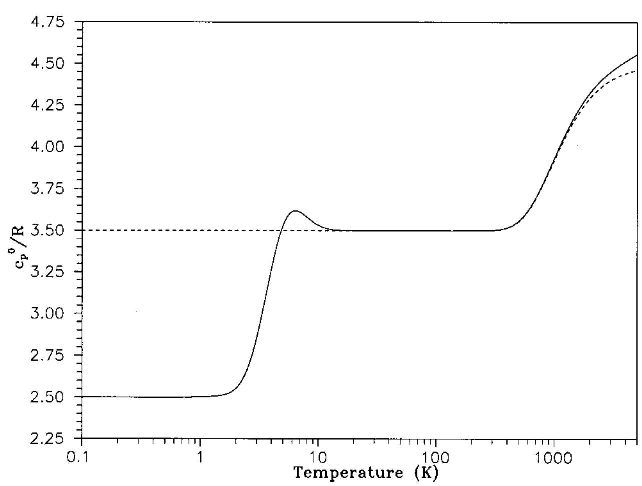

FIG. 12. Ideal gas heat capacity of naturally occurring nitrogen (solid line) and calculations from the RRHO model without electronic states or quantum mechanical corrections (dashed line).

where $X=\omega_e x_e/\omega_e$, $\delta=\alpha_e/B_e$, and $\gamma=B_e/\omega_e$. With the addition of these corrections, differences between Eq. (17) and the sum of Eqs. (16), (46), and (47) are less than 0.002% between 20 and 500 K, 0.01% at 1000 K, and 0.05% at 2000 K.

At high temperatures, nitrogen dissociates, $N_2 \leftrightarrow N+N$, and the equilibrium constant $K_p(\mathrm{T})$ can be calculated by the following statistical thermodynamics equation (Landau and Lifshitz, 1980),

$$K_p(T)=\frac{[P_\mathrm{N}]^2}{P_{\mathrm{N}_2}}=kT\left[\frac{\pi m_\mathrm{N}kT}{h^2}\right]^{3/2}\frac{q(N)^2}{q(N_2)}\exp\left(-\frac{\Delta E}{kT}\right). \tag{48}$$

The dissociation of molecular nitrogen is shown in Table 14. Values shown in the table are calculated by taking into account the electronic degeneracy of 4 in the ground state of the nitrogen atom (spectroscopic term, ^4S) and the dissociation energy of 7.37 eV (Herzberg, 1950). The thermal dissociation of nitrogen below 2000 K is negligible, and the calculated ideal gas heat capacity corresponds to the fluid system with nondissociated molecular nitrogen. Above 3000 K, the ideal gas heat capacity of nitrogen would be a mole fraction weighted sum (ideal mixture) of N_2 and atomic N $(3R/2)$. However, in this study the calculated c_p^0 values are for molecular nitrogen up to 5000 K (see the Appendix for numerical data).

The following empirical form has been developed to reproduce values calculated from Eq. (17) to within 0.01% in the temperature range between 20 and 5000 K,

$$\frac{c_p^0}{R}=a_0+a_1T+a_2T^2+a_3T^3+a_4\frac{u^2\exp(u)}{[\exp(u)-1]^2}, \tag{49}$$

where the ideal gas constant, R, is 8.314 510 J/(mol K) (Cohen and Taylor, 1988), T is in kelvins, $a_0=3.5$, $a_1=3.066\,469\times10^{-6}$, $a_2=4.701\,240\times10^{-9}$, $a_3=-3.987\,984\times10^{-13}$, $a_4=1.012\,941$, and $u=3364.011\,\mathrm{K}/T$. These values were compared to values given in Barieau and Tully (1967), Hilsenrath (1955), and Jacobsen *et al.* (1986), and the average agreement among these sources is within 0.005% for temperatures below 900 K and within 0.025% for temperatures between 900 and 2500 K. Comparisons of values calculated using this equation to the ideal gas heat capacity data are given in Fig. 13. The data of Boyes (1992), Ewing and Trusler (1992), and Costa Gomes and Trusler (1998) are given as two different symbols in this figure. One symbol shows the deviations be-

TABLE 14. Dissociation of nitrogen at high temperatures

T(K)	$K_p(T)$ (MPa)	Percent Dissociation at 0.1 MPa	Percent Dissociation at 1000 MPa
2000	1.01×10^{-13}	1.0×10^{-4}	1.0×10^{-6}
3000	2.25×10^{-7}	0.10	0.0015
4000	3.54×10^{-2}	5.6	0.06
5000	3.01×10^{-2}	35.0	0.55

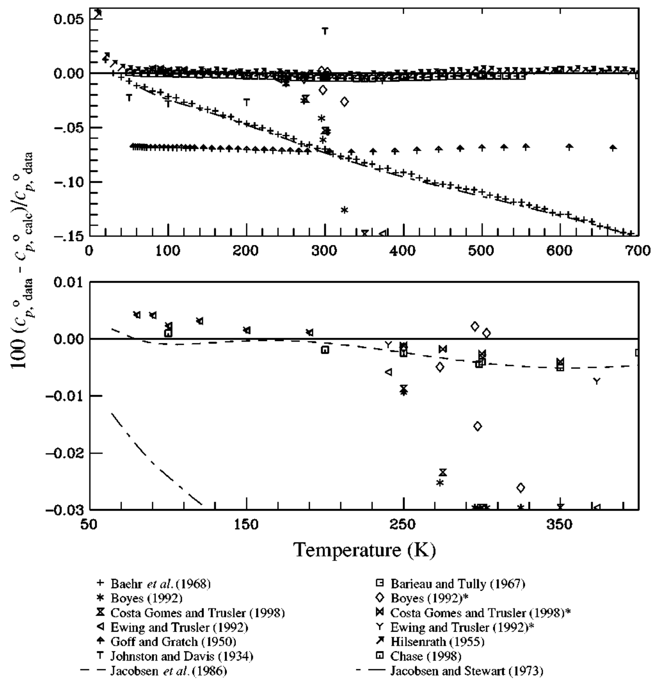

FIG. 13. Comparisons of ideal gas heat capacities calculated with the ancillary equation to experimental data. The data marked with an asterisk have been corrected to account for the vibrational contribution.

tween Eq. (49) and c_p^0 values obtained from the acoustical measurements discussed in Sec. 4.1.2. The other symbol shows similar deviations, except that the vibrational contribution from c_p^0 is added to the experimental values.

At temperatures below 46 K, the heat capacity of nitrogen, represented by Eq. (17), increases with decreasing temperature, and reaches a maximum of 3.62 R at 6.4 K (see Fig. 12). Equation (49) does not account for this maximum, nor does it account for the decrease in heat capacity to 2.5 R near 0 K where the rotational modes are not excited. The addition of the following terms to Eq. (49) accounts for the transition from 2.5 to 3.5 R, and the peak at 6.4 K,

$$\frac{c_p^0}{R}=\frac{c_{p,\mathrm{Eq.(49)}}^0}{R}-1+[1+1416T^{-6.3}+120.2\times\exp(-T^{0.94})-406.6\exp(-2T^{0.65})]^{-1}. \quad (50)$$

The maximum difference between Eq. (50) and Eq. (17) is 0.1%. The contribution from these additional terms is negligible above 46 K. Because the integrals required [in Eq. (15)] would have to be evaluated numerically, it is not recommended that these terms be used in the equation for the ideal gas Helmholtz energy in the equation of state.

4.1.2. Effects of Vibrational Relaxation Time on the Speed of Sound

Complex relaxation phenomena occur in experiments to determine the speed of sound. Compression phenomena associated with sound wave propagation result in local density changes in the fluids. Relaxation phenomena result from molecular mechanisms within the fluid that delay the attainment of equilibrium temperature and/or pressure after a change of state is imposed by the traveling sound wave. If the associated delays (relaxation times) are relatively short in comparison to the period of the sound wave, the effect upon sound speed may be nearly negligible. Translational, rotational, and vibrational relaxations are often treated independently in theoretical analyses. This is not strictly correct because there is an exchange of energy between the various modes associated with molecular collisions.

The effect of relaxation phenomena on heat capacity is evident in the differences between acoustic measurements and sound speeds calculated using thermodynamic models. The differences in the values of sound speed occur because the short time scale of acoustic measurements does not allow the attainment of thermal equilibrium among the various modes. The thermodynamic speed of sound from an equation of state, defined as

$$w_{\mathrm{eos}}^2=\left(\frac{\partial p}{\partial \rho}\right)_s, \quad (51)$$

would only be observable in an experiment at the limit of zero frequency. However, experiments are conducted at finite audio frequencies, and the observed values are the actual phase speeds of the sound waves. Fortunately, for most gases, the effect of frequency on the measurements is negligible up to frequencies of about 1 MHz or more. However, according to Costa Gomes and Trusler (1998), the frequencies for nitrogen at which the effects are significant are much lower than those for many other gases. Sound speed values measured at frequencies above 1 Hz for nitrogen do not include the effects of the vibrational mode upon the heat capacities which are accounted for in the thermodynamic speed of sound.

Because the vibrational relaxation time for nitrogen is very long compared to the period of sound waves at usual experimental conditions, the vibrational modes of the heat capacity are not detected in acoustical measurements. For nitrogen, these effects become important at temperatures above 250 K. Ideal gas heat capacity values determined from such measurements do not reflect the contribution from vibration. Values of the acoustical speed of sound, w_{acs}, can be adjusted to the thermodynamic speed of sound, w_{eos}, according to

$$w_{\mathrm{eos}}=w_{\mathrm{acs}}\sqrt{\frac{c_p}{c_v}\left(\frac{c_v-c_{\mathrm{vib}}}{c_p-c_{\mathrm{vib}}}\right)}, \quad (52)$$

where c_{vib} is the vibrational contribution to the heat capacity at the temperature of the ideal gas thermodynamic state. As a good approximation, the exponential term in Eq. (49) can be considered the vibrational contribution. Further information on the relationship between heat capacity and speed of sound is given by Costa Gomes and Trusler (1998) and Trusler (1991).

4.1.3. Ideal Gas Helmholtz Energy

Combining Eqs. (49) and (15) results in the following simplified equation for the ideal gas Helmholtz energy,

$$\alpha^0 = \ln \delta + a_1 \ln \tau + a_2 + a_3\tau + a_4\tau^{-1} + a_5\tau^{-2} + a_6\tau^{-3} + a_7 \ln[1-\exp(-a_8\tau)], \tag{53}$$

where

$$a_1 = 2.5,$$

$$a_2 = -12.769\,527\,08,$$

$$a_3 = -0.007\,841\,63,$$

$$a_4 = -1.934\,819\times 10^{-4},$$

$$a_5 = -1.247\,742\times 10^{-5},$$

$$a_6 = 6.678\,326\times 10^{-8},$$

$$a_7 = 1.012\,941,$$

and

$$a_8 = 26.657\,88.$$

4.2. Properties of the Real Fluid

Unlike the equations for the ideal gas, the real fluid behavior is described using empirical methods that are only loosely tied with theoretical models. The terms in the equation are empirical, although certain demands on the functional form of the equation of state were considered (see Span and Wagner, 1997 and Span, 2000). The coefficients of the equation reported here depend solely on the experimental data described in Secs. 2 and 3.

4.2.1. Selected Database

The units adopted for this work were kelvins (ITS-90) for temperature, megapascals for pressure, and moles per cubic decimeter for density. Units of the experimental data were converted as necessary from those of the original publications to these units. All temperatures were converted to the International Temperature Scale of 1990 (ITS-90) as suggested by Preston-Thomas (1990).

The $p\rho T$ data selected for the determination of the coefficients of the equation of state are shown in Fig. 14. Data used in fitting the equation of state for nitrogen were selected to avoid redundancy in various regions of the surface. In total, 3649 data points out of the 8187 available for $p\rho T$ data were used and 1175 data points out of the 2389 available for speed of sound were used. In addition to these data, 234 isochoric heat capacity data, all of the saturated liquid heat capacity data, 61 enthalpy difference data, 44 isobaric heat capacity data, 14 heat of vaporization data, 203 Joule–Thomson data, and five shock tube data points were used in the fit. The 58 vapor pressure, 52 saturated liquid density, and 51 saturated vapor density data by Nowak *et al.* (1997) were used directly in the nonlinear algorithms to ensure a highly accurate description of the thermal phase equilibrium properties. Linearized Maxwell data were calculated from Eqs. (4)–(6) to define the saturation properties when linear algorithms were used to establish the functional form of preliminary equations (see Span, 2000). The selected data are summarized in Table 15 which includes the statistical analysis of the fit to the data. This is discussed further in Sec. 4.2.3.

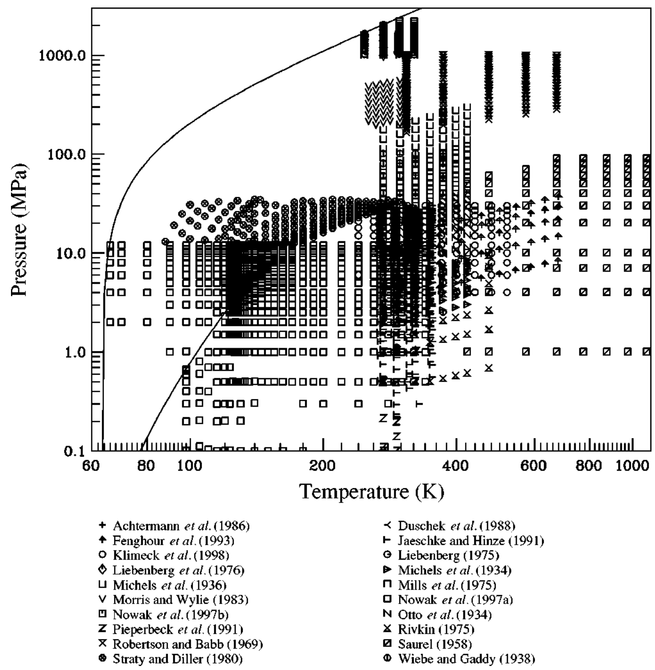

FIG. 14. Selected $p\rho T$ data used in determining the coefficients of the equation of state.

4.2.2. Fitting Procedures

Each point used in the least-squares determination of the coefficients of the equation of state was assigned a weighting factor. The weights used in the fitting process were calculated using the experimental uncertainties as stated by the authors. Where individual uncertainties for different variables are given, the error propagation formula (sometimes called the theorem of propagation of variance) was used to calculate the total uncertainties. The functions for weighting were calculated using a preliminary equation of state for the partial derivatives required for estimating variances using the error propagation formula. However, in several instances, the error propagation weights were modified by the assignment of arbitrary multiplicative factors to increase or reduce the effect of a particular data set on the overall representation of the surface.

The functional forms of preliminary equations for the residual part of the Helmholtz energy were optimized with a modified form of the algorithm developed by Setzmann and Wagner (1989). In this algorithm, nonlinear data are linearized (see, e.g., Setzmann and Wagner, 1991). To improve the representation of the accurate speed of sound data and of the shock tube data available for nitrogen, the final functional form was developed with the nonlinear regression analysis

TABLE 15. Summary of comparisons of the selected data in six different regions of the surface of state

Author	No. of data used	Temp. range (K)	Pressure range (MPa)	Average absolute deviations (AAD) in %					
							Supercritical fluid		
				Gas	Liquid	Crit. region[a]	LD[b]	MD[b]	HD[b]
			$p\rho T$ data[c]						
Michels *et al.* (1934)	56	273–423	1.93–8.58	—	—	—	0.016	—	—
Otto *et al.* (1934)	63	273–423	4.62–42.0	—	—	—	0.016	0.025	—
Michels *et al.* (1936)	147	273–423	19.5–300.0	—	—	—	—	0.010	0.030
Wiebe and Gaddy (1938)	31	273–373	2.53–101.0	—	—	—	0.014	0.008	0.011
Saurel (1958)	85	423–1074	1.01–91.2	—	—	—	0.061	0.157	—
Robertson and Babb (1969)	169	308–673	164.0–1011.0	—	—	—	—	—	0.054
Liebenberg (1975)	228	248–321	321.0–1016.0	—	—	—	—	—	0.463
Mills *et al.* (1975)	43	248–321	1000.0–2200.0	—	—	—	—	—	0.615
Rivkin (1975)	24	373–473	0.60–9.63	—	—	—	0.032	—	—
Liebenberg *et al.* (1976)	5	273	1000.0–1800.0	—	—	—	—	—	0.582
Straty and Diller (1980)	174	88–300	12.2–34.8	—	0.017	—	—	0.016	0.014
Morris and Wylie (1983)	48	253–308	197.0–559.0	—	—	—	—	—	0.034
Achtermann *et al.* (1986)	35	323	1.07–28.7	—	—	—	0.010	0.042	—
Duschek *et al.* (1988)	127	273–323	0.50–8.01	—	—	—	0.004	—	—
Jaeschke and Hinze (1991)[d]	129	273–353	0.22–30.2	—	—	—	0.007	0.014	—
Jaeschke and Hinze (1991)[e]	499	269–353	0.22–28.7	—	—	—	0.005	0.011	—
Pieperbeck *et al.* (1991)	124	273–323	0.10–12.1	—	—	—	0.003	—	—
Fenghour *et al.* (1993)	50	290–680	3.54–37.0	—	—	—	0.077	—	—
Nowak *et al.* (1997a)	920	66–340	0.10–12.0	0.003	0.002	0.004	0.003	0.004	0.001
Nowak *et al.* (1997b)	172	125–126	3.20–3.39	0.020	—	0.002	—	—	—
Klimeck *et al.* (1998)	197	240–520	1.11–30.1	—	—	—	0.001	0.001	—
			Isochoric heat capacities						
Weber (1981)	61	91–242	1.77–33.3	—	0.403	0.503	—	0.421	0.339
Magee (1991)	173	66–307	3.06–33.7	—	0.829	1.312	0.527	0.421	0.648
			Speeds of sound						
Hodge (1937)	11	300	0.10–10.1	—	—	—	0.129	—	—
Dobbs and Finegold (1960)	29	77–90	0.29–13.6	—	0.116	—	—	—	—
Van Itterbeek and Van Dael (1961)	44	77–90	0.44–19.7	—	0.221	—	—	—	—
Van Itterbeek and Van Dael (1962)	13	69–91	sat. liquid	—	0.453	—	—	—	—
Van Itterbeek and Van Dael (1962)	91	64–91	0.11–97.0	—	0.322	—	—	—	—
El-Hakeem (1965)	11	273–294	0.10–7.09	—	—	—	0.024	—	—
Van Dael *et al.* (1966)	37	65–126	sat. liquid	—	0.212	2.297	—	—	—
Vasserman and Selevanyuk (1967)	78	500–1001	0.10–100.0	—	—	—	0.144	0.197	—
Mills *et al.* (1975)	72	248–321	300.0–2200.0	—	—	—	—	—	0.380
Nishitake and Hanayama (1975a)	12	298	308.0–1471.0	—	—	—	—	—	0.932
Nishitake and Hanayama (1975b)	15	298	308.0–1765.0	—	—	—	—	—	1.211
Younglove and McCarty (1980)	237	80–350	0.03–1.51	0.108	—	—	0.045	—	—
Kortbeek *et al.* (1988)	134	123–298	85.0–1000.0	—	0.594	—	—	—	0.392
Sharif and Groves (1989)	30	273–298	7.10–31.9	—	—	—	0.185	0.221	—
Boyes (1992)[f]	112	250–325	0.05–6.64	—	—	—	0.001	—	—
Ewing and Trusler (1992)[f]	98	80–373	0.00–0.58	0.001	—	—	0.001	—	—
Costa Gomes and Trusler (1998)[f]	72	250–350	0.10–30.1	—	—	—	0.002	0.005	—
			Isobaric and saturated liquid heat capacities						
Benedict (1937b)	8	303	0.10–608.0	—	—	—	0.178	—	1.434
Mage *et al.* (1963)	28	118–274	1.01–13.8	—	—	—	3.439	0.319	0.483
Magee (1991)	102	65–121	sat. liquid	—	0.300	—	—	—	—
			Enthalpy differences						
Roebuck and Osterberg (1935)	203	199–574	0.20–22.4	—	—	—	0.142 K[g]	—	—
Furukawa and McCoskey (1953)	9	68–78	vaporization		0.189	—	—	—	—
Mage *et al.* (1963)	5	119–124	vaporization		0.439	3.556	—	—	—
Grini and Owren (1997)	19	160–270	0.29–15.0	—	—	—	0.139	0.085	—
			Second virial coefficients						
Duschek *et al.* (1988)	6	273–323	—	0.363[h]	—	—	—	—	—
Ewing and Trusler (1992)	14	75–700	—	0.400	—	—	—	—	—
Nowak *et al.* (1997a)	29	98–340	—	0.186[h]	—	—	—	—	—
			Third virial coefficients						
Nowak *et al.* (1997a)	29	98–340	—	3.784	—	—	—	—	—

[a]Corresponds to an extended critical region with $0.98 \leqslant T/T_c \leqslant 1.1$ and $0.7 \leqslant \rho/\rho_c \leqslant 1.4$.
[b]The supercritical fluid is divided into three subregions (LD: $\rho/\rho_c \leqslant 0.6$; MD: $0.6 < \rho/\rho_c < 1.5$; HD: $\rho/\rho_c \geqslant 1.5$).
[c]Deviations in pressure are given in place of deviations in density in the critical region.
[d]Burnett measurements.
[e]Refractive index measurements.
[f]Data corrected for missing vibrational contribution, see Sec. 4.1.2.
[g]Average absolute deviation of temperature differences calculated for near isenthalpic expansions.
[h]The data points between 300 and 340 K were omitted due to large relative deviations which resulted from very small values of B_{exp}.

TABLE 16. Data types used in linear and nonlinear optimization algorithms

Property	Linear optimization used directly	Linear optimization used linearized	Nonlinear optimization used directly
$p\rho T$	×		×
Isochoric heat capacity, c_v	×		×
Speed of sound, w		×	×
w of the saturated liquid, w'		×	×
w of the saturated vapor, w''		×	×
Isobaric heat capacity, c_p		×	×
c_p of the saturated liquid, c_p'		×	×
c_p of the saturated vapor, c_p''		×	×
Saturated liquid heat capacity, c_σ		×	×
Enthalpy, h		×	×
Heat of vaporization, Δh_{vap}		×	×
Shock tube data			×
Internal energy, u	×		×
Joule–Thomson coefficient, μ_J			×
Second virial coefficient, B	×		×
Third virial coefficient, C	×		×
Vapor pressure, p_σ		×	×
Saturated liquid density, ρ'		×	×
Saturated vapor density, ρ''		×	×

developed by Tegeler *et al.* (1997). By use of a combination of linear and nonlinear techniques, this algorithm enables a direct consideration of linear and nonlinear data and determines the functional form that yields the most accurate representation of both kinds of data. Table 16 lists data types that were used in the linear and the nonlinear algorithms.

The bank of terms used as the basis for both the linear and the nonlinear optimization procedure,

$$\alpha^r=\sum_{i=1}^{4}\sum_{j=0}^{32} N_{i,j}\delta^i\tau^{j/8}+\sum_{i=1}^{8}\sum_{j=0}^{16} N_{i,j}\delta^i\tau^{j/4}\exp(-\delta)$$
$$+\sum_{i=1}^{8}\sum_{j=0}^{16} N_{i,j}\delta^i\tau^{j/2}\exp(-\delta^2)$$
$$+\sum_{i=1}^{8}\sum_{j=0}^{16} N_{i,j}\delta^i\tau^{j}\exp(-\delta^3)+\sum_{i=1}^{10}\sum_{j=0}^{24} N_{i,j}\delta^i\tau^{j}$$
$$\times\exp(-\delta^4)+\sum_{i=1}^{10}\sum_{j=5}^{16} N_{i,j}\delta^i\tau^{2j}\exp(-\delta^5)$$
$$+\sum_{i=8}^{15}\sum_{j=5}^{16} N_{i,j}\delta^i\tau^{2j}\exp(-\delta^6)+\sum_{i=1}^{48} N_i\delta^{d_i}\tau^{t_i}$$
$$\times\exp(-\phi_i(\delta-1)^2-\beta_i(\tau-\gamma_i)^2), \qquad (54)$$

contained a total of 838 terms, including simple polynomial terms, combinations of polynomials with exponential expressions, and modified Gaussian bell-shaped terms that were introduced by Setzmann and Wagner (1991) to improve the representation of data in the critical region. The density and temperature exponents used in Eq. (54) were selected in a way which fulfills certain demands on the functional form of reference equations of state, see Span and Wagner (1997) and Span (2000). The parameters of the 48 Gaussian bell-shaped terms covered the ranges $1\leqslant d_i\leqslant 3$, $0\leqslant t_i\leqslant 3$, $15\leqslant\phi_i\leqslant 25$, $275\leqslant\beta_i\leqslant 325$, and $1.13\leqslant\gamma_i\leqslant 1.25$. Neither the importance of the critical region of nitrogen nor the data situation in this region made it necessary to use the complex nonanalytical terms developed by Span and Wagner (1996) for an improved description of caloric data in the immediate vicinity of the critical point. The residua used in both the linear and nonlinear algorithms correspond to common formulations recently explained in detail by Span (2000).

4.2.3. Equation for the Residual Helmholtz Energy

From the 838 terms in the bank of terms, Eq. (54), the optimization algorithms selected the final functional form for the residual Helmholtz energy given by

$$\alpha^r(\delta,\tau)=\sum_{k=1}^{6} N_k\delta^{i_k}\tau^{j_k}+\sum_{k=7}^{32} N_k\delta^{i_k}\tau^{j_k}\exp(-\delta^{l_k})$$
$$+\sum_{k=33}^{36} N_k\delta^{i_k}\tau^{j_k}\exp(-\phi_k(\delta-1)^2$$
$$-\beta_k(\tau-\gamma_k)^2). \qquad (55)$$

The coefficients N_k of this equation are given in Tables 17 and 18. Table 15 gives an overview of the quality of the fit of the new equation, and includes columns indicating the average absolute deviations (AAD) for the selected values from each data set. This table also shows the temperature and pressure ranges of the data.

4.3. Derived Thermodynamic Properties

Since Eq. (10) corresponds to one of the four fundamental equations known in thermodynamics, both thermal and caloric properties of nitrogen can be calculated directly. The

TABLE 17. Parameters and coefficients of the equation of state

k	N_k	i_k	j_k	l_k	k	N_k	i_k	j_k	l_k
1	0.924 803 575 275	1.0	0.25	0	19	$-0.435\,762\,336\,045\times10^{-1}$	1.0	4.0	2
2	−0.492 448 489 428	1.0	0.875	0	20	$-0.723\,174\,889\,316\times10^{-1}$	2.0	6.0	2
3	0.661 883 336 938	2.0	0.5	0	21	$0.389\,644\,315\,272\times10^{-1}$	3.0	6.0	2
4	$-0.192\,902\,649\,201\times10^{1}$	2.0	0.875	0	22	$-0.212\,201\,363\,910\times10^{-1}$	4.0	3.0	2
5	$-0.622\,469\,309\,629\times10^{-1}$	3.0	0.375	0	23	$0.408\,822\,981\,509\times10^{-2}$	5.0	3.0	2
6	0.349 943 957 581	3.0	0.75	0	24	$-0.551\,990\,017\,984\times10^{-4}$	8.0	6.0	2
7	0.564 857 472 498	1.0	0.5	1	25	$-0.462\,016\,716\,479\times10^{-1}$	4.0	16.0	3
8	$-0.161\,720\,005\,987\times10^{1}$	1.0	0.75	1	26	$-0.300\,311\,716\,011\times10^{-2}$	5.0	11.0	3
9	−0.481 395 031 883	1.0	2.0	1	27	$0.368\,825\,891\,208\times10^{-1}$	5.0	15.0	3
10	0.421 150 636 384	3.0	1.25	1	28	$-0.255\,856\,846\,220\times10^{-2}$	8.0	12.0	3
11	$-0.161\,962\,230\,825\times10^{-1}$	3.0	3.5	1	29	$0.896\,915\,264\,558\times10^{-2}$	3.0	12.0	4
12	0.172 100 994 165	4.0	1.0	1	30	$-0.441\,513\,370\,350\times10^{-2}$	5.0	7.0	4
13	$0.735\,448\,924\,933\times10^{-2}$	6.0	0.5	1	31	$0.133\,722\,924\,858\times10^{-2}$	6.0	4.0	4
14	$0.168\,077\,305\,479\times10^{-1}$	6.0	3.0	1	32	$0.264\,832\,491\,957\times10^{-3}$	9.0	16.0	4
15	$-0.107\,626\,664\,179\times10^{-2}$	7.0	0.0	1	33	$0.196\,688\,194\,015\times10^{2}$	1.0	0.0	2
16	$-0.137\,318\,088\,513\times10^{-1}$	7.0	2.75	1	34	$-0.209\,115\,600\,730\times10^{2}$	1.0	1.0	2
17	$0.635\,466\,899\,859\times10^{-3}$	8.0	0.75	1	35	$0.167\,788\,306\,989\times10^{-1}$	3.0	2.0	2
18	$0.304\,432\,279\,419\times10^{-2}$	8.0	2.5	1	36	$0.262\,767\,566\,274\times10^{4}$	2.0	3.0	2

functions used for calculating pressure, compressibility factor, internal energy, enthalpy, entropy, Gibbs energy, isochoric heat capacity, isobaric heat capacity, and the speed of sound from Eq. (10) are given in Eqs. (56)–(64). These functions were used in calculating the tables of thermodynamic properties of nitrogen given in the Appendix.

$$p=\rho RT\left[1+\delta\left(\frac{\partial\alpha^r}{\partial\delta}\right)_\tau\right] \tag{56}$$

$$Z=\frac{p}{\rho RT}=1+\delta\left(\frac{\partial\alpha^r}{\partial\delta}\right)_\tau \tag{57}$$

$$\frac{u}{RT}=\tau\left[\left(\frac{\partial\alpha^0}{\partial\tau}\right)_\delta+\left(\frac{\partial\alpha^r}{\partial\tau}\right)_\delta\right] \tag{58}$$

$$\frac{h}{RT}=\tau\left[\left(\frac{\partial\alpha^0}{\partial\tau}\right)_\delta+\left(\frac{\partial\alpha^r}{\partial\tau}\right)_\delta\right]+\delta\left(\frac{\partial\alpha^r}{\partial\delta}\right)_\tau+1 \tag{59}$$

$$\frac{s}{R}=\tau\left[\left(\frac{\partial\alpha^0}{\partial\tau}\right)_\delta+\left(\frac{\partial\alpha^r}{\partial\tau}\right)_\delta\right]-\alpha^0-\alpha^r \tag{60}$$

$$\frac{g}{RT}=1+\alpha^0+\alpha^r+\delta\left(\frac{\partial\alpha^r}{\partial\delta}\right)_\tau \tag{61}$$

$$\frac{c_v}{R}=-\tau^2\left[\left(\frac{\partial^2\alpha^0}{\partial\tau^2}\right)_\delta+\left(\frac{\partial^2\alpha^r}{\partial\tau^2}\right)_\delta\right] \tag{62}$$

$$\frac{c_p}{R}=\frac{c_v}{R}+\frac{\left[1+\delta\left(\frac{\partial\alpha^r}{\partial\delta}\right)_\tau-\delta\tau\left(\frac{\partial^2\alpha^r}{\partial\delta\partial\tau}\right)\right]^2}{\left[1+2\delta\left(\frac{\partial\alpha^r}{\partial\delta}\right)_r+\delta^2\left(\frac{\partial^2\alpha^r}{\partial\delta^2}\right)_\tau\right]} \tag{63}$$

$$\frac{w^2M}{RT}=1+2\delta\left(\frac{\partial\alpha^r}{\partial\delta}\right)_\tau+\delta^2\left(\frac{\partial^2\alpha^r}{\partial\delta^2}\right)_\tau-\frac{\left[1+\delta\left(\frac{\partial\alpha^r}{\partial\delta}\right)_\tau-\delta\tau\left(\frac{\partial^2\alpha^r}{\partial\delta\partial\tau}\right)\right]^2}{\tau^2\left[\left(\frac{\partial^2\alpha^0}{\partial\tau^2}\right)_\delta+\left(\frac{\partial^2\alpha^r}{\partial\tau^2}\right)_\delta\right]} \tag{64}$$

The value of the molar mass, M, was taken from IUPAC (1995). The relations for the fugacity coefficient and the second and third virial coefficients are given in Eqs. (65)–(67).

$$\phi=\exp[Z-1-\ln(Z)+\alpha^r] \tag{65}$$

$$B(T)=\frac{1}{\rho_c}\left(\frac{\partial\alpha^r}{\partial\delta}\right)_{\delta=0} \tag{66}$$

$$C(T)=\frac{1}{\rho_c^2}\left(\frac{\partial^2\alpha^r}{\partial\delta^2}\right)_{\delta=0} \tag{67}$$

Equations (68)–(78) give relations for typical derived properties and coefficients, such as the first derivative of pressure with respect to density at constant temperature $(\partial p/\partial\rho)_T$, the second derivative of pressure with respect to density at constant temperature $(\partial^2 p/\partial\rho^2)_T$, the first derivative of pressure with respect to temperature at constant density $(\partial p/\partial T)_\rho$, the Joule–Thomson coefficient (μ_J), the isentro-

TABLE 18. Parameters of the Gaussian bell-shaped terms in the equation of state

k	ϕ_k	β_k	γ_k
33	20	325	1.16
34	20	325	1.16
35	15	300	1.13
36	25	275	1.25

pic expansion coefficient (k), the isothermal expansion coefficient (k_T), the volume expansivity (β), the adiabatic compressibility (β_s), the adiabatic bulk modulus (B_s), the isothermal compressibility (κ), and the isothermal bulk modulus (K_T).

$$\left(\frac{\partial p}{\partial \rho}\right)_T = RT\left[1+2\delta\left(\frac{\partial \alpha^r}{\partial \delta}\right)_\tau + \delta^2\left(\frac{\partial^2 \alpha^r}{\partial \delta^2}\right)_\tau\right] \tag{68}$$

$$\left(\frac{\partial^2 p}{\partial \rho^2}\right)_T = \frac{RT}{\rho}\left[2\delta\left(\frac{\partial \alpha^r}{\partial \delta}\right)_\tau + 4\delta^2\left(\frac{\partial^2 \alpha^r}{\partial \delta^2}\right)_\tau + \delta^3\left(\frac{\partial^3 \alpha^r}{\partial \delta^3}\right)_\tau\right] \tag{69}$$

$$\left(\frac{\partial p}{\partial T}\right)_\rho = R\rho\left[1+\delta\left(\frac{\partial \alpha^r}{\partial \delta}\right)_\tau - \delta\tau\left(\frac{\partial^2 \alpha^r}{\partial \delta \partial \tau}\right)\right] \tag{70}$$

$$\mu_J = \left(\frac{\partial T}{\partial p}\right)_h = \frac{T\beta-1}{\rho c_p} \tag{71}$$

$$k = -\frac{v}{p}\left(\frac{\partial p}{\partial v}\right)_s = \frac{w^2\rho M}{p} \tag{72}$$

$$k_T = -\frac{v}{p}\left(\frac{\partial p}{\partial v}\right)_T = \frac{\rho}{p}\left(\frac{\partial p}{\partial \rho}\right)_T \tag{73}$$

$$\beta = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_p = \frac{1}{\rho}\left(\frac{\partial p}{\partial T}\right)_\rho\left(\frac{\partial \rho}{\partial p}\right)_T \tag{74}$$

$$\beta_s = \frac{1}{kp} = -\frac{1}{v}\left(\frac{\partial v}{\partial p}\right)_s \tag{75}$$

$$B_s = kp = -v\left(\frac{\partial p}{\partial v}\right)_s \tag{76}$$

$$\kappa = \frac{1}{k_T p} = -\frac{1}{v}\left(\frac{\partial v}{\partial p}\right)_T \tag{77}$$

$$K_T = k_T p = -v\left(\frac{\partial p}{\partial v}\right)_T \tag{78}$$

The derivatives of the equation for the ideal gas Helmholtz energy, Eq. (53), are

$$\tau\left(\frac{\partial \alpha^0}{\partial \tau}\right)_\delta = a_1 + a_3\tau - a_4\tau^{-1} - 2a_5\tau^{-2} - 3a_6\tau^{-3} + a_7 a_8 \tau\left[\frac{1}{\exp(a_8\tau)-1}\right] \tag{79}$$

and

$$\tau^2\left(\frac{\partial^2 \alpha^0}{\partial \tau^2}\right)_\delta = -a_1 + 2a_4\tau^{-1} + 6a_5\tau^{-2} + 12a_6\tau^{-3} - a_7 a_8^2 \tau^2 \frac{\exp(a_8\tau)}{[\exp(a_8\tau)-1]^2}, \tag{80}$$

where a_1 through a_8 are given in Eq. (53). The required derivatives of the equation for the residual Helmholtz energy, Eq. (55), with respect to δ or τ are given in Eqs. (81)–(86).

$$\delta\left(\frac{\partial \alpha^r}{\partial \delta}\right)_\tau = \sum_{k=1}^{6} i_k N_k \delta^{i_k}\tau^{j_k} + \sum_{k=7}^{32} N_k \delta^{i_k}\tau^{j_k}\exp(-\delta^{l_k}) \times (i_k - l_k\delta^{l_k}) + \sum_{k=33}^{36} N_k \delta^{i_k}\tau^{j_k}\exp(-\phi_k(\delta-1)^2 - \beta_k(\tau-\gamma_k)^2)[i_k - 2\delta\phi_k(\delta-1)] \tag{81}$$

$$\delta^2\left(\frac{\partial^2 \alpha^r}{\partial \delta^2}\right)_\tau = \sum_{k=1}^{6} i_k(i_k-1) N_k \delta^{i_k}\tau^{j_k} + \sum_{k=7}^{32} N_k \delta^{i_k}\tau^{j_k} \times \exp(-\delta^{l_k})[(i_k - l_k\delta^{l_k})(i_k - 1 - l_k\delta^{l_k}) - l_k^2\delta^{l_k}] + \sum_{k=33}^{36} N_k \delta^{i_k}\tau^{j_k}\exp(-\phi_k(\delta-1)^2 - \beta_k(\tau-\gamma_k)^2)\{[i_k - 2\varphi_k\delta(\delta-1)]^2 - i_k - 2\delta^2\varphi_k\} \tag{82}$$

$$\delta^3\left(\frac{\partial^3 \alpha^r}{\partial \delta^3}\right)_\tau = \sum_{k=1}^{6} i_k(i_k-1)(i_k-2) N_k \delta^{i_k}\tau^{j_k} + \sum_{k=7}^{32} N_k \delta^{i_k}\tau^{j_k}\exp(-\delta^{l_k})\{i_k(i_k-1)(i_k-2) + \delta^{l_k}[-2l_k + 6i_k l_k - 3i_k^2 l_k - 3i_k l_k^2 + 3l_k^2 - l_k^3] + \delta^{2l_k}[3i_k l_k^2 - 3l_k^2 + 3l_k^3] - l_k^3\delta^{3l_k}\} + \sum_{k=33}^{36} N_k \delta^{i_k}\tau^{j_k}\exp(-\varphi_k(\delta-1)^2 - \beta_k(\tau-\gamma_k)^2) \times \left\{\begin{matrix}[-2\varphi_k(\delta-1)\delta]^3 + i_k(2-3i_k+i_k^2) + 3(2\varphi_k\delta)^2(\delta-1)[-i_k+\delta(1+i_k)] \\ -2\varphi_k\delta[(3i_k^2-3i_k)(\delta-1)+3\delta i_k]\end{matrix}\right\} \tag{83}$$

$$\tau\left(\frac{\partial\alpha^r}{\partial\tau}\right)_\delta=\sum_{k=1}^{6} j_kN_k\delta^{i_k}\tau^{j_k}+\sum_{k=7}^{32} j_kN_k\delta^{i_k}\tau^{j_k}\exp(-\delta^{l_k})+\sum_{k=33}^{36} N_k\delta^{i_k}\tau^{j_k}\exp(-\phi_k(\delta-1)^2-\beta_k(\tau-\gamma_k)^2)[j_k-2\tau\beta_k(\tau-\gamma_k)] \quad (84)$$

$$\tau^2\left(\frac{\partial^2\alpha^r}{\partial\tau^2}\right)_\delta=\sum_{k=1}^{6} j_k(j_k-1)N_k\delta^{i_k}\tau^{j_k}+\sum_{k=7}^{32} j_k(j_k-1)N_k\delta^{i_k}\tau^{j_k}\exp(-\delta^{l_k})+\sum_{k=33}^{36} N_k\delta^{i_k}\tau^{j_k}\exp(-\phi_k(\delta-1)^2-\beta_k(\tau-\gamma_k)^2)\{[j_k-2\beta_k\tau(\tau-\gamma_k)]^2-j_k-2\tau^2\beta_k\} \quad (85)$$

$$\delta\tau\left(\frac{\partial^2\alpha^r}{\partial\delta\partial\tau}\right)=\sum_{k=1}^{6} i_kj_kN_k\delta^{i_k}\tau^{j_k}+\sum_{k=7}^{32} j_kN_k\delta^{i_k}\tau^{j_k}\times\exp(-\delta^{l_k})(i_k-l_k\delta^{l_k})+\sum_{k=33}^{36} N_k\delta^{i_k}\tau^{j_k}\times\exp(-\phi_k(\delta-1)^2-\beta_k(\tau-\gamma_k)^2)\times[i_k-2\delta\phi_k(\delta-1)][j_k-2\tau\beta_k(\tau-\gamma_k)] \quad (86)$$

5. Comparisons of the Equation of State to Experimental Data

The accuracy of the equation of state is discussed here by comparing property values calculated with the equation of state to experimental data and by statistically analyzing the results of these comparisons. The statistics are based on the percent deviation in any property, X, defined as

$$\%\Delta X=100\left(\frac{X_{\text{data}}-X_{\text{calc}}}{X_{\text{data}}}\right). \quad (87)$$

Using this definition, the percent average absolute deviation is defined as

$$\text{AAD}=\frac{1}{n}\sum_{i=1}^{n}|\%\Delta X_i|, \quad (88)$$

where n is the number of data points.

For comparison, values calculated from the equations of state by Jacobsen *et al.* (1986) and by Jacobsen and Stewart (1973) are plotted as dashed lines in all of the diagrams shown in the following sections, except for those which show enthalpy differences (for properties such as enthalpy differences, two equations of state cannot be compared by plotting simple lines). When a property range is listed in the header of a given plot, the dashed lines correspond to the first value listed in the header. The discussion in the following sections focuses solely on the new equation of state. The performances of the older equations are not discussed, unless a comparison between both equations allows conclusions to be drawn with regard to the quality of the new equation of state.

The equation of Jacobsen and Stewart (1973) is virtually identical to the standard for nitrogen properties that was implemented in the NIST Thermophysical Properties of Pure Fluids Database (NIST12, formerly called NIST MIPROPS), which was available from the Standard Reference Data Program of the National Institute of Standards and Technology (Friend, 1992). The equation presented here has replaced the old standard surface for nitrogen and is available in version 5.0 of NIST12 (Lemmon *et al.*, 2000), and, upon formal adoption by the relevant standards organizations, is expected to become the consensus standard to be used for contractual and calibration purposes.

5.1. Comparisons with Vapor Pressures and Saturation Densities

Figures 15, 16, and 17 show comparisons of vapor pressures and saturated liquid and vapor densities calculated from the equation of state with experimental data. The solid lines in these figures represent the ancillary equations reported in Sec. 2.6. At temperatures above 70 K, relative differences between the vapor pressure data of Nowak *et al.* and calculated values are within ±0.01%. At temperatures below 70 K, the differences increase up to 0.026% at T_{tp}.

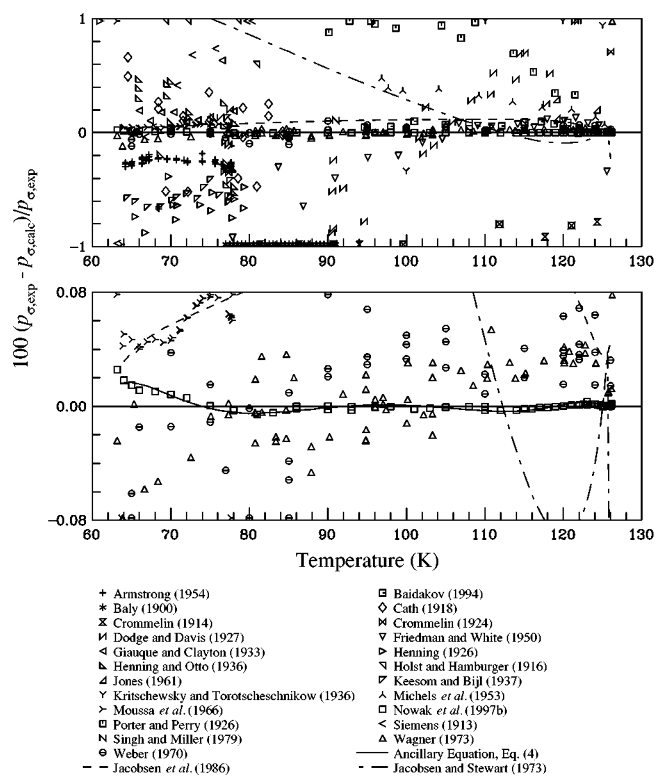

FIG. 15. Comparisons of vapor pressures calculated with the equation of state to experimental data.

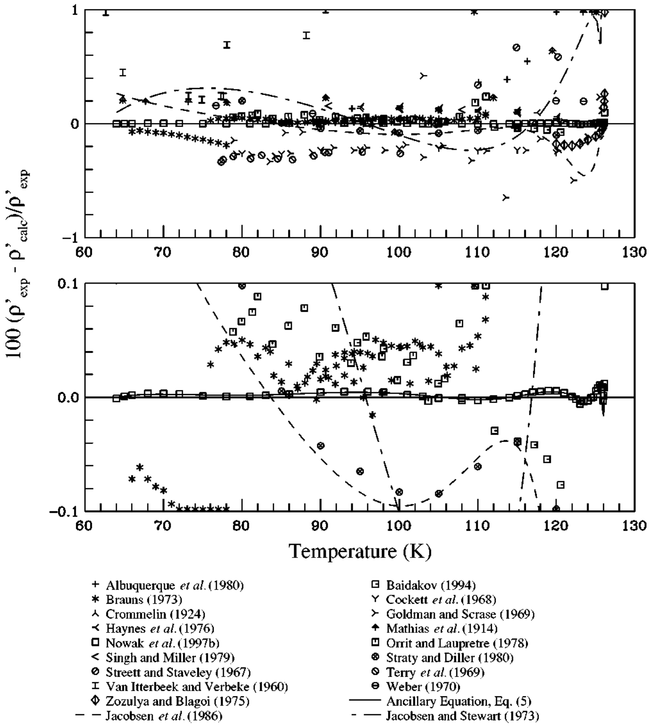

FIG. 16. Comparisons of saturated liquid densities calculated with the equation of state to experimental data.

However, these enlarged percent deviations are still well within the uncertainty of the low temperature data, see Sec. 2.3.

Up to temperatures of 125 K, the new equation of state represents the saturated liquid density data of Nowak *et al.* within $\pm 0.01\%$. Close to the critical temperature, larger deviations are observed, but they are still within the increased experimental uncertainty of the data. The same is true for saturated vapor densities, except for the fact that slightly larger deviations are also observed at temperatures below 70 K. These higher deviations at low temperatures are directly related to the enlarged relative uncertainty of the vapor pressure and stay well within the uncertainty of the experimental data.

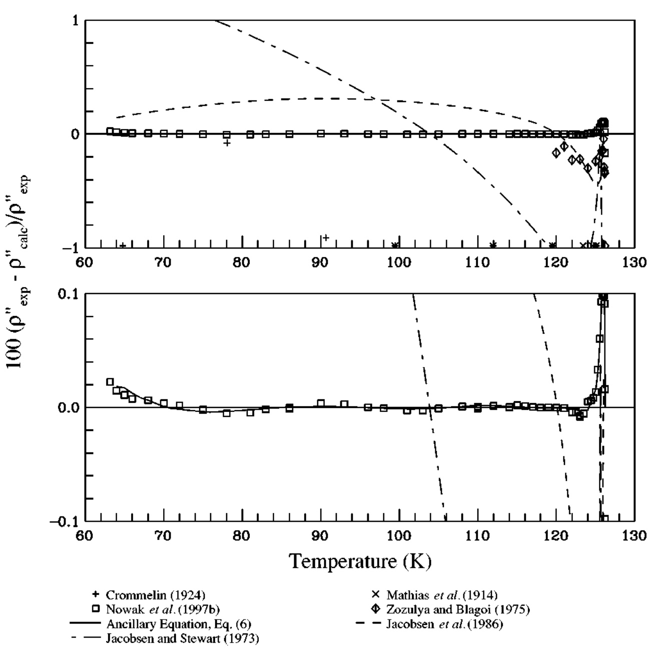

FIG. 17. Comparisons of saturated vapor densities calculated with the equation of state to experimental data.

Differences between calculated values using the equation of state and the vapor pressure data of Weber (1970), Wagner (1973), and Moussa *et al.* (1966) are within $\pm 0.1\%$. For the saturated liquid densities, differences between calculated values and the data of Baidakov (1994), Brauns (1973), Orrit and Laupretre (1978), and Straty and Diller (1980) are generally within $\pm 0.1\%$. Differences between saturated vapor densities calculated from the equation of state and the data of Zozulya and Blagoi (1975) are within $\pm 0.35\%$, except at the highest temperature.

5.2. Comparisons of the Equation of State for Nitrogen with other Experimental Data

Table 15 compares selected experimental data sets that were used in fitting the equation of state including $p\rho T$, isochoric, isobaric and saturation heat capacities, speed of sound, enthalpies, and second and third virial coefficients. Figures 18–22 show deviations of the equation of state to selected experimental data. Figure 18 shows comparisons of

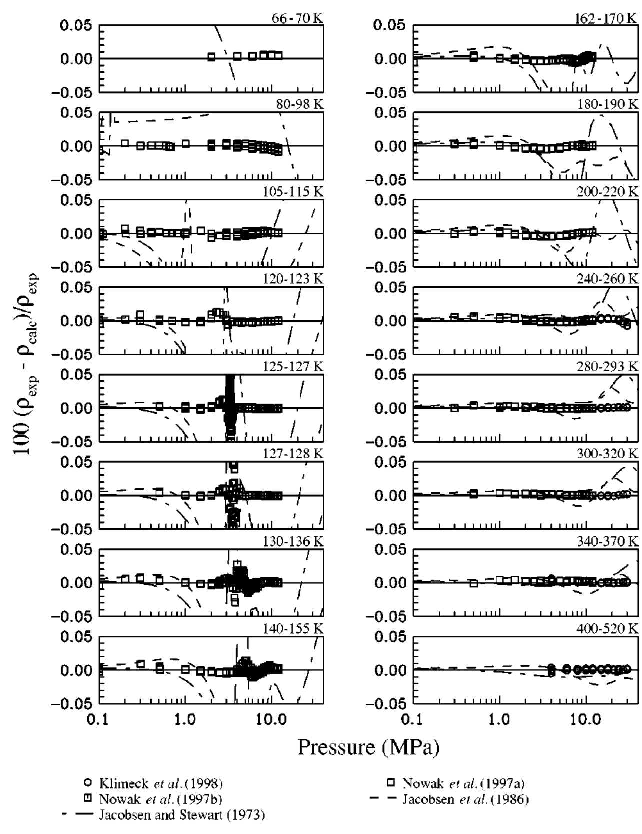

FIG. 18. Comparisons of densities calculated with the equation of state to the experimental data of Klimeck *et al.* (1998) and Nowak *et al.* (1997a,b).

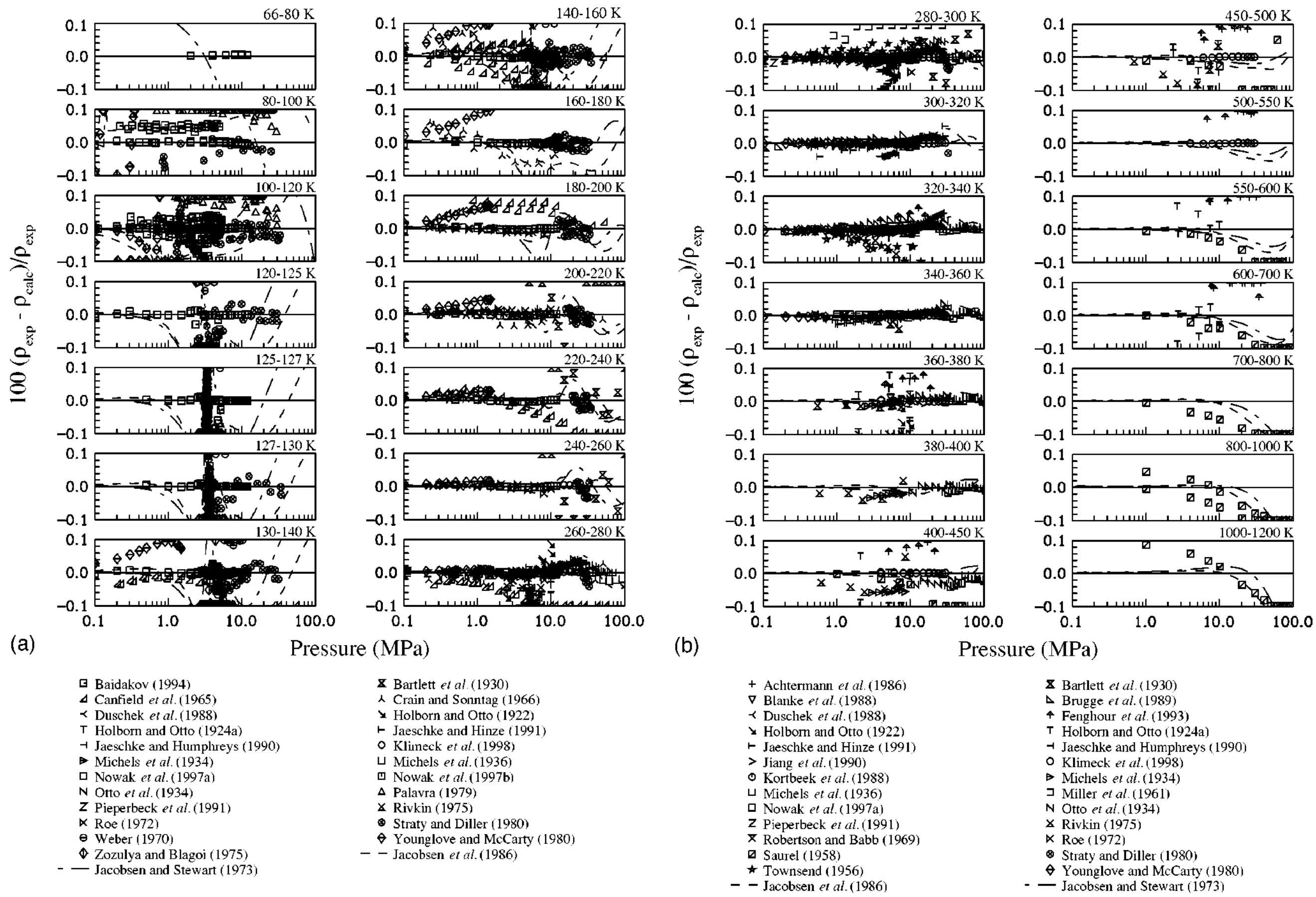

FIG. 19. Comparisons of densities calculated with the equation of state to accurate experimental data.

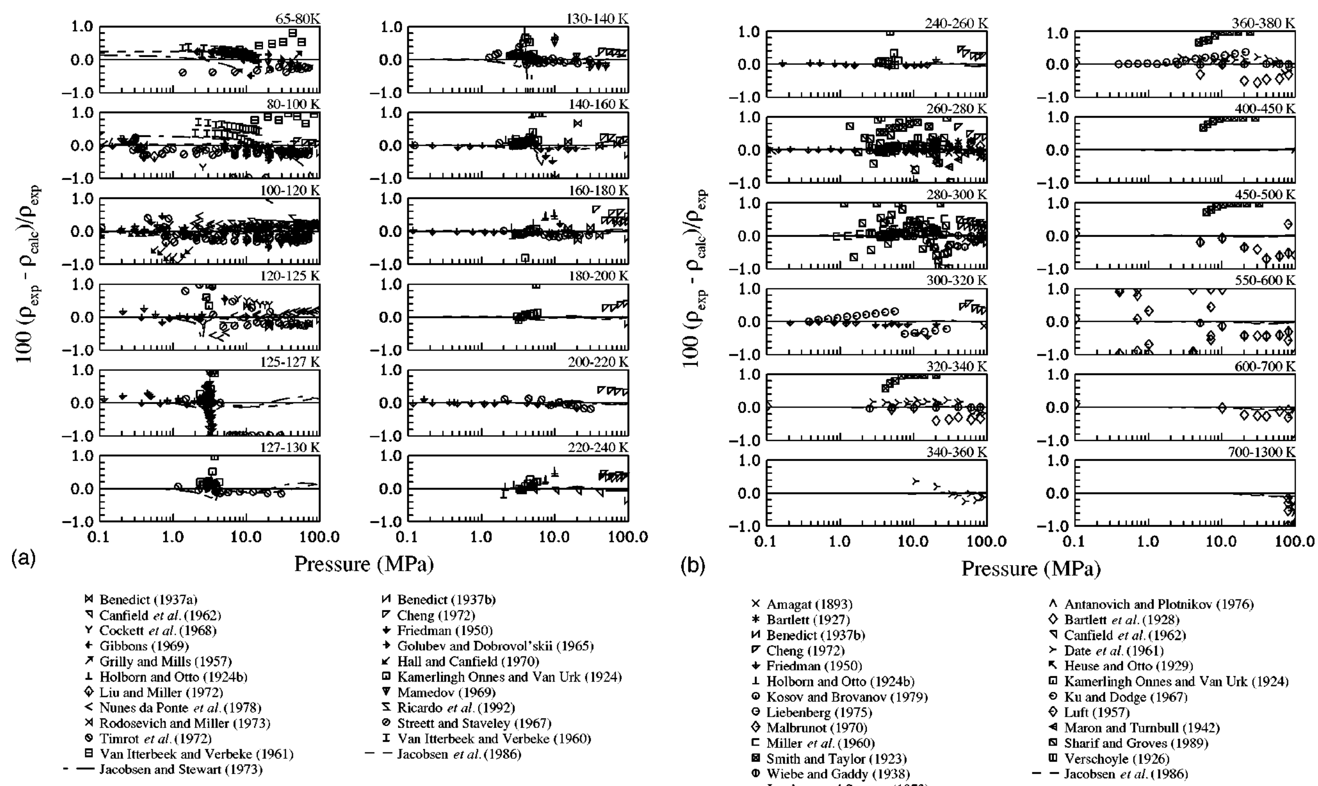

FIG. 20. Comparisons of densities calculated with the equation of state to experimental data with higher uncertainties.

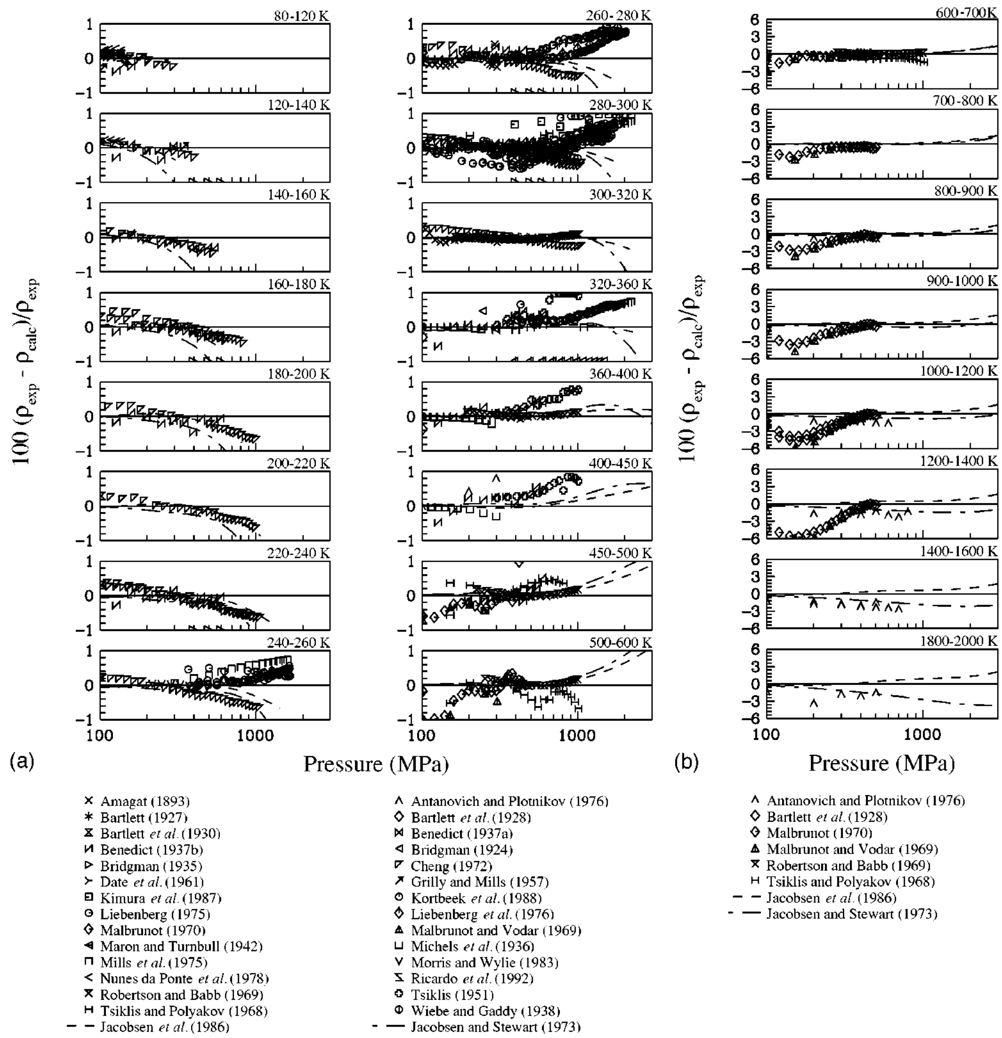

FIG. 21. Comparisons of densities calculated with the equation of state to experimental data at pressures greater than 100 MPa.

densities calculated from the equation of state with the experimental data of Klimeck *et al.* (1998) and Nowak *et al.* (1997a, 1997b). Figure 19 shows comparisons of densities calculated from the equation of state with experimental data that have uncertainties generally within 0.1% in density. Comparisons with data with experimental uncertainties generally greater than 0.1% in density are shown in Fig. 20. Figure 21 shows comparisons of densities calculated from the equation of state with experimental data at high temperatures and pressures. Figure 22 shows comparisons of pressures calculated from the equation of state with the experimental data in the critical region of nitrogen. Comparisons of second virial coefficients calculated using the equation of state to reported values are shown in Fig. 23.

Comparisons between experimental data and values calculated from the equation of state are shown for the speed of sound in Figs. 24 and 25, for the isobaric heat capacities in Fig. 26, for the isochoric heat capacities in Fig. 27, and for saturation heat capacities in Fig. 28. Comparisons of enthalpy differences are shown in Fig. 29. The few data available for the Joule–Thomson coefficient and for heats of vaporization are not helpful in assessing the performance of the new equation of state and do not justify further figures.

Highly accurate measurements for the gas region at temperatures below the critical temperature include the $p\rho T$ data of Nowak *et al.* (1997a) and the speed of sound data of Ewing and Trusler (1992) and Younglove and McCarty (1980). These data are highly consistent with each other, except for the speed of sound data of Younglove and McCarty close to the phase boundary, which deviate from the values of Ewing and Trusler (1992) by as much as $\pm 0.7\%$. This large inconsistency is most likely caused by precondensation effects in the apparatus of Younglove and McCarty, see Mehl and Moldover (1982). The corresponding data were used only with reduced weights when establishing the new equation of state.

In the low temperature liquid region, the $p\rho T$ surface is represented by the data of Nowak *et al.* (1997a), which extend up to 12 MPa. For temperatures above 80 K, the data of Straty and Diller (1980) extend the range where accurate $p\rho T$ data are available, to pressures of 35 MPa. At higher pressures no accurate $p\rho T$ data are available, but the speed

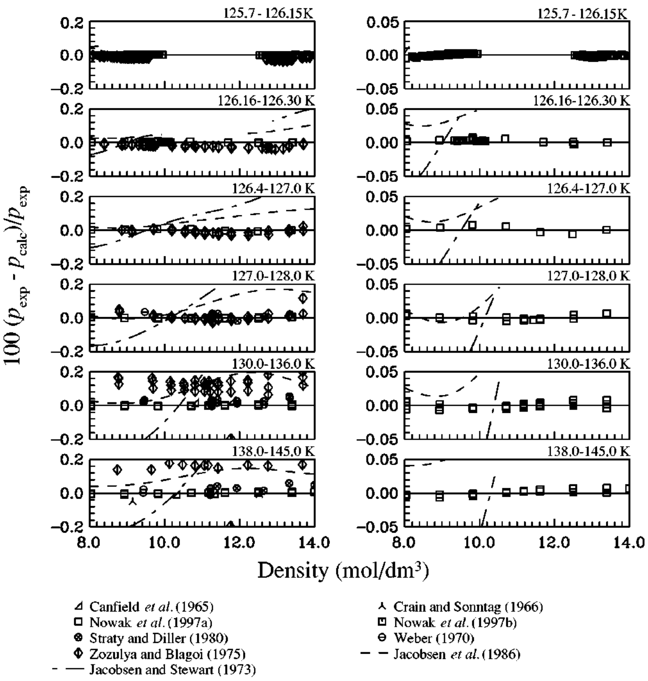

FIG. 22. Comparisons of pressures calculated with the equation of state to experimental data in the critical region.

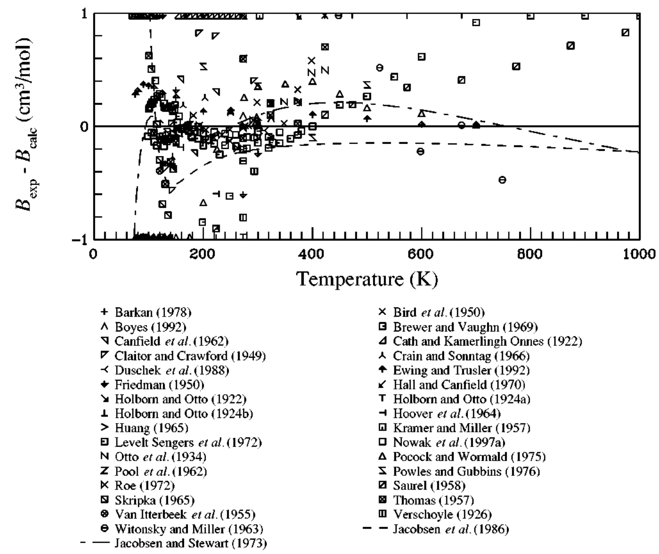

FIG. 23. Comparisons of second virial coefficients calculated with the equation of state to experimental data.

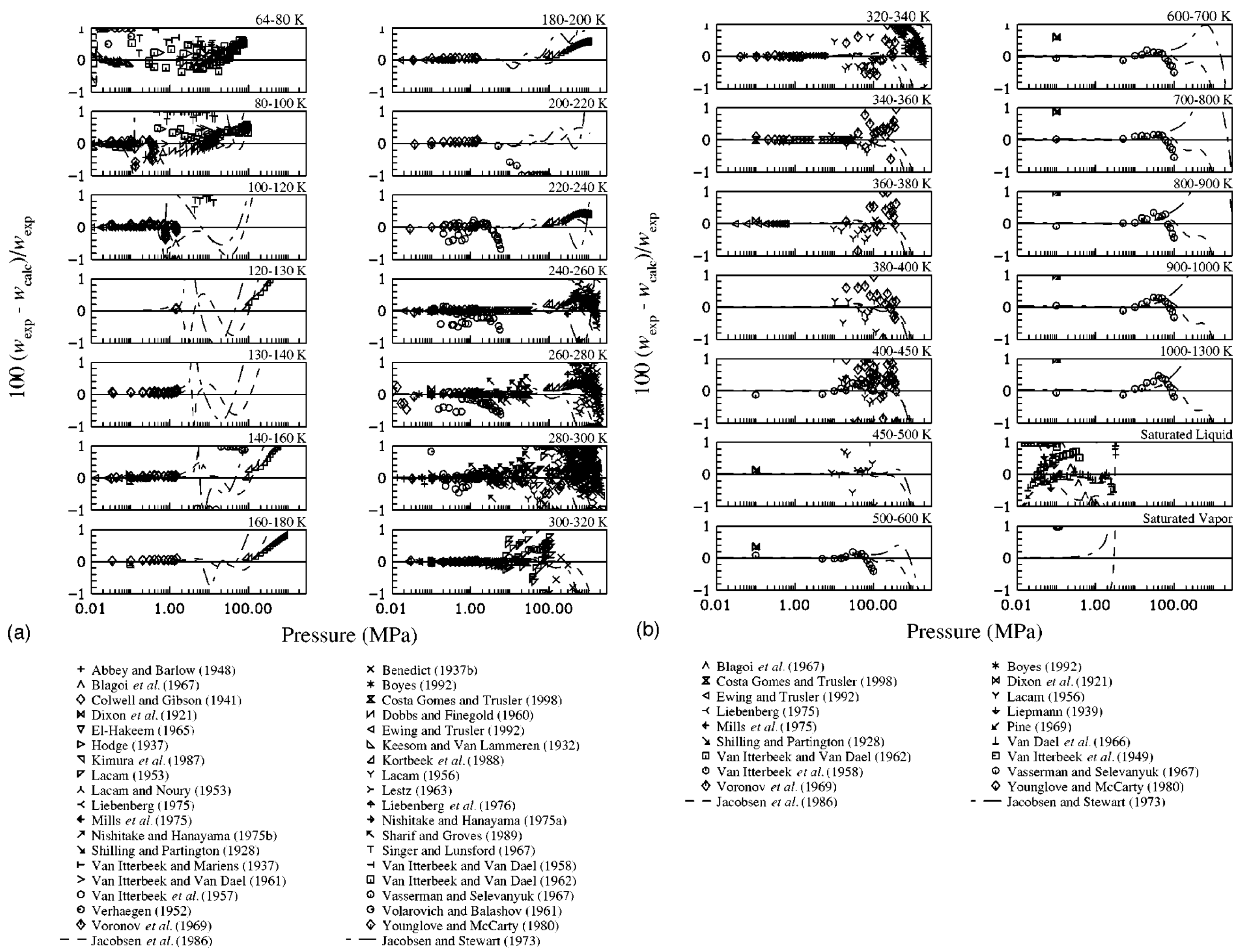

FIG. 24. Comparisons of sound speeds calculated with the equation of state to experimental data.

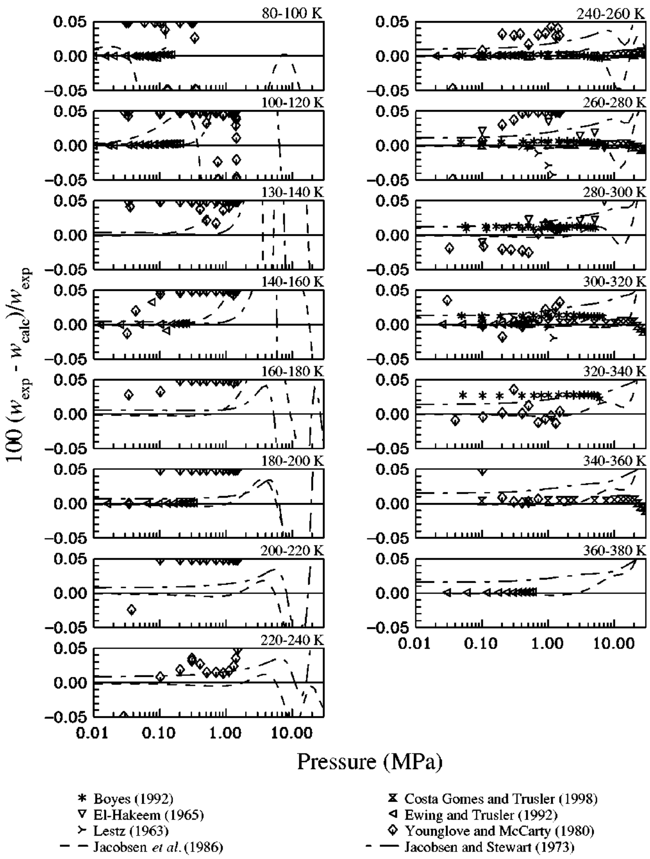

FIG. 25. Comparisons of sound speeds calculated with the equation of state to experimental data and corrected experimental data in the vapor phase.

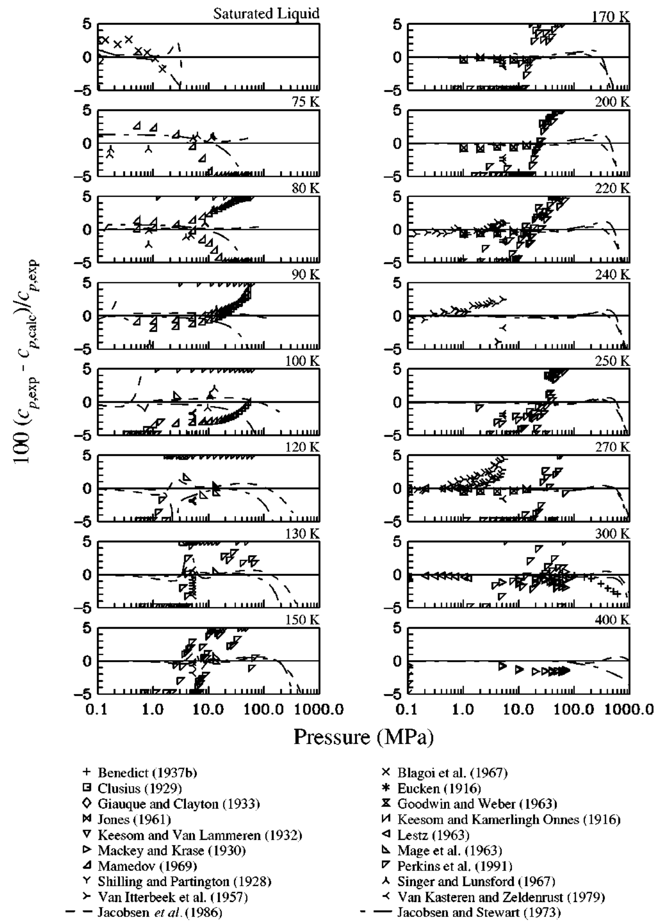

FIG. 26. Comparisons of isobaric heat capacities calculated with the equation of state to experimental data.

of sound data of Van Itterbeek and Van Dael (1962) reach up to 97 MPa even at very low temperatures. The representation of the caloric properties of liquid nitrogen depends mainly on the speed of sound data of Dobbs and Finegold (1960) and Van Itterbeek and Van Dael (1961, 1962), and on the isochoric heat capacity data measured by Magee (1991) and Weber (1981).

In the critical region, the data of Nowak *et al.* (1997a, 1997b) improve the description of thermal properties which were formally dependent on the data of Zozulya and Blagoi (1975) and of Weber (1970) in the equation of state of Jacobsen *et al.* (1986). Unfortunately, there are no accurate caloric data available in this region.

In the supercritical region at temperatures below 240 K, the description of the $p\rho T$ surface depends mainly on the data of Nowak *et al.* (1997a) and Straty and Diller (1980). The caloric properties of nitrogen are accurately described by the speed of sound data of Ewing and Trusler (1992) and Younglove and McCarty (1980), by the isochoric heat capacities of Magee (1991) and Weber (1981), and by the enthalpy differences measured by Grini and Owren (1997).

For temperatures between about 250 and 350 K, nitrogen has been investigated intensively as one of the main components of natural gases and as a calibration fluid for applications in the gas industry. The most accurate available $p\rho T$ data are the recent data of Nowak *et al.* (1997a) up to 12 MPa and of Klimeck *et al.* (1998) up to 30 MPa, but in this region the reference data are supplemented by several other data sets of at least comparable uncertainty (Achtermann *et al.*, 1986; Duschek *et al.*, 1988; Jaeschke and Hinze, 1991; and Pieperbeck *et al.*, 1991). For pressures above 30 MPa, the most accurate $p\rho T$ data are still those of Michels *et al.* (1936). The representation of the caloric properties depends mainly on the speed of sound measurements of Boyes (1992) and Costa Gomes and Trusler (1998) at pressures up to 30 MPa. These data are supplemented by other measurements (Hodge, 1937; El-Hakeem, 1965; and Sharif and Groves, 1989; for pressures below 2 MPa: Ewing and Trusler, 1992 and Younglove and McCarty, 1980). Relevant data for other caloric properties are available up to 307 K (Magee, 1991 and Grini and Owren, 1997).

At higher temperatures, the data of Klimeck *et al.* (1998) extend up to 520 K. These data are supplemented by other accurate $p\rho T$ data (Michels *et al.*, 1936) up to 473 K. The only recent data at higher temperatures are those of Fenghour *et al.* (1993) which reach up to 679 K. Above this temperature, the data set consists mainly of the apparently less accurate measurements of Saurel (1958). Other high temperature $p\rho T$ data (Malbrunot and Vodar, 1969; Malbrunot, 1970; and Antanovich and Plotnikov, 1976) are inconsistent with

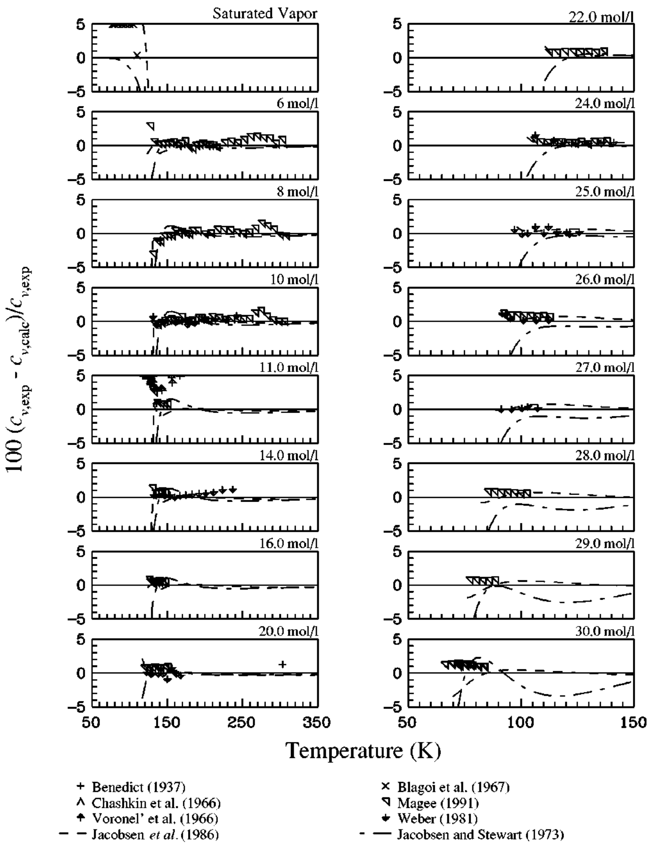

FIG. 27. Comparisons of isochoric heat capacities calculated with the equation of state to experimental data.

more accurate data at temperatures where the data sets overlap. The only accurate caloric data at high temperatures are the speed of sound data of Vasserman and Selevanyuk (1967).

At high pressures, the data set for nitrogen consists primarily of speed of sound and $p\rho T$ data, but compared to the lower pressure data, the accuracy of the high pressure data is substantially lower. Up to 300 MPa, the data of Michels *et al.* (1936) yield the best description of the $p\rho T$ surface, although they show significantly increased uncertainties for pressures above 100 MPa. Above 300 MPa, the data of Morris and Wylie (1983) and Robertson and Babb (1969) deviate

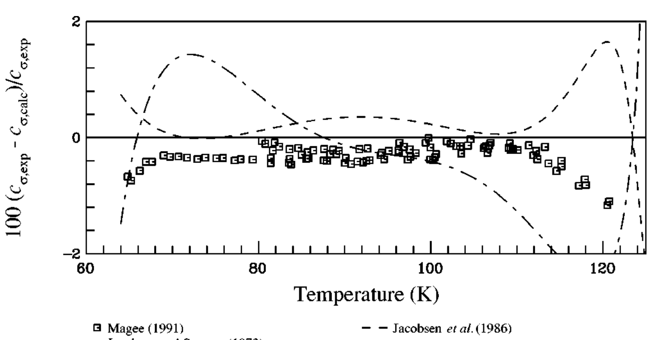

FIG. 28. Comparisons of saturated liquid heat capacities calculated with the equation of state to experimental data.

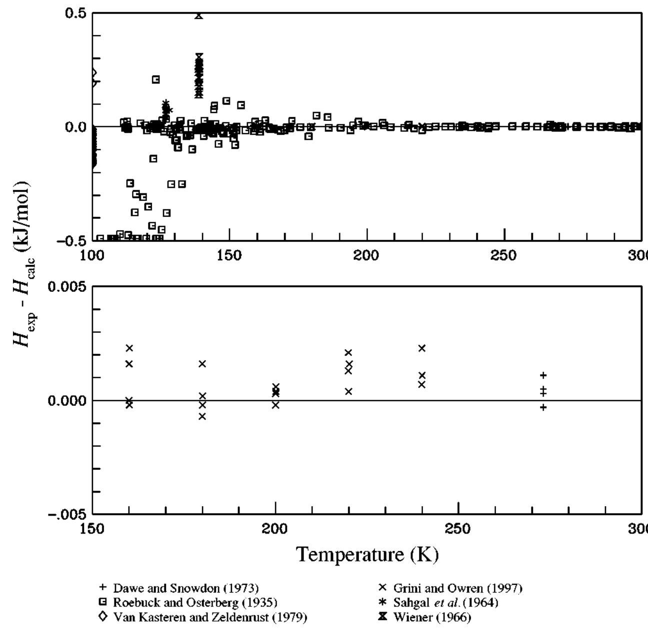

FIG. 29. Comparisons of enthalpy differences calculated with the equation of state to experimental data.

by about $\pm 0.1\%$ in density, while all other data sets appear to be less accurate. Accurate information on the speed of sound at very high pressures was available only for temperatures between 248 and 321 K (Nishitake and Hanayama, 1975a, 1975b; Liebenberg, 1975; Mills *et al.*, 1975; Liebenberg *et al.*, 1976), until Kortbeek *et al.* (1988) extended the temperature range down to 123 K.

Only a few reliable data sets are available for caloric properties along the phase boundaries. The c_σ data measured by Magee (1991) describe the heat capacity of the saturated liquid within $\pm 0.5\%$ and provide reliable results for the heat capacities in the two-phase liquid. For the speed of sound in the saturated liquid, the data of Van Itterbeek and Van Dael (1962) and Van Dael *et al.* (1966) are accurate to within $\pm 0.5\%$. No reliable data have been published for caloric properties of the saturated vapor.

5.3. Representation of Properties in the Critical Region

Thermal properties in the critical region are represented by the new equation of state within the uncertainty of the most accurate experimental results. This was shown in Fig. 22 for properties at homogeneous states. Even in the immediate vicinity of the critical point, the $p\rho T$ data of Nowak *et al.* (1997a, 1997b) are reproduced within $\pm 0.01\%$ in pressure. Figure 30 shows the representation of thermal properties of the coexisting phases close to the critical temperature. Up to the critical temperature, the vapor pressure is represented within $\pm 0.005\%$. For the densities of the coexisting phases, slightly enlarged deviations on the order of $\pm 0.1\%$ in density are observed in the critical region. However, considering the large compressibility and thermal expansivity in the critical

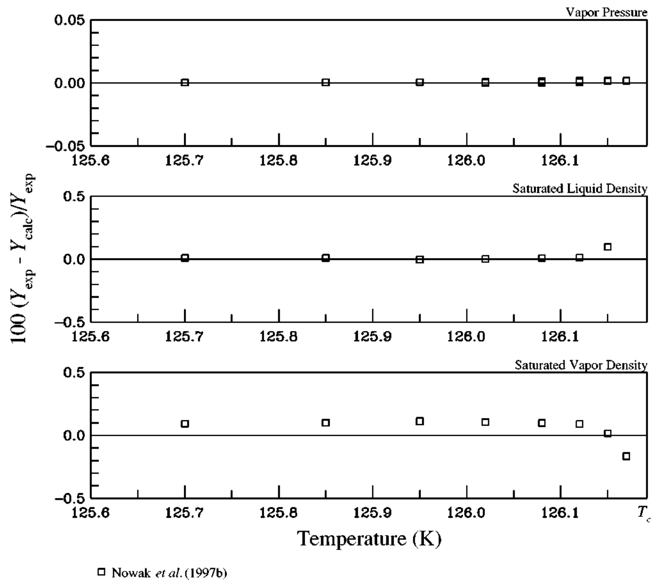

FIG. 30. Comparisons of saturation properties in the critical region calculated with the equation of state to experimental data.

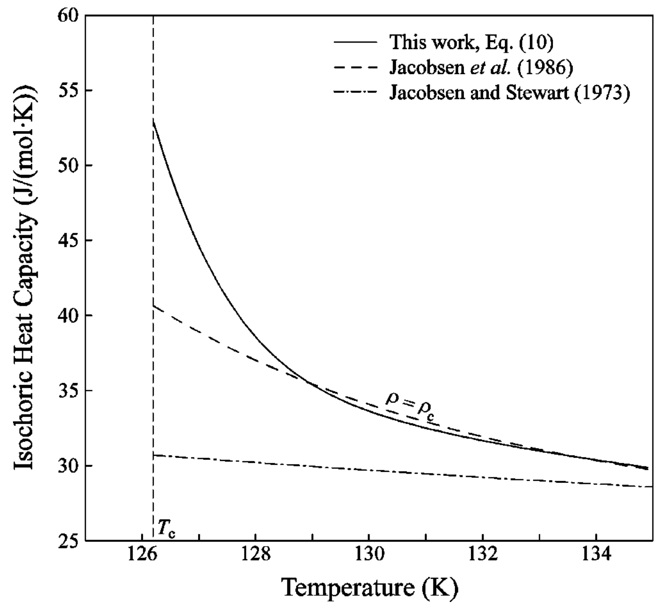

FIG. 31. Comparisons of the isochoric heat capacity on the critical isochore between calculations from the new equation of state and from the equations of Jacobsen *et al.* (1986) and Jacobsen and Stewart (1973).

region, deviations of $\pm 0.1\%$ in density are quite small and well within the uncertainty of the experimental data.

Since the new equation of state describes the thermal properties in the critical region very accurately, it should also be able to describe isobaric heat capacities accurately, since the isobaric heat capacity depends mainly on derivatives of thermal properties in the critical region. For details on the representation of caloric properties in the critical region, see Span and Wagner (1996) or Span (2000). Since the new equation is purely analytic, it is limited in its ability to fulfill theoretical predictions for the isochoric heat capacity and the speed of sound in the limit of vanishing distance to the critical point. Figure 31 shows the isochoric heat capacity on the critical isochore of nitrogen calculated from the equation presented here, and from the equations of Jacobsen *et al.* (1986) and Jacobsen and Stewart (1973). The mBWR equation by Jacobsen and Stewart yields the expected result for classical equations of state, it is unable to follow the increase in the isochoric heat capacity, and calculated values are far too small in the critical region. The more recent equation by Jacobsen *et al.* is able to follow the expected plot of the isochoric heat capacity up to $T > T_c + 2.5\,\mathrm{K}$. The new equation gives reliable results for $T > T_c + 0.5\,\mathrm{K}$, but closer to the critical temperature it is also unable to follow the theoretically expected divergence of the isochoric heat capacity. Corresponding results can be found for the speed of sound as seen in Fig. 32; the two recent equations yield similar results on the 135 K isotherm ($T \approx T_c + 8.8\,\mathrm{K}$), while the mBWR equation of state predicts values that are too high. On the 128 K isotherm ($T \approx T_c + 1.8\,\mathrm{K}$), the new equation and the equation by Jacobsen *et al.* yield similar results, but only the new equation predicts the theoretically expected pronounced minimum around the critical isochore. This effect becomes stronger when looking directly at the critical isotherm, but the new equation is still not able to predict the extremely sharp minimum of the speed of sound that is expected very close to the critical point.

Except in the immediate vicinity of the critical point ($|T - T_c| < 0.5\,\mathrm{K}$ and $|\rho - \rho_c| < 2\,\mathrm{mol/dm^3}$), the new equation of state yields reliable values for all thermal and caloric properties in the critical region of nitrogen. The predicted values for the isochoric heat capacity and for the speed of sound do not agree with theoretical expectations close to the critical point. Based on this assessment, the new equation can be used to calculate properties for any kind of scientific

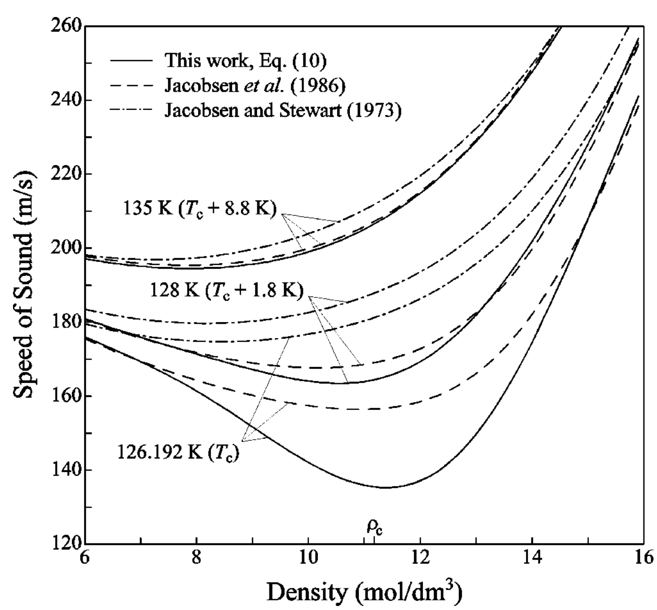

FIG. 32. Comparisons of the speed of sound in the critical region between calculations from the new equation of state and from the equations of Jacobsen *et al.* (1986) and Jacobsen and Stewart (1973).

or technical application in the critical region of nitrogen, but it should not be used for theoretical studies where the limiting behavior of the isochoric heat capacity or of the speed of sound is decisive.

5.4. Extrapolation Behavior

5.4.1. Ideal Curves of Nitrogen

Plots of certain ''ideal curves'' are useful in assessing the behavior of an equation of state in regions away from the available data (Deiters and de Reuck, 1997; Span and Wagner, 1997; Span, 2000) as well as in revealing inconsistencies in the available data sets. The characteristic curves considered in this work are the ideal curve, given by the equation

$$Z=1, \tag{89}$$

the Boyle curve,

$$\left(\frac{\partial Z}{\partial \nu}\right)_T=0, \tag{90}$$

the Joule–Thomson inversion curve,

$$\left(\frac{\partial Z}{\partial T}\right)_p=0, \tag{91}$$

and the Joule inversion curve,

$$\left(\frac{\partial Z}{\partial T}\right)_\nu=0. \tag{92}$$

These characteristic curves for the equation of state for nitrogen are illustrated in Fig. 33. Although the curves in this figure do not provide numerical information, reasonable shapes without visible oscillations as shown indicate qualitatively correct extrapolation behavior of the equation of state (Span and Wagner, 1997).

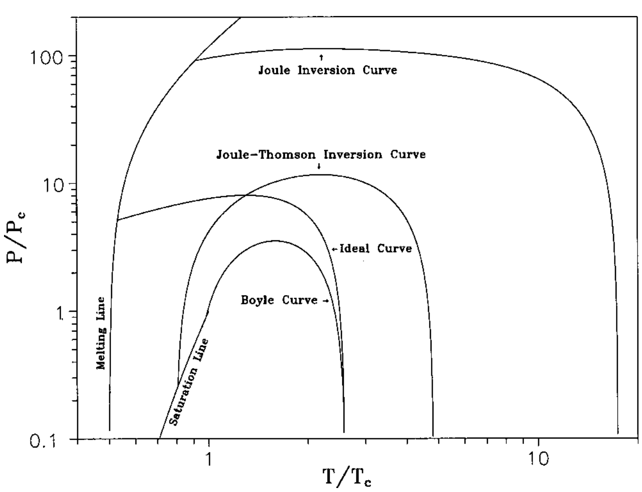

FIG. 33. Characteristic curves.

5.4.2. Hugoniot Curve

One method used to demonstrate the extrapolation behavior of an equation of state at extreme temperatures and pressures is the examination of the Hugoniot curve. The Hugoniot curve is the locus of states accessible to a fluid after a shock wave that occurs at a specified initial state. The conservation relations for fluid properties before and after the shock wave taken from Nellis and Mitchell (1980) and the equation of state presented here was used to generate the Hugoniot curve for nitrogen. The equations for the conservation of mass, momentum, and energy across the shock wave are

$$p-p_o=\rho_o(w_s-w_o)(w_p-w_o), \tag{93}$$

$$v=v_o\left[1-\frac{(w_p-w_o)}{(w_s-w_o)}\right], \tag{94}$$

and

$$u-u_o=0.5(p+p_o)(v_o-v), \tag{95}$$

where p_o is the initial pressure, ρ_o is the initial mass density, u_o is the initial molar internal energy, v_o is the initial molar volume, w_o is the initial velocity of the material ahead of the shock front, p is the final shock pressure, v is the final molar volume, and u is the final molar internal energy. The velocity of the shock wave is w_s and the velocity of the material downstream from the shock front is w_p. Combining Eqs. (93) and (94) results in

$$v=v_0\left(1-\frac{p-p_o}{\rho_o w_s^2}\right). \tag{96}$$

Rearrangement of Eq. (95) results in

$$v=\frac{-2(u-u_o)}{p+p_o}+v_o. \tag{97}$$

To calculate the Hugoniot curve for nitrogen for a specified upstream state (p_0,T_0) and downstream pressure (p), a value for the shock wave velocity w_s is estimated and the molar volume ν at the downstream state is calculated by means of Eq. (96). Using the calculated molar volume, the temperature and internal energy u are calculated using the equation of state for nitrogen. A second value of the molar volume at the downstream state is then calculated with Eq. (97). If the molar volumes calculated from Eqs. (96) and (97) differ, a new estimate for the shock wave velocity is made and the process is repeated. The iteration continues until the specific volumes are the same within a specified criterion. Figure 34 shows the Hugoniot curve for nitrogen calculated using this process for an initial state on the bubble line at 77.5 K, as specified by Nellis and Mitchell. The reported shock tube points above 30 GPa were not included because nitrogen spontaneously dissociates above 30 GPa (Nellis and Mitchell, 1980).

Preliminary equations for nitrogen which were established by choosing a suitable functional form (Span and Wagner, 1997) showed a qualitatively correct plot of the Hugoniot

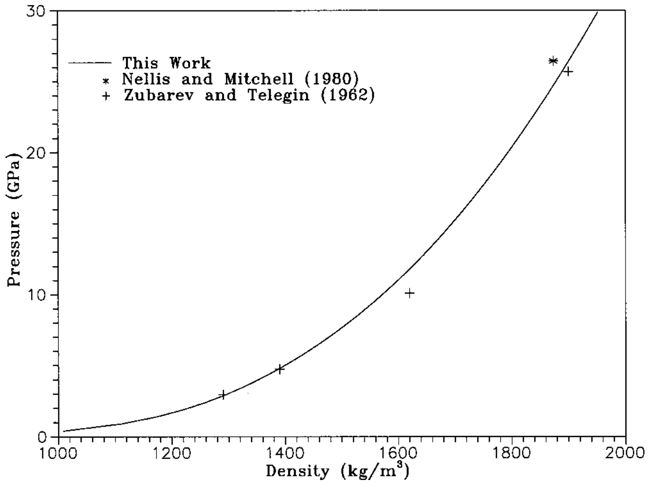

FIG. 34. Calculated Hugoniot curve.

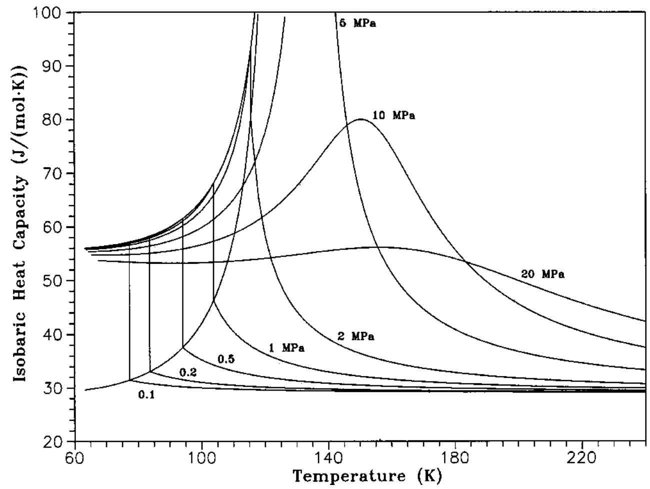

FIG. 36. Isobaric heat capacity versus temperature diagram.

curve, however, the deviations between measured values and the calculated Hugoniot curve were considered inadequate. Therefore the data measured with a shock tube apparatus (Nellis and Mitchell, 1980; Zubarev and Telegin, 1962) were added to the direct nonlinear fit to improve the extrapolation behavior of the equation of state beyond 2000 K and 2000 MPa. As shown in Fig. 34, the Hugoniot curve of the final equation of state agrees well with the data of Nellis and Mitchell (1980) and Zubarev and Telegin (1962) indicating that the equation of state presented here extrapolates well to extreme temperatures and pressures. However, the assessment of the extrapolation behavior of the formulation should not be based solely on Fig. 34 at extreme temperatures and pressures, since the plot of Hugoniot curves is not always an unequivocal criterion for reasonable extrapolation behavior. To further assess the extrapolation behavior of the formulation, the isothermal behavior at extreme pressures and densities is discussed in the next section.

5.4.3. Property Plots

Plots of constant property lines on various thermodynamic coordinates are useful in assessing the behavior of an equation of state, especially when plotted for derived properties. The equation of state for nitrogen developed here was used to produce isobaric plots of isochoric heat capacity (Fig. 35), isobaric heat capacity (Fig. 36), and speed of sound (Fig. 37) versus temperature. The resulting plots show no indication of incorrect behavior in the low temperature gas and liquid region, close to the phase boundaries, or at supercritical states, although such behavior may be encountered even for substances with extensive data sets if inconsistencies in the data set are not detected.

To verify the results found in the previous sections based on the evaluation of ideal and Hugoniot curves, Fig. 38 plots pressure versus density along isotherms. This diagram indicates that the equation of state presented here exhibits reasonable behavior up to extreme temperatures and pressures.

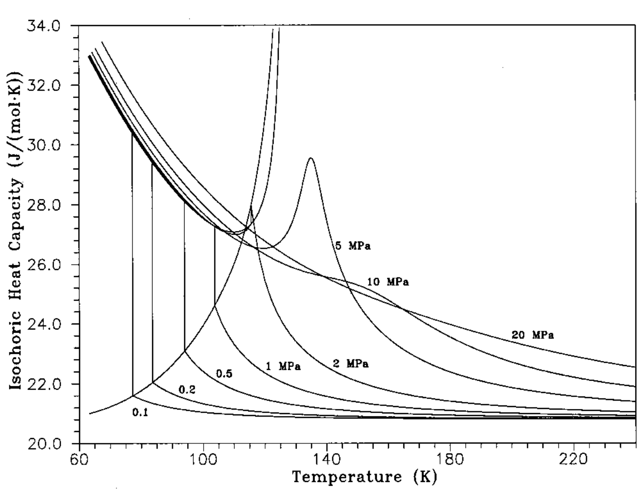

FIG. 35. Isochoric heat capacity versus temperature diagram.

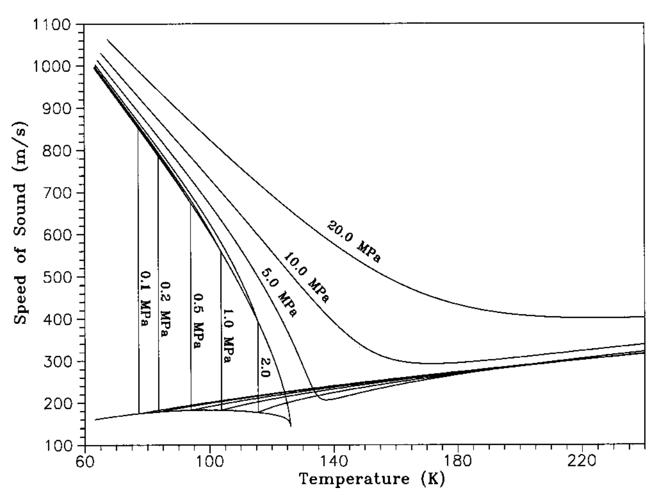

FIG. 37. Speed of sound versus temperature diagram.

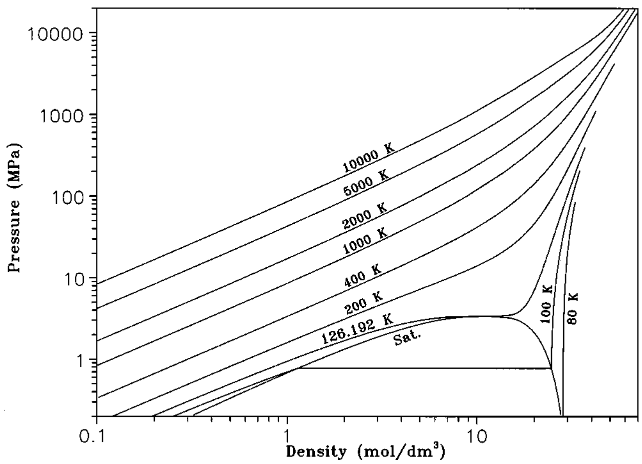

FIG. 38. Pressure versus density diagram.

6. Estimated Uncertainty of Calculated Properties

Based on the comparisons of calculated properties to available experimental data, the new reference equation of state describes the $p\rho T$ surface with an estimated uncertainty of 0.02% in density (at the 95% confidence level) from the triple point up to temperatures of 523 K and pressures up to 12 MPa and from temperatures of 240 to 523 K at pressures less than 30 MPa. The uncertainty in pressure in the critical region is estimated to be 0.02%. Further information is given in Fig. 39. In the gaseous and supercritical region, the speed of sound can be calculated with a typical uncertainty of 0.005%−0.1%. At liquid states and at high pressures, the uncertainty increases to 0.5%−1.5% as shown in Fig. 40.

For pressures up to 30 MPa, the estimated uncertainty for heat capacities ranges from 0.3% at gaseous and gas-like supercritical states up to 0.8% at liquid states and at certain gaseous and supercritical states at low temperatures. At pressures above 30 MPa, the uncertainty of calculated isobaric heat capacities is difficult to assess due to the unsatisfactory data situation. Allowing a very conservative estimation, the uncertainty is 2% for pressures up to 200 MPa and larger at higher pressures. However, experience with state-of-the-art multiparameter equations of state shows that errors will be much smaller in most cases, but this statement is difficult to prove without a suitable database. Figure 41 gives details on the estimated uncertainty of calculated isobaric heat capaci-

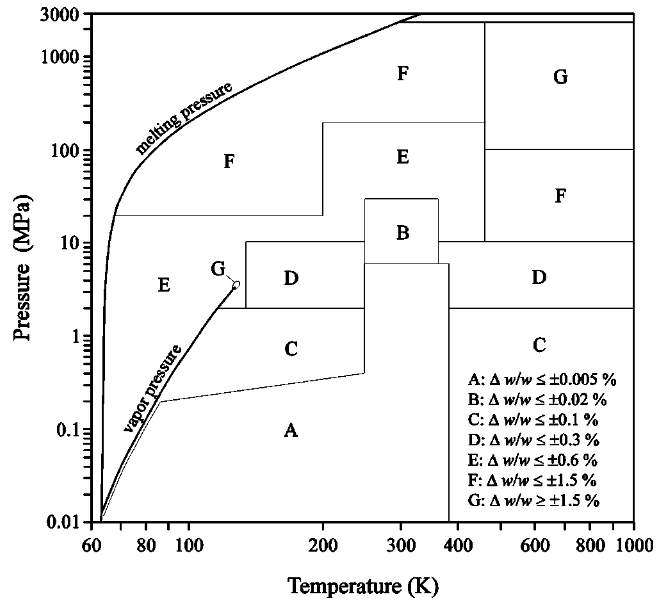

FIG. 40. Estimated uncertainties in the speed of sound for the new equation of state.

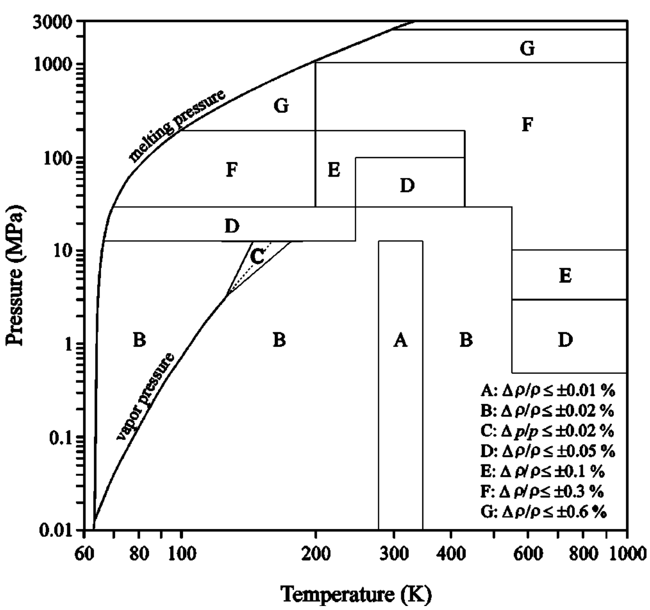

FIG. 39. Estimated uncertainties in density for the new equation of state.

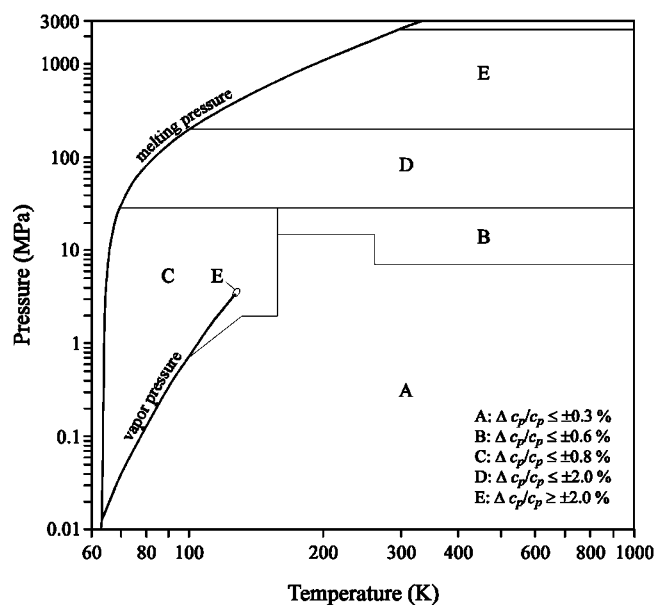

FIG. 41. Estimated uncertainties in the isobaric heat capacity for the new equation of state.

TABLE 19. Parameters and coefficients of the calibration equation of state

k	N_k	i_k	j_k	k	N_k	i_k	j_k
1	−0.409 226 050 427	1.0	−1.0	6	$0.112\,593\,677\,045\times10^{-1}$	3.0	0.0
2	0.583 733 818 214	1.0	−0.875	7	$-0.604\,379\,290\,033\times10^{-1}$	3.0	2.875
3	$-0.132\,040\,812\,535\times10^{1}$	1.0	1.625	8	$0.567\,224\,683\,248\times10^{-2}$	4.0	−0.125
4	$0.854\,602\,646\,673\times10^{-1}$	2.0	0.125	9	$-0.496\,167\,879\,044\times10^{-2}$	6.0	−1.0
5	0.207 794 266 769	2.0	3.5	10	$0.572\,786\,635\,566\times10^{-2}$	6.0	−0.875

ties. Uncertainties of calculated isochoric heat capacities are generally of the same order as those for the isobaric heat capacities. The relative uncertainties of isobaric heat capacities correspond to the upper limit for the relative uncertainties of calculated isobaric enthalpy differences. In general, the relative uncertainties of enthalpy differences will be smaller for large temperature intervals.

Saturation values can be calculated from the equation of state by application of the Maxwell criterion. The estimated uncertainties of vapor pressure, saturated liquid density, and saturated vapor density are in general 0.02% for each property. For details on enlarged uncertainties in the critical region and at low temperatures, see Sec. 5.1. As discussed in Sec. 5.4, the new formulation yields a reasonable extrapolation behavior up to the limits of chemical stability of nitrogen.

7. The Calibration Equation

In order to describe the thermodynamic behavior of nitrogen in the so-called ''natural-gas region'' for instrument calibration purposes, a limited range equation of state was developed. This equation is valid from 270 to 350 K at pressures up to 30 MPa and its general functional form is identical to Eq. (10). For the ideal gas heat capacity used in Eq. (15), the simplified equation

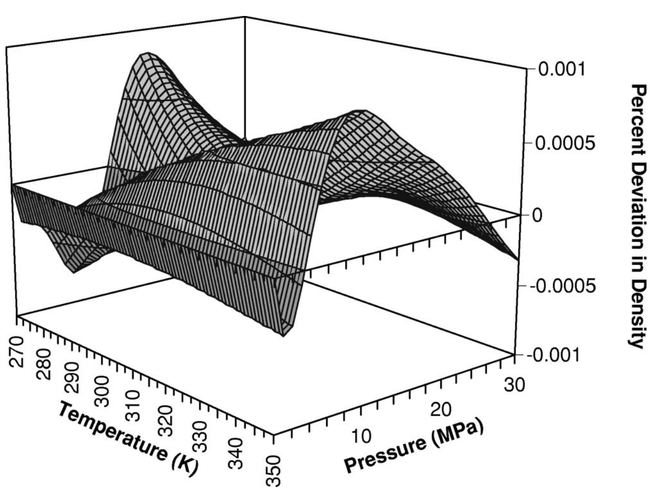

FIG. 42. Comparisons of densities calculated with the calibration equation to densities calculated with the reference equation of state.

$$\frac{c_p^0}{R}=3.500\,571+1.115\,488\times10^{-20}T^7 \tag{98}$$

with T in kelvins was used, which is valid from 270 to 350 K. The ideal gas Helmholtz energy equation can then be expressed as

$$\alpha^0=\ln(\delta)+2.500\,571\ln(\tau)-12.769\,41-0.008\,137\,875\tau \\ -1.015\,078\,5\times10^{-7}\tau^{-7}. \tag{99}$$

The residual Helmholtz energy contribution to the equation of state is given by

$$\alpha^r(\delta,\tau)=\sum_{k=1}^{10}N_k\delta^{i_k}\tau^{j_k}. \tag{100}$$

The coefficients N_k of this equation are given in Table 19. The associated equation for pressure is given by

$$p=\rho RT\left[1+\sum_{k=1}^{10}i_kN_k\delta^{i_k}\tau^{j_k}\right]. \tag{101}$$

The maximum deviation between values calculated from Eqs. (100) or (101) and those from Eq. (10) is ±0.001% in density in the specified range as shown in Fig. 42. The accompanying maximum deviation in the speed of sound is ±0.002% at pressures less than 7 MPa and ±0.006% for higher pressures. Thus the wide-range equation and the simplified equation can be used alternatively in the range of validity of the calibration equation without causing significant inconsistencies. The following calculation is given for validation of computer programs written by users of the calibration equation: (1) $T=270$ K, $\rho=12$ mol/dm^3, $p=30.5557$ MPa, $h=6468.33$ J/mol, and $w=483.073$ m/s.

8. Acknowledgments

We gratefully acknowledge the suggestions of Malcolm Chase of the National Institute of Standards and Technology in Gaithersburg, Maryland. R. Span and W. Wagner are grateful to the Deutsche Forschungsgemeinschaft (DFG) for its financial support of this project.

9. References

Abbey, R. L. and G. E. Barlow, Aust. J. Sci. Res. **A1**, 175 (1948).

Achtermann, H. J., T. K. Bose, H. Rogener, and J. M. St-Arnaud, Int. J. Thermophys. **7**, 709 (1986).

Albuquerque, G. M. N., J. C. G. Calado, M. N. da Ponte, and L. A. K. Staveley, Cryogenics **20**, 416 (1980).

Amagat, E. A., Ann. Chem. Phys. **29**, 68 (1893).

Angus, S., K. M. de Reuck, B. Armstrong, R. T Jacobsen, and R. B. Stewart, *International Thermodynamic Tables of the Fluid State-Volume 6: Nitrogen*, International Union of Pure and Applied Chemistry, Chemical Data Series, Number 20 (Pergamon, Oxford, 1979).

Antanovich, A. A. and M. A. Plotnikov, Sov. Phys. Dokl. **21**, 99 (1976).

Armstrong, G. T., J. Res. Natl. Bur. Stand. **53**, 263 (1954).

Baehr, H. D., H. Hartmann, H. C. Pohl, and H. Schomacker, *Thermodynamische Funktionen Idealer Gase fur Temperaturen bis 6000 K* (Springer-Verlag, New York, 1968).

Baidakov, V. G., High Temp. **32**, 635 (1994).

Baly, E. C. C., Proc. R. Soc. **1**, 157 (1900).

Barieau, R. E. and P. C. Tully, *Zero Pressure Thermodynamic Properties of Nitrogen Gas* (Bureau of Mines Information Circular 8319, 1967).

Barkan, E. S., Sov. Phys. Tech. Phys. **23**, 721 (1978).

Bartlett, E. P., J. Am. Chem. Soc. **49**, 687 (1927).

Bartlett, E. P., H. L. Cupples, and T. H. Tremearne, J. Am. Chem. Soc. **50**, 1275 (1928).

Bartlett, E. P., H. C. Hetherington, H. M. Kvalnes, and T. H. Tremearne, J. Am. Chem. Soc. **52**, 1363 (1930).

Benedict, M., J. Am. Chem. Soc. **59**, 2224 (1937a).

Benedict, M., J. Am. Chem. Soc. **59**, 2233 (1937b).

Bird, R. B., E. L. Spotz, and J. O. Hirschfelder, J. Chem. Phys. **18**, 1395 (1950).

Blagoi, Yu. P., A. E. Butko, S. A. Mikhailenko, and V. V. Yakuba, Sov. Phys. Acoust. **12**, 355 (1967).

Blanke, W., M. Jescheck, and D. Rimkus, PTB-Mitteilungen **98**, 187 (1988).

Boyes, S. J., Ph.D. dissertation, University of London, 1992.

Brauns, P., Information prepared by ELF-ERAP in cooperation with Center d'Etudes Nucleaires de Grenoble, personal communication to R. B. Stewart (1973).

Brewer, J. and G. W. Vaughn, J. Chem. Phys. **50**, 2960 (1969).

Bridgman, P. W., Proc. Am. Acad. Arts Sci. **59**, 173 (1924).

Bridgman, P. W., Proc. Am. Acad. Arts Sci. **70**, 1 (1935).

Brugge, H. B., C. A. Hwang, W. J. Rogers, J. C. Holste, K. R. Hall, W. Lemming, G. J. Esper, K. N. Marsh, and B. E. Gammon, Physica A **156**, 382 (1989).

Canfield, F. B., T. W. Leland, and R. Kobayashi, Adv. Cryog. Eng. **8**, 146 (1962).

Canfield, F. B., T. W. Leland, and R. Kobayashi, J. Chem. Eng. Data **10**, 92 (1965).

Cath, P. G., Communs. Phys. Lab. Univ. Leiden, Number 152, 45 (1918).

Cath, P. G. and H. Kamerlingh Onnes, Communs. Phys. Lab. Univ. Leiden, Number 156, 1 (1922).

Chase, M. W. Jr., J. Phys. Chem. Ref. Data, Monograph 9 (1998).

Chashkin, Y. R., V. G. Gorbunova, and A. V. Voronel, Sov. Phys. JETP **22**, 304 (1966).

Cheng, V. M., Ph.D. dissertation, Princeton University, Princeton, New Jersey, 1972.

Cheng, V. M., W. B. Daniels, and R. K. Crawford, Phys. Rev. B **11**, 3972 (1975).

Claitor, L. C. and D. B. Crawford, Trans. ASME **71**, 885 (1949).

Clusius, K., Z. Phys. Chem. (Leipzig) **B3**, 41 (1929).

Clusius, K. and K. Schleich, Helv. Phys. Acta **41**, 1342 (1958).

Cockett, A. H., K. Goldman, and N. G. Scrase, Proceedings of the Second International Cryo. Eng. Conference, 1968 (unpublished), p. 276.

Cohen, E. R. and B. N. Taylor, J. Phys. Chem. Ref. Data **17**, 1795 (1988).

Coleman, T. C., Ph.D. dissertation, Worcester Polytechnic Institute, Worcester, Massachusetts, 1970.

Colwell, R. C. and L. H. Gibson, J. Acoust. Soc. Am. **12**, 436 (1941).

Costa Gomes, M. F. and J. P. M. Trusler, J. Chem. Thermodyn. **30**, 527 (1998).

Cox, J. D., D. D. Wagman, and V. A. Medvedev, *CODATA Key Values for Thermodynamics, Final Report of the CODATA Task Group on Key Values for Thermodynamics* (Hemisphere, New York, 1989).

Crain, R. W. Jr. and R. Sonntag, Adv. Cryog. Eng. **11**, 379 (1966).

Crommelin, C. A., Communs. Phys. Lab. Univ. Leiden, Number 60, 3 (1924).

Crommelin, C. A., Communs. Phys. Lab. Univ. Leiden, Number 145d, 27–32 (1914); translation of Versl. Gewone Vergad. Afd. Natuurkd., K. Ned. Akad. Wet. **23**, 991 (1914).

Date, K., G. Kobuya, and H. Iwasaki, Bull. Chem. Res. Inst. Non Aqueous Solutions **10**, 67 (1961).

Dawe, R. A. and P. N. Snowdon, Proceedings of the Sixth Symposium on Thermophysical Properties, 1973 (unpublished), p. 213.

Deiters, U. K. and K. M. de Reuck, Pure Appl. Chem. **69**, 1237 (1997).

Dixon, H. B., C. Campbell, and A. Parker, Proc. R. Soc. London, Ser. A **100**, 1 (1921).

Dobbs, E. R. and L. Finegold, J. Acoust. Soc. Am. **32**, 1215 (1960).

Dodge, B. F. and H. N. Davis, J. Chem. Soc., London **49**, 610 (1927).

Duschek, W., R. Kleinrahm, W. Wagner, and M. Jaeschke, J. Chem. Thermodyn. **20**, 1069 (1988).

El-Hakeem, A. S., J. Chem. Phys. **42**, 3132 (1965).

Eucken, A., Verh. Deut. Phys. Ges. **18**, 4 (1916).

Ewing, M. B. and J. P. M. Trusler, Physica A **184**, 415 (1992).

Fenghour, A., W. A. Wakeham, D. Ferguson, A. C. Scott, and J. T. R. Watson, J. Chem. Thermodyn. **25**, 831 (1993).

Friedman, A. S., Ph.D. dissertation, Ohio State University, Columbus, 1950.

Friedman, A. S. and D. White, J. Am. Chem. Soc. **72**, 3931 (1950).

Friend, D. G., *NIST Standard Reference Database 12: NIST Thermophysical Properties of Pure Fluids, Version 3.0* (National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, 1992).

Furukawa, G. T. and R. E. McCoskey, National Advisory Committee for Aeronautics, Tech. Note, Number 2969 (1953).

Giauque, W. F. and J. O. Clayton, J. Am. Chem. Soc. **55**, 4875 (1933).

Gibbons, R. M., Cryogenics **9**, 251 (1969).

Goff, J. A. and S. Gratch, Trans. ASME **72**, 741 (1950).

Goldman, K. and N. G. Scrase, Physica **44**, 555 (1969).

Golubev, I. F. and O. A. Dobrovol'skii, *Measurement of the Density of Nitrogen and Hydrogen at Low Temperatures and High Pressures by the Method of Hydrostatic Weighing*, translated by J. E. Baker, from Gazovaya Promyshlennost, pp. 43–47, 1964 (U.K.A.E.A. Research Group, Atomic Energy Research Establishment, Harwell, England, 1965).

Goodwin, R. D. and L. A. Weber, NBS Technical Note 183 (1963).

Grilly, E. R. and R. L. Mills, Phys. Rev. **105**, 1140 (1957).

Grini, P. G. and G. A. Owren, J. Chem. Thermodyn. **29**, 37 (1997).

Hall, K. R. and F. B. Canfield, Physica **47**, 219 (1970).

Haynes, W. M., M. J. Hiza, and N. V. Frederick, Rev. Sci. Instrum. **47**, 1237 (1976).

Henning, F., Z. Phys. **40**, 775 (1926).

Henning, F. and J. Otto, Phys. Z. **37**, 633 (1936).

Herzberg, G., *Molecular Spectra and Molecular Structure, I. Spectra of Diatomic Molecules* (Van Norstrand Reinhold, New York, 1950).

Heuse, W. and J. Otto, Ann. Phys. **2**, 1012 (1929).

Hilsenrath, J., *Tables of Thermal Properties of Gases, Chapter 2. The Thermodynamic Properties of Air, Chapter 7. The Thermodynamic Properties of Nitrogen* (NBS Circular 564, 1955).

Hirschfelder, J. O., R. J. Buehler, H. A. McGee, and J. R. Sutton, Ind. Eng. Chem. **50**, 375 (1958).

Hodge, A. H., J. Chem. Phys. **5**, 974 (1937).

Holborn, L. and J. Otto, Z. Phys. **10**, 367 (1922).

Holborn, L. and J. Otto, Z. Phys. **23**, 77 (1924a).

Holborn, L. and J. Otto, Z. Phys. **30**, 320 (1924b).

Holleran, E. M., R. E. Walker, and C. M. Ramos, Cryogenics, **15**, 210 (1975).

Holst, G. and L. Hamburger, Z. Phys. Chem. **91**, 513 (1916).

Hoover, A. E., F. B. Canfield, R. Kobayashi, and T. W. Leland, Jr., J. Chem. Eng. Data **9**, 568 (1964).

Huang, F. F., Advanced Thermophysical Properties Extreme Temp. Pressures, Proceedings of the Third Symposium on Thermophysical Properties 1965 (unpublished), p. 98.

Huber, K. P. and G. Herzberg, *Molecular Spectra and Molecular Structure*, Volume 4, Constants of Diatomic Molecules (Van Nostrand Reinhold, New York, 1979).

IUPAC Commission on Atomic Weights and Isotopic Abundances, J. Phys. Chem. Ref. Data **24**, 1561 (1995).
Jacobsen, R. T and R. B. Stewart, J. Phys. Chem. Ref. Data **2**, 757 (1973).
Jacobsen, R. T, R. B. Stewart, and M. Jahangiri, J. Phys. Chem. Ref. Data **15**, 735 (1986).
Jaeschke, M. and A. E. Humphreys, *The GERG Databank of High Accuracy Compressibility Factor Measurements* (data by GASUNIE), GERG Technical Monograph 4 (Verlag des Vereins Deutscher Ingenieure: Düsseldorf, Germany, 1990).
Jaeschke, M. and H. M. Hinze, Fortschr.-Ber. VDI, Series 3, Number 262 (1991).
Jiang, S., Y. Wang, and J. Shi, Fluid Phase Equilibria **57**, 105 (1990).
Johnston, H. L. and C. O. Davis, J. Am. Chem. Soc. **56**, 271 (1934).
Jones, M. L., Ph.D. dissertation, University of Michigan, 1961.
Justi, E., Ann. Phys. **10**, 983 (1931).
Justi, E. and H. Luder, Forschung auf dem Gebiete des Ingeniurwesens **6**, 209 (1935).
Kamerlingh Onnes, H. and A. T. Van Urk, Communs. Phys. Lab. Univ. Leiden, Number **169**, 33 (1924).
Keesom, W. H. and A. Bijl, Physica **4**, 305 (1937).
Keesom, W. H. and H. Kamerlingh Onnes, Communs. Phys. Lab. Univ. Leiden, Number **149**, 1 (1916).
Keesom, W. H. and J. A. Van Lammeren, Proc. Acad. Sci. Amsterdam **35**, 727 (1932).
Keesom, W. H. and J. H. C. Lisman, Physica **1**, 735 (1934).
Kessel'man, P. M. and S. F. Gorykdn, Inz.-Fiz. Zh. **8**, 396 (1965).
Kimura, M., Y. Hanayama, and T. Nishitake, Jpn. J. Appl. Phys. **26**, 1366 (1987).
Kirshenbaum, I. and H. C. Urey, J. Chem. Phys. **10**, 706 (1942).
Klimeck, J., R. Kleinrahm, and W. Wagner, J. Chem. Thermodyn. **30**, 1571 (1998).
Kortbeek, P. J., N. J. Trappeniers, and S. N. Biswas, Int. J. Thermophys. **9**, 103 (1988).
Kosov, N. D. and I. S. Brovanov, Inz.-Fiz. Zh. **36**, 627 (1979).
Kramer, G. M. and J. G. Miller, J. Phys. Chem. **61**, 785 (1957).
Kritschewsky, I. R. and N. S. Torotscheschnikow, Z. Phys. Chem. Abt. A **176**, 338 (1936).
Ku, P. A. and B. F. Dodge, J. Chem. Eng. Data **12**, 158 (1967).
Lacam, A., J. des Recherches du CNRS **34**, 25 (1956).
Lacam, A., J. Phys. Radium **14**, 351 (1953).
Lacam, A. and J. Noury, Compt. Rend. **236**, 2039 (1953).
Laher, R. R. and F. R. Gilmore, J. Phys. Chem. Ref. Data **20**, 685 (1991).
Landau, L. D. and E. M. Lifshitz, *Statistical Physics. Part 1* (Pergamon, New York, 1980).
Lemmon, E. W., A. P. Peskin, M. O. McLinden, and D. G. Friend, *NIST Standard Reference Database 12: Thermodynamic and Transport Properties of Pure Fluids*, Version 5 (National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, 2000).
Lestz, S. S., J. Chem. Phys. **38**, 2830 (1963).
Levelt Sengers, J. M. H., M. Klein, and J. S. Gallagher, *Pressure-Volume-Temperature Relationships of Gases. Virial Coefficients*, American Institute of Physics Handbook, 3rd Edition (McGraw-Hill, New York, 1972).
Levelt Sengers, J. M. H., W. L. Greer, and J. V. Sengers, J. Phys. Chem. Ref. Data **5**, 1 (1976).
Liebenberg, D. H., personal correspondence to R. T Jacobsen (1975).
Liebenberg, D. H., R. L. Mills, and J. C. Bronson, *Equation of State of Nitrogen to 21 kBar from Simultaneous Measurement of PVT and Sound Velocity* (Los Alamos Scientific Laboratory, University of California, Paper LA-UR 75-420, 1976).
Liepmann, H. W., Helv. Phys. Acta **12**, 421 (1939).
Liu, Y. P. and R. C. Miller, J. Chem. Thermodyn. **4**, 85 (1972).
Luft, L., Ind. Eng. Chem. **49**, 2035 (1957).
Mackey, B. H. and N. W. Krase, Ind. Eng. Chem. **22**, 1060 (1930).
Mage, D. T., M. L. Jones, Jr., D. L. Katz, and J. R. Roebuck, Chem. Eng. Prog. **59**, 61 (1963).
Magee, J. W., J. Res. Natl. Inst. Stand. Technol. **96**, 725 (1991).
Malbrunot, P., *Mesure des Parameters D'Etat des gaz denses a Temperatures Elevees. Application A L'Azote*, translated into English by S. Angus and E. Adalian (IUPAC Thermodynamic Tables Project Center, PC/T11, London, 1970).
Malbrunot, P. and B. Vodar, C. R. Acad. Sci. Paris **268B**, 1337 (1969).
Mamedov, A. M., Za Tekh. Prog. (Baku) **11**, 20 (1969).
Maron, S. H. and D. Turnbull, Ind. Eng. Chem. **34**, 544 (1942).
Mathias, E., H. Kamerlingh Onnes, and C. A. Crommelin, Communs. Phys. Lab. Univ. Leiden, Number 145, 19 (1914).
Mehl, J. B. and M. R. Moldover, J. Chem. Phys. **77**, 455 (1982).
Michels, A., T. Wassenaar, W. De Graaff, and C. Prins, Physica **19**, 26 (1953).
Michels, A., H. Wouters, and J. DeBoer, Physica **1**, 587 (1934).
Michels, A., H. Wouters, and J. DeBoer, Physica **3**, 585 (1936).
Miller, J. E., L. Stroud, and L. W. Brandt, J. Chem. Eng. Data **5**, 6 (1960).
Miller, J. E., L. W. Brandt, and L. Stroud, *Compressibility Factors for Helium and Helium-Nitrogen Mixtures* (Bureau of Mines, Volume RI-5845, 1961).
Mills, R. L., personal communication from the Los Alamos Scientific Laboratory with R. B. Stewart (1976).
Mills, R. L., D. H. Liebenberg, and J. C. Bronson, J. Chem. Phys. **63**, 1198 (1975).
Morris, E. C. and R. G. Wylie, J. Chem. Phys. **79**, 2983 (1983).
Moussa, M. R., R. Muijlwijk, and H. Van Dijk, Physica **32**, 900 (1966).
Nellis, W. J. and A. C. Mitchell, J. Chem. Phys. **73**, 6137 (1980).
Nishitake, T. and Y. Hanayama, J. Phys. Soc. Jpn. **39**, 1065 (1975a).
Nishitake, T. and Y. Hanayama, *Proceedings of the Fourth International Conference on High Pressure, Kyoto, Japan* [Rev. Phys. Chem. Jpn., Special Issue 534 (1975b)].
Nowak, P., R. Kleinrahm, and W. Wagner, J. Chem. Thermodyn. **29**, 1137 (1997a).
Nowak, P., R. Kleinrahm, and W. Wagner, J. Chem. Thermodyn. **29**, 1157 (1997b).
Nunes da Ponte, M., W. B. Streett, and L. A. K. Staveley, J. Chem. Thermodyn. **10**, 151 (1978).
Orrit, J. E. and J. M. Laupretre, Adv. Cryog. Eng. **23**, 573 (1978).
Otto, J., A. Michels, and H. Wouters, Phys. Z. **35**, 97 (1934).
Palavra, A. M., *Effect of Pressure and Temperature on Excess Properties in the System Argon-Nitrogen*, Instituto Superior Tecnico Universidade Tecnica De Lisboa, Master's thesis (1979).
Pavese, F., J. Ancsin, D. N. Astrov, J. Bonhoure, G. Bonnier, G. T. Furukawa, R. C. Kemp, H. Maas, R. L. Rusby, H. Sakurai, and L. Shan-Kang, Metrologia **20**, 127 (1984).
Perkins, R. A., H. M. Roder, D. G. Friend, and C. A. Nieto de Castro, Physica A **173**, 332 (1991).
Pestak, M. W. and M. H. W. Chan, Phys. Rev. B **30**, 274 (1984).
Pieperbeck, N., R. Kleinrahm, and W. Wagner, J. Chem. Thermodyn. **23**, 175 (1991).
Pine, A. S., J. Chem. Phys. **51**, 5171 (1969).
Pocock, G. and C. J. Wormald, J. Chem. Soc., Faraday Trans. 1 **71**, 705 (1975).
Pool, R. A. H., G. Saville, T. M. Herrington, B. D. C. Shields, and L. A. K. Staveley, Trans. Faraday Soc. **58**, 1692 (1962).
Porter, F. and J. H. Perry, J. Am. Chem. Soc. **48**, 2059 (1926).
Powles, J. G. and K. E. Gubbins, Chem. Phys. Lett. **38**, 405 (1976).
Preston-Thomas, H., Metrologia **12**, 7 (1976).
Preston-Thomas, H., Metrologia **27**, 3 (1990).
Ricardo, A. A., S. F. Barreiros, M. Nunes da Ponte, G. M. N. Albuquerque, and J. C. G. Calado, J. Chem. Thermodyn. **24**, 1281 (1992).
Rivkin, S. L., Thermophys. Prop. Matter Substances **8**, 190 (1975).
Robertson, S. L. and S. E. Babb, Jr., J. Chem. Phys. **50**, 4560 (1969).
Robinson, D. W., Proc. R. Soc. London, Ser. A **225**, 393 (1954).
Rodosevich, J. B. and R. C. Miller, AIChE J. **19**, 729 (1973).
Roe, D. R., Ph.D. dissertation, Imperial College, London, 1972.
Roebuck, J. R. and H. Osterberg, Phys. Rev. **48**, 450 (1935).
Sahgal, P. N., J. M. Geist, A. Jambhekar, and G. M. Wilson, Adv. Cryog. Eng. **10**, 224 (1964).
Saurel, J., J. des Recherches du CNRS, Number 42, 22 (1958).
Setzmann, U. and W. Wagner, Int. J. Thermophys. **10**, 1103 (1989).
Setzmann, U. and W. Wagner, J. Phys. Chem. Ref. Data **20**, 1061 (1991).
Sharif, M. A. R. and T. K. Groves, Chem. Eng. Commun. **86**, 199 (1989).
Shilling, W. G. and J. R. Partington, Philos. Mag. **6**, 920 (1928).
Siemens, H. V., Ann. Phys. **42**, 871 (1913).
Simon, F., M. Ruhemann, and W. A. M. Edwards, Z. Phys. Chem. Abt. B **6**, 331 (1930).
Singer, J. R. and J. H. Lunsford, J. Chem. Phys. **47**, 811 (1967).
Singh, S. P. and R. C. Miller, J. Chem. Thermodyn. **11**, 395 (1979).

Skripka, V. G., Tr., Vses. Nauchno-Issled. Inst. Kislorodn. Mashinostr. **10**, 163 (1965).
Smith, L. B. and R. S. Taylor, J. Am. Chem. Soc. **45**, 2107 (1923).
Smukala, J., R. Span, and W. Wagner, J. Phys. Chem. Ref. Data **29**, 1053 (2000).
Span, R., *Multiparameter Equations of State-An Accurate Source of Thermodynamic Property Data* (Springer, Berlin, 2000).
Span, R., E. W. Lemmon, R. T Jacobsen, and W. Wagner, Int. J. Thermophys. **19**, 1121 (1998).
Span, R. and W. Wagner, Int. J. Thermophys. **18**, 1415 (1997).
Span, R. and W. Wagner, J. Phys. Chem. Ref. Data **25**, 1509 (1996).
Steinfeld, J. I., *An Introduction to Modern Molecular Spectroscopy* (Harper and Row, New York, 1974).
Straty, G. C. and D. E. Diller, J. Chem. Thermodyn. **12**, 927 (1980).
Streett, W. B. and L. A. K. Staveley, Adv. Cryog. Eng. **12**, 363 (1967).
Sychev, V. V., A. A. Vasserman, A. D. Kozlov, G. A. Spiridonov, and V. A. Tsymarny, *Thermodynamic Properties of Nitrogen* (Hemisphere, New York, 1987).
Tegeler, Ch., R. Span, and W. Wagner, J. Phys. Chem. Ref. Data **28**, 779 (1999).
Tegeler, Ch., R. Span, and W. Wagner, VDI Fortschritt-Bericht, Series 3, Number 480 (1997).
Terry, M. J., J. T. Lynch, M. Bunclark, K. R. Mansell, and L. A. K. Staveley, J. Chem. Thermodyn. **1**, 413 (1969).
Thomas, W., Z. Phys. **147**, 92 (1957).
Timrot, D. L., V. E. Lyusternik, and E. E. Ustyuzhanin, Teplofiz. Svoistva Veshchestv Nizk. Temp., Mater. Vses. Soveshch. **1**, 59 (1972).
Townsend, P. W., Ph.D. dissertation, Faculty of Pure Science, Columbia University, New York, 1956.
Trusler, J. P. M., *Physical Acoustics and Metrology of Fluids*, The Adam Hilger Series on Measurement Science and Technology (IOP, Bristol, England, 1991).
Tsiklis, D. S., Akad. Nauk SSSR Dokl. **79**, 289 (1951).
Tsiklis, D. S. and E. V. Polyakov, Sov. Phys. Dokl. **12**, 901 (1968).
Van Dael, W., A. Van Itterbeek, A. Cops, and J. Thoen, Physica **32**, 611 (1966).
Van Itterbeek, A. and P. Mariens, Physica **4**, 207 (1937).
Van Itterbeek, A. and W. Van Dael, Bull. IIR Annexe., p. 295 (1958).
Van Itterbeek, A. and W. Van Dael, Cryogenics **1**, 226 (1961).
Van Itterbeek, A. and W. Van Dael, Physica **28**, 861 (1962).
Van Itterbeek, A. and O. Verbeke, Cryogenics **2**, 79 (1961).
Van Itterbeek, A. and O. Verbeke, Physica **26**, 931 (1960).
Van Itterbeek, A., A. De Bock, and L. Verhagen, Physica **15**, 624 (1949).
Van Itterbeek, A., G. Forrez, C. G. Sluijter, and G. Vaes, Intl. Inst. Refr., Comm. 1, Delft, The Netherlands, p. 155 (1958).
Van Itterbeek, A., H. Lambert, and G. Forrez, Appl. Sci. Res., Sect. A **6**, 15 (1955).
Van Itterbeek, A., W. De Rop, and G. Forrez, Appl. Sci. Res. **6**, 421 (1957).
Van Kasteren, P. H. G. and H. Zeldenrust, Ind. Eng. Chem. Fundam. **18**, 339 (1979).
Vasserman, A. A. and V. I. Selevanyuk, Akust. Zh. **13**, 131 (1967).
Verhaegen, L., Verhandel. Koninkl. Vlaam. Acad. Wetenschap, Belg. Kl. Wetenschap, Number **38**, 27 (1952).
Verschoyle, T. T. H., Proc. R. Soc. **A3**, 552 (1926).
Verschoyle, T. T. H., Trans. Roy. Soc. **A230**, 189 (1931).
Volarovich, M. B. and D. B. Balashov, Primlnanie ul Traakustiki kissledsvaniiu vish hestva, Number **13**, 63 (1961).
Voronel, A. V., V. G. Gorbunova, Y. P. Chaskin, and V. V. Shchekochikhina, Sov. Phys. JETP **23**, 597 (1966).
Voronov, F. F., L. L. Pitaevskaya, and A. V. Bilevich, Russ. J. Phys. Chem. **43**, 321 (1969).
Wagner, W., Cryogenics **13**, 470 (1973).
Wagner, W., and A. Pruß, J. Phys. Chem. Ref. Data, to be submitted, 2001.
Weber, L. A., J. Chem. Thermodyn. **2**, 839 (1970).
Weber, L. A., J. Chem. Thermodyn. **13**, 389 (1981).
White, D., A. S. Friedman, and H. L. Johnston, J. Am. Chem. Soc. **73**, 5713 (1951).
Wiebe, R. and V. L. Gaddy, J. Am. Chem. Soc. **60**, 2300 (1938).
Wiener, L. D., Proc. Symp. Thermodyn. Fluids, Part 2, 58th National Meeting, Dallas, Texas 1966 (unpublished).
Witonsky, R. J. and J. G. Miller, J. Am. Chem. Soc. **85**, 282 (1963).
Younglove, B. A. and R. C. McCarty, J. Chem. Thermodyn. **12**, 1121 (1980).
Zozulya, V. N. and Y. P. Blagoi, Sov. J. Low Temp. Phys. **1**, 562 (1975).
Zubarev, V. N. and G. S. Telegin, Sov. Phys. Dokl. **7**, 34 (1962).

10. Appendix: Thermodynamic Properties of Nitrogen

Tables are given here for the ideal gas heat capacity for naturally occurring nitrogen calculated from Eq. (50), saturation properties as a function of temperature, saturation properties as a function of pressure, and single phase state points from 0.1 to 1000 MPa at temperatures from the melting line to 1000 K. Saturation properties are calculated using the Maxwell criteria and are also shown in the single phase state points table defining the boundary between the liquid and the vapor. Densities and other derived properties are calculated from the equation of state given in Eqs. (8), (53), and (55).

Ideal gas heat capacity of undissociated naturally occurring nitrogen

T/K	c_p^0/R	T/K	c_p^0/R	T/K	c_p^0/R	T/K	c_p^0/R
0.2	2.5000	70.0	3.5003	470.0	3.5430	1800.0	4.2818
0.4	2.5000	75.0	3.5003	480.0	3.5477	1820.0	4.2867
0.6	2.5002	80.0	3.5004	490.0	3.5526	1840.0	4.2916
0.8	2.5010	85.0	3.5004	500.0	3.5578	1860.0	4.2963
1.0	2.5026	90.0	3.5004	510.0	3.5632	1880.0	4.3009
1.2	2.5048	95.0	3.5004	520.0	3.5689	1900.0	4.3054
1.4	2.5082	100.0	3.5004	350.0	3.5748	1920.0	4.3098
1.6	2.5153	105.0	3.5004	540.0	3.5809	1940.0	4.3141
1.8	2.5292	110.0	3.5005	550.0	3.5872	1960.0	4.3183
2.0	2.5534	115.0	3.5005	560.0	3.5937	1980.0	4.3224
2.2	2.5900	120.0	3.5005	570.0	3.6004	2000.0	4.3265
2.4	2.6398	125.0	3.5005	580.0	3.6073	2050.0	4.3361
2.6	2.7021	130.0	3.5005	590.0	3.6143	2100.0	4.3453
2.8	2.7749	135.0	3.5006	600.0	3.6215	2150.0	4.3540
3.0	2.8554	140.0	3.5006	620.0	3.6362	2200.0	4.3622
3.2	2.9405	145.0	3.5006	640.0	3.6514	2250.0	4.3701
3.4	3.0271	150.0	3.5006	660.0	3.6670	2300.0	4.3776
3.6	3.1122	155.0	3.5006	680.0	3.6829	2350.0	4.3847
3.8	3.1934	160.0	3.5007	700.0	3.6990	2400.0	4.3915
4.0	3.2687	165.0	3.5007	720.0	3.7153	2450.0	4.3979
4.2	3.3369	170.0	3.5007	740.0	3.7317	2500.0	4.4041
4.4	3.3971	175.0	3.5007	760.0	3.7480	2550.0	4.4101
4.6	3.4490	180.0	3.5007	780.0	3.7644	2600.0	4.4157
4.8	3.4927	185.0	3.5008	800.0	3.7807	2650.0	4.4212
5.0	3.5285	190.0	3.5008	820.0	3.7968	2700.0	4.4264
5.2	3.5571	195.0	3.5008	840.0	3.8128	2750.0	4.4314
5.4	3.5791	200.0	3.5008	860.0	3.8287	2800.0	4.4363
5.6	3.5954	205.0	3.5009	880.0	3.8443	2850.0	4.4409
5.8	3.6067	210.0	3.5009	900.0	3.8597	2900.0	4.4454
6.0	3.6139	215.0	3.5009	920.0	3.8748	2950.0	4.4497
6.2	3.6176	220.0	3.5010	940.0	3.8897	3000.0	4.4539
6.4	3.6185	225.0	3.5010	960.0	3.9043	3050.0	4.4580
6.6	3.6172	230.0	3.5010	980.0	3.9186	3100.0	4.4619
6.8	3.6143	235.0	3.5011	1000.0	3.9326	3150.0	4.4657
7.0	3.6100	240.0	3.5011	1020.0	3.9463	3200.0	4.4693
7.2	3.6049	245.0	3.5012	1040.0	3.9598	3250.0	4.4729
7.4	3.5991	250.0	3.5013	1060.0	3.9729	3300.0	4.4763
7.6	3.5930	255.0	3.5014	1080.0	3.9857	3350.0	4.4797
7.8	3.5868	260.0	3.5015	1100.0	3.9982	3400.0	4.4830
8.0	3.5805	265.0	3.5016	1120.0	4.0104	3450.0	4.4862
8.2	3.5743	270.0	3.5017	1140.0	4.0222	3500.0	4.4893
8.4	3.5684	275.0	3.5019	1160.0	4.0338	3550.0	4.4923
8.6	3.5626	280.0	3.5021	1180.0	4.0451	3600.0	4.4952
8.8	3.5572	285.0	3.5022	1200.0	4.0562	3650.0	4.4981
9.0	3.5521	290.0	3.5025	1220.0	4.0669	3700.0	4.5009
9.2	3.5473	295.0	3.5027	1240.0	4.0773	3750.0	4.5037
9.4	3.5429	300.0	3.5030	1260.0	4.0875	3800.0	4.5064
9.6	3.5388	305.0	3.5033	1280.0	4.0974	3850.0	4.5090
9.8	3.5350	310.0	3.5036	1300.0	4.1071	3900.0	4.5116
10.0	3.5316	315.0	3.5040	1320.0	4.1165	3950.0	4.5141
11.0	3.5185	320.0	3.5044	1340.0	4.1257	4000.0	4.5166
12.0	3.5107	325.0	3.5049	1360.0	4.1346	4050.0	4.5190
13.0	3.5062	330.0	3.5054	1380.0	4.1432	4100.0	4.5214
14.0	3.5037	335.0	3.5059	1400.0	4.1517	4150.0	4.5238
15.0	3.5023	340.0	3.5065	1420.0	4.1599	4200.0	4.5261
16.0	3.5015	345.0	3.5071	1440.0	4.1679	4250.0	4.5284
17.0	3.5011	350.0	3.5078	1460.0	4.1757	4300.0	4.5307
18.0	3.5009	355.0	3.5086	1480.0	4.1833	4350.0	4.5329
19.0	3.5007	360.0	3.5094	1500.0	4.1907	4400.0	4.5351
20.0	3.5006	365.0	3.5102	1520.0	4.1980	4450.0	4.5373
21.0	3.5006	370.0	3.5111	1540.0	4.2050	4500.0	4.5394
22.0	3.5005	375.0	3.5121	1560.0	4.2118	4550.0	4.5415
23.0	3.5005	380.0	3.5131	1580.0	4.2185	4600.0	4.5436
24.0	3.5004	385.0	3.5142	1600.0	4.2250	4650.0	4.5457
25.0	3.5004	390.0	3.5154	1620.0	4.2313	4700.0	4.5477
30.0	3.5003	395.0	3.5166	1640.0	4.2375	4750.0	4.5498
35.0	3.5003	400.0	3.5179	1660.0	4.2436	4800.0	4.5518
40.0	3.5003	410.0	3.5207	1680.0	4.2494	4850.0	4.5538
45.0	3.5003	420.0	3.5237	1700.0	4.2552	4900.0	4.5558
50.0	3.5003	430.0	3.5270	1720.0	4.2607	4950.0	4.5578
55.0	3.5003	440.0	3.5306	1740.0	4.2662	5000.0	4.5598
60.0	3.5003	450.0	3.5345	1760.0	4.2715		
65.0	3.5003	460.0	3.5386	1780.0	4.2767		

Thermodynamic properties of nitrogen on the saturation line as a function of temperature

T K	p MPa	ρ mol/dm^3	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
63.151	0.012 523	30.957	-4222.6	67.951	32.95	56.03	995.3
		0.024 07	1814.7	163.55	21.01	29.65	161.1
64	0.014 60	30.833	-4175.0	68.699	32.79	56.07	986.6
		0.027 73	1837.4	162.64	21.03	29.71	162.1
65	0.017 40	30.685	-4118.8	69.569	32.59	56.12	976.4
		0.032 59	1863.9	161.61	21.06	29.79	163.2
66	0.020 62	30.537	-4062.6	70.426	32.40	56.17	966.2
		0.038 10	1890.1	160.62	21.09	29.87	164.3
67	0.024 30	30.387	-4006.3	71.270	32.21	56.23	956.0
		0.044 30	1916.0	159.66	21.12	29.97	165.4
68	0.028 48	30.237	-3950.0	72.103	32.02	56.29	945.9
		0.051 26	1941.6	158.74	21.16	30.07	166.4
69	0.033 21	30.085	-3893.5	72.924	31.83	56.36	935.8
		0.059 03	1966.8	157.86	21.20	30.18	167.4
70	0.038 54	29.933	-3837.0	73.735	31.65	56.43	925.7
		0.067 68	1991.7	157.00	21.24	30.30	168.4
71	0.044 53	29.779	-3780.4	74.535	31.46	56.51	915.7
		0.077 27	2016.2	156.18	21.28	30.43	169.4
72	0.051 21	29.624	-3723.7	75.325	31.28	56.60	905.6
		0.087 87	2040.3	155.38	21.32	30.56	170.3
73	0.058 66	29.468	-3666.9	76.105	31.11	56.69	895.5
		0.099 54	2063.9	154.61	21.37	30.71	171.2
74	0.066 91	29.311	-3610.0	76.875	30.93	56.79	885.4
		0.112 36	2087.1	153.86	21.42	30.87	172.1
75	0.076 04	29.153	-3553.0	77.637	30.76	56.90	875.3
		0.126 38	2109.9	153.14	21.47	31.04	173.0
76	0.086 10	28.993	-3495.8	78.389	30.59	57.02	865.2
		0.141 70	2132.1	152.44	21.53	31.22	173.8
77	0.097 15	28.832	-3438.5	79.133	30.43	57.14	855.0
		0.158 38	2153.9	151.76	21.58	31.41	174.6
78	0.109 26	28.670	-3381.1	79.869	30.26	57.28	844.8
		0.176 50	2175.1	151.10	21.65	31.62	175.3
79	0.122 47	28.506	-3323.5	80.597	30.10	57.42	834.6
		0.196 13	2195.7	150.46	21.71	31.84	176.0
80	0.136 87	28.341	-3265.7	81.317	29.95	57.58	824.4
		0.217 37	2215.8	149.84	21.78	32.07	176.7
81	0.152 51	28.175	-3207.8	82.030	29.80	57.75	814.1
		0.240 30	2235.3	149.23	21.85	32.32	177.4

Thermodynamic properties of nitrogen on the saturation line as a function of temperature—Continued

T K	p MPa	ρ mol/dm^3	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
82	0.169 47	28.006	-3149.6	82.736	29.65	57.93	803.7
		0.265 00	2254.2	148.64	21.92	32.59	178.0
83	0.187 80	27.837	-3091.3	83.436	29.50	58.13	793.4
		0.291 57	2272.5	148.06	21.99	32.87	178.6
84	0.207 57	27.665	-3032.7	84.129	29.36	58.34	782.9
		0.320 10	2290.1	147.49	22.07	33.17	179.2
85	0.228 86	27.492	-2973.9	84.815	29.21	58.57	772.4
		0.350 69	2307.0	146.94	22.16	33.50	179.7
86	0.251 74	27.316	-2914.8	85.496	29.08	58.81	761.9
		0.383 44	2323.2	146.40	22.24	33.84	180.2
87	0.276 26	27.139	-2855.5	86.172	28.94	59.07	751.3
		0.418 46	2338.6	145.87	22.33	34.20	180.6
88	0.302 51	26.960	-2795.9	86.842	28.81	59.35	740.6
		0.455 86	2353.3	145.36	22.43	34.59	181.0
89	0.330 55	26.779	-2736.0	87.507	28.69	59.65	729.8
		0.495 76	2367.2	144.85	22.53	35.01	181.4
90	0.360 46	26.595	-2675.8	88.167	28.56	59.97	719.0
		0.538 28	2380.3	144.35	22.63	35.45	181.8
91	0.392 30	26.409	-2615.2	88.823	28.44	60.32	708.1
		0.583 55	2392.5	143.85	22.74	35.92	182.1
92	0.426 16	26.221	-2554.3	89.475	28.33	60.69	697.1
		0.631 71	2403.9	143.37	22.85	36.43	182.4
93	0.462 10	26.030	-2493.0	90.123	28.21	61.09	686.0
		0.682 91	2414.3	142.89	22.97	36.97	182.6
94	0.500 20	25.836	-2431.3	90.767	28.11	61.52	674.8
		0.737 29	2423.8	142.42	23.09	37.55	182.8
95	0.540 52	25.640	-2369.1	91.408	28.00	61.98	663.5
		0.795 04	2432.4	141.95	23.22	38.18	183.0
96	0.583 16	25.440	-2306.5	92.046	27.90	62.48	652.1
		0.856 33	2439.8	141.49	23.35	38.85	183.1
97	0.628 17	25.238	-2243.4	92.682	27.80	63.03	640.6
		0.921 34	2446.3	141.03	23.49	39.57	183.2
98	0.675 65	25.031	-2179.8	93.315	27.71	63.61	628.9
		0.990 29	2451.6	140.57	23.63	40.34	183.3
99	0.725 66	24.822	-2115.6	93.946	27.62	64.25	617.1
		1.0634	2455.7	140.12	23.79	41.18	183.3
100	0.778 27	24.608	-2050.8	94.576	27.54	64.93	605.2
		1.1409	2458.6	139.67	23.95	42.09	183.3
101	0.833 58	24.390	-1985.4	95.204	27.46	65.68	593.2
		1.2231	2460.3	139.22	24.11	43.08	183.2

Thermodynamic properties of nitrogen on the saturation line as a function of temperature—Continued

T K	p MPa	ρ mol/dm^3	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
102	0.891 66	24.168	-1919.3	95.832	27.39	66.50	581.0
		1.3103	2460.6	138.77	24.29	44.16	183.1
103	0.952 59	23.941	-1852.5	96.459	27.33	67.39	568.6
		1.4027	2459.5	138.32	24.47	45.33	182.9
104	1.016 44	23.709	-1784.8	97.087	27.27	68.37	556.0
		1.5008	2456.9	137.87	24.66	46.61	182.7
105	1.083 31	23.471	-1716.3	97.715	27.21	69.44	543.3
		1.6049	2452.8	137.42	24.86	48.01	182.5
106	1.153 27	23.228	-1646.9	98.345	27.17	70.63	530.4
		1.7155	2447.0	136.97	25.07	49.56	182.2
107	1.226 42	22.978	-1576.5	98.977	27.13	71.94	517.2
		1.8331	2439.4	136.51	25.28	51.28	181.9
108	1.302 83	22.721	-1505.0	99.611	27.11	73.39	503.9
		1.9582	2429.9	136.04	25.51	53.19	181.6
109	1.382 59	22.457	-1432.3	100.25	27.09	75.02	490.3
		2.0916	2418.3	135.57	25.75	55.33	181.2
110	1.465 81	22.184	-1358.3	100.89	27.08	76.85	476.4
		2.2339	2404.5	135.10	26.01	57.76	180.8
111	1.552 57	21.902	-1282.8	101.54	27.09	78.91	462.3
		2.3860	2388.4	134.61	26.28	60.53	180.3
112	1.642 97	21.610	-1205.8	102.19	27.11	81.27	447.9
		2.5490	2369.6	134.11	26.59	63.72	179.7
113	1.737 11	21.306	-1127.1	102.85	27.15	83.97	433.2
		2.7240	2347.9	133.60	26.92	67.44	179.2
114	1.835 10	20.989	-1046.3	103.52	27.21	87.10	418.1
		2.9124	2323.0	133.08	27.30	71.81	178.5
115	1.937 04	20.658	-963.36	104.20	27.29	90.77	402.7
		3.1162	2294.6	132.53	27.72	77.01	177.7
116	2.043 06	20.310	-877.87	104.90	27.40	95.14	386.8
		3.3373	2262.2	131.97	28.19	83.29	176.9
117	2.153 28	19.943	-789.44	105.61	27.54	100.4	370.4
		3.5786	2225.1	131.38	28.72	91.00	176.0
118	2.267 84	19.552	-697.58	106.34	27.73	107.0	353.5
		3.8435	2182.8	130.75	29.32	100.7	175.0
119	2.386 89	19.134	-601.61	107.10	27.98	115.3	335.8
		4.1370	2134.1	130.09	30.00	113.1	173.9
120	2.510 58	18.682	-500.60	107.89	28.31	126.3	317.3
		4.4653	2077.8	129.38	30.77	129.7	172.6
121	2.639 12	18.187	-393.22	108.73	28.76	141.4	297.7
		4.8380	2011.9	128.60	31.68	152.9	171.2

Thermodynamic properties of nitrogen on the saturation line as a function of temperature—Continued

T K	p MPa	ρ mol/dm^3	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
122	2.772 70	17.633	-277.39	109.62	29.38	163.7	276.5
		5.2696	1933.5	127.74	32.78	187.6	169.5
123	2.911 61	16.997	-149.62	110.59	30.32	200.3	253.3
		5.7846	1837.6	126.75	34.18	244.9	167.4
124	3.056 18	16.230	-3.0925	111.71	31.83	271.2	227.0
		6.4301	1714.7	125.56	36.12	356.6	164.7
125	3.206 87	15.210	179.37	113.10	34.68	468.3	195.5
		7.3244	1541.7	124.00	39.28	665.1	160.3
126	3.364 53	13.281	492.37	115.50	43.40	3138.	151.0
		9.1106	1194.9	121.08	47.44	4521.	148.4
126.192	3.395 80	11.184	818.91	118.07			

Thermodynamic properties of nitrogen on the saturation line as a function of pressure

T K	p MPa	ρ mol/dm^3	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
63.151	0.012523	30.957	-4222.6	67.951	32.95	56.03	995.3
		0.024 07	1814.7	163.55	21.01	29.65	161.1
65.817	0.02	30.564	-4072.9	70.269	32.43	56.16	968.0
		0.037 04	1885.3	160.80	21.08	29.86	164.1
68.334	0.03	30.186	-3931.1	72.379	31.95	56.31	942.5
		0.053 76	1950.1	158.44	21.17	30.11	166.8
70.254	0.04	29.894	-3822.7	73.939	31.60	56.45	923.2
		0.070 03	1998.0	156.79	21.25	30.33	168.7
71.826	0.05	29.651	-3733.6	75.188	31.31	56.58	907.3
		0.085 96	2036.1	155.52	21.31	30.54	170.2
73.170	0.06	29.442	-3657.3	76.236	31.08	56.71	893.8
		0.101 64	2067.9	154.48	21.38	30.74	171.4
74.349	0.07	29.256	-3590.1	77.142	30.87	56.83	881.9
		0.117 11	2095.1	153.61	21.44	30.93	172.4
75.405	0.08	29.088	-3529.9	77.942	30.69	56.95	871.2
		0.132 43	2118.9	152.86	21.49	31.11	173.3
76.363	0.09	28.935	-3475.0	78.660	30.53	57.06	861.5
		0.147 60	2140.1	152.19	21.55	31.29	174.1
77.244	0.10	28.793	-3424.6	79.313	30.39	57.17	852.5
		0.162 65	2159.1	151.60	21.60	31.46	174.7
77.355	0.101325	28.775	-3418.2	79.395	30.37	57.19	851.4
		0.164 64	2161.5	151.53	21.61	31.49	174.8
78.819	0.12	28.536	-3333.9	80.466	30.13	57.40	836.5
		0.192 47	2192.1	150.57	21.70	31.80	175.9
80.207	0.14	28.307	-3253.8	81.465	29.92	57.62	822.2
		0.221 97	2219.9	149.71	21.79	32.12	176.9
81.451	0.16	28.099	-3181.5	82.350	29.73	57.83	809.4
		0.251 23	2243.9	148.96	21.88	32.44	177.7
82.584	0.18	27.907	-3115.6	83.145	29.56	58.05	797.7
		0.280 29	2265.0	148.30	21.96	32.75	178.4
83.626	0.20	27.729	-3054.6	83.870	29.41	58.26	786.8
		0.309 19	2283.6	147.70	22.04	33.06	179.0
84.592	0.22	27.562	-2997.9	84.536	29.27	58.47	776.7
		0.337 97	2300.2	147.17	22.12	33.36	179.5
85.496	0.24	27.405	-2944.6	85.154	29.15	58.68	767.2
		0.366 65	2315.1	146.67	22.20	33.66	179.9
86.345	0.26	27.256	-2894.4	85.730	29.03	58.90	758.2
		0.395 25	2328.6	146.22	22.27	33.96	180.3
87.147	0.28	27.113	-2846.8	86.270	28.92	59.11	749.7
		0.423 80	2340.8	145.80	22.35	34.26	180.7
87.907	0.30	26.977	-2801.4	86.780	28.83	59.32	741.6
		0.452 29	2352.0	145.40	22.42	34.56	181.0
88.631	0.32	26.846	-2758.1	87.262	28.73	59.53	733.8
		0.480 75	2362.2	145.03	22.49	34.85	181.3

Thermodynamic properties of nitrogen on the saturation line as a function of pressure—Continued

T K	p MPa	ρ mol/dm^3	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
89.323	0.34	26.720	-2716.6	87.721	28.65	59.75	726.4
		0.509 20	2371.5	144.68	22.56	35.15	181.6
89.985	0.36	26.598	-2676.7	88.157	28.57	59.96	719.2
		0.537 63	2380.1	144.35	22.63	35.44	181.8
90.621	0.38	26.480	-2638.2	88.575	28.49	60.18	712.2
		0.566 06	2388.0	144.04	22.70	35.74	182.0
91.233	0.40	26.366	-2601.1	88.975	28.42	60.40	705.5
		0.594 49	2395.3	143.74	22.76	36.04	182.2
92.670	0.45	26.093	-2513.3	89.909	28.25	60.95	689.7
		0.665 66	2411.0	143.05	22.93	36.79	182.5
93.995	0.50	25.837	-2431.6	90.764	28.11	61.52	674.9
		0.737 01	2423.8	142.42	23.09	37.55	182.8
95.227	0.55	25.595	-2355.0	91.553	27.98	62.09	660.9
		0.808 64	2434.1	141.84	23.25	38.32	183.0
96.380	0.60	25.364	-2282.6	92.288	27.86	62.69	647.7
		0.880 61	2442.4	141.31	23.40	39.11	183.2
97.466	0.65	25.142	-2213.8	92.977	27.76	63.29	635.2
		0.952 99	2448.9	140.82	23.56	39.92	183.2
98.493	0.70	24.928	-2148.2	93.626	27.67	63.92	623.1
		1.0258	2453.8	140.35	23.71	40.75	183.3
99.469	0.75	24.722	-2085.3	94.241	27.58	64.56	611.6
		1.0992	2457.2	139.91	23.86	41.60	183.3
100.399	0.80	24.522	-2024.8	94.826	27.51	65.23	600.4
		1.1731	2459.5	139.49	24.01	42.48	183.2
101.288	0.85	24.327	-1966.5	95.385	27.44	65.91	589.7
		1.2477	2460.5	139.09	24.16	43.38	183.2
102.140	0.90	24.136	-1910.0	95.920	27.38	66.62	579.2
		1.3228	2460.5	138.71	24.31	44.31	183.1
102.958	0.95	23.950	-1855.3	96.433	27.33	67.35	569.1
		1.3988	2459.6	138.34	24.46	45.28	182.9
103.747	1.00	23.768	-1802.0	96.928	27.28	68.11	559.2
		1.4754	2457.7	137.99	24.61	46.27	182.8
105.243	1.10	23.413	-1699.6	97.868	27.20	69.72	540.2
		1.6311	2451.5	137.31	24.91	48.37	182.4
106.644	1.20	23.068	-1601.7	98.751	27.14	71.45	521.9
		1.7904	2442.3	136.67	25.21	50.64	182.0
107.964	1.30	22.731	-1507.6	99.588	27.11	73.34	504.4
		1.9536	2430.2	136.06	25.50	53.11	181.6
109.213	1.40	22.400	-1416.6	100.38	27.09	75.39	487.4
		2.1211	2415.6	135.47	25.80	55.82	181.1
110.399	1.50	22.073	-1328.3	101.15	27.08	77.64	470.8
		2.2934	2398.4	134.90	26.11	58.82	180.6
111.530	1.60	21.749	-1242.2	101.88	27.10	80.12	454.7
		2.4709	2378.8	134.35	26.44	62.16	180.0

Thermodynamic properties of nitrogen on the saturation line as a function of pressure—Continued

T K	p MPa	ρ mol/dm^3	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
112.611	1.70	21.426	-1157.9	102.59	27.13	82.87	439.0
		2.6543	2356.7	133.80	26.79	65.92	179.4
113.646	1.80	21.103	-1075.1	103.28	27.18	85.93	423.5
		2.8441	2332.2	133.27	27.16	70.18	178.7
114.641	1.90	20.779	-993.40	103.96	27.26	89.38	408.3
		3.0412	2305.2	132.73	27.56	75.03	178.0
115.599	2.00	20.452	-912.52	104.62	27.35	93.29	393.2
		3.2462	2275.7	132.20	28.00	80.62	177.3
116.521	2.10	20.121	-832.16	105.27	27.47	97.77	378.3
		3.4604	2243.5	131.66	28.46	87.11	176.5
117.412	2.20	19.785	-752.00	105.91	27.62	103.0	363.5
		3.6847	2208.4	131.12	28.96	94.72	175.6
118.274	2.30	19.441	-671.73	106.55	27.80	109.1	348.7
		3.9209	2170.1	130.58	29.50	103.8	174.7
119.108	2.40	19.087	-590.98	107.18	28.01	116.3	333.9
		4.1705	2128.5	130.02	30.08	114.7	173.7
119.916	2.50	18.722	-509.32	107.82	28.28	125.2	318.9
		4.4361	2082.9	129.44	30.70	128.1	172.7
120.700	2.60	18.341	-426.24	108.47	28.61	136.3	303.7
		4.7207	2032.9	128.84	31.39	145.1	171.6
121.461	2.70	17.940	-341.09	109.13	29.02	150.5	288.2
		5.0283	1977.6	128.22	32.16	167.0	170.4
122.200	2.80	17.514	-252.99	109.80	29.54	169.6	272.1
		5.3647	1916.0	127.55	33.03	196.7	169.1
122.918	2.90	17.053	-160.69	110.51	30.22	196.4	255.3
		5.7382	1846.3	126.84	34.05	238.8	167.6
123.616	3.00	16.545	-62.249	111.26	31.15	237.3	237.6
		6.1621	1766.0	126.05	35.29	303.2	165.9
124.295	3.10	15.964	45.692	112.08	32.47	307.0	218.4
		6.6591	1670.7	125.16	36.87	413.0	163.6
124.955	3.20	15.265	169.91	113.03	34.50	452.4	197.1
		7.2755	1551.2	124.08	39.09	640.3	160.5
125.597	3.30	14.313	329.32	114.25	38.18	930.9	171.9
		8.1402	1382.8	122.63	42.74	1370.	155.4
126.192	3.3958	11.184	818.91	118.07			

Thermodynamic properties of nitrogen

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
		0.1 MPa					
63.170	30.960	-4222.8	-4219.6	67.955	32.95	56.02	995.6
65	30.690	-4120.2	-4117.0	69.556	32.60	56.11	976.9
70	29.937	-3839.0	-3835.7	73.724	31.65	56.42	926.2
75	29.155	-3555.9	-3552.5	77.632	30.76	56.89	875.5
77.244	28.793	-3428.0	-3424.6	79.313	30.39	57.17	852.5
77.244	0.162 65	1544.3	2159.1	151.60	21.60	31.46	174.7
80	0.156 33	1605.7	2245.4	152.70	21.48	31.15	178.3
85	0.146 15	1715.8	2400.0	154.57	21.31	30.72	184.5
90	0.137 32	1824.5	2552.8	156.32	21.20	30.41	190.5
95	0.129 56	1932.4	2704.3	157.96	21.11	30.19	196.2
100	0.122 68	2039.6	2854.7	159.50	21.05	30.01	201.6
105	0.116 52	2146.2	3004.4	160.96	21.00	29.88	206.9
110	0.110 98	2252.5	3153.5	162.35	20.97	29.77	212.1
115	0.105 96	2358.4	3302.2	163.67	20.94	29.68	217.1
120	0.101 38	2464.0	3450.4	164.93	20.92	29.61	222.0
125	0.097200	2569.5	3598.3	166.14	20.90	29.55	226.7
130	0.093355	2674.8	3745.9	167.30	20.88	29.50	231.4
135	0.089809	2779.9	3893.3	168.41	20.87	29.46	235.9
140	0.086528	2884.9	4040.6	169.48	20.86	29.43	240.4
145	0.083482	2989.8	4187.6	170.51	20.85	29.40	244.7
150	0.080647	3094.6	4334.5	171.51	20.85	29.37	249.0
160	0.075524	3303.9	4628.0	173.40	20.84	29.33	257.3
170	0.071021	3513.1	4921.1	175.18	20.83	29.29	265.4
180	0.067029	3722.0	5213.9	176.85	20.82	29.27	273.2
190	0.063466	3930.8	5506.5	178.44	20.82	29.25	280.7
200	0.060265	4139.5	5798.9	179.93	20.81	29.23	288.1
210	0.057374	4348.2	6091.1	181.36	20.81	29.22	295.3
220	0.054749	4556.7	6383.2	182.72	20.81	29.21	302.3
230	0.052355	4765.2	6675.2	184.02	20.81	29.20	309.1
240	0.050162	4973.6	6967.1	185.26	20.81	29.19	315.8
250	0.048147	5182.0	7259.0	186.45	20.81	29.18	322.3
260	0.046287	5390.4	7550.8	187.60	20.81	29.18	328.7
270	0.044567	5598.7	7842.5	188.70	20.81	29.17	335.0
280	0.042970	5807.1	8134.3	189.76	20.81	29.17	341.2
290	0.041484	6015.4	8426.0	190.78	20.81	29.17	347.2
300	0.040098	6223.8	8717.7	191.77	20.82	29.17	353.2
310	0.038801	6432.2	9009.4	192.73	20.82	29.17	359.0
320	0.037586	6640.6	9301.2	193.65	20.83	29.18	364.7
330	0.036445	6849.1	9593.0	194.55	20.84	29.18	370.4
340	0.035371	7057.7	9884.8	195.42	20.85	29.19	375.9
350	0.034359	7266.3	10 177	196.27	20.86	29.20	381.4
400	0.030060	8311.6	11 638	200.17	20.94	29.27	407.5
450	0.026718	9362.1	13 105	203.63	21.08	29.40	431.8
500	0.024045	10 421	14 580	206.73	21.27	29.59	454.6
550	0.021858	11 490	16 065	209.57	21.51	29.84	476.0
600	0.020037	12 573	17 564	212.17	21.80	30.12	496.3
700	0.017175	14 785	20 607	216.86	22.44	30.76	533.9
800	0.015028	17 063	23 717	221.02	23.12	31.44	568.4
900	0.013359	19 409	26 894	224.76	23.78	32.10	600.7
1000	0.012023	21 817	30 135	228.17	24.39	32.70	631.1

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
			0.2 MPa				
63.192	30.963	-4222.5	-4216.1	67.959	32.96	56.01	996.0
65	30.697	-4121.2	-4114.7	69.540	32.60	56.09	977.5
70	29.945	-3840.2	-3833.6	73.707	31.66	56.40	926.9
75	29.163	-3557.3	-3550.5	77.613	30.77	56.86	876.3
80	28.348	-3271.6	-3264.5	81.304	29.95	57.56	824.9
83.626	27.729	-3061.8	-3054.6	83.870	29.41	58.26	786.8
83.626	0.309 19	1636.7	2283.6	147.70	22.04	33.06	179.0
85	0.303 04	1668.8	2328.8	148.24	21.94	32.78	180.8
90	0.282 90	1783.7	2490.6	150.09	21.67	32.00	187.3
95	0.265 62	1896.2	2649.2	151.81	21.47	31.45	193.5
100	0.250 56	2007.2	2805.4	153.41	21.34	31.04	199.3
105	0.237 27	2116.9	2959.8	154.91	21.23	30.74	205.0
110	0.225 43	2225.7	3112.9	156.34	21.15	30.50	210.4
115	0.214 80	2333.7	3264.8	157.69	21.09	30.31	215.6
120	0.205 18	2441.2	3416.0	158.98	21.05	30.15	220.6
125	0.196 44	2548.3	3566.4	160.21	21.01	30.03	225.5
130	0.188 44	2654.9	3716.3	161.38	20.98	29.92	230.3
135	0.181 10	2761.3	3865.7	162.51	20.95	29.83	235.0
140	0.174 32	2867.4	4014.7	163.59	20.93	29.76	239.5
145	0.168 06	2973.2	4163.3	164.64	20.92	29.70	244.0
150	0.162 24	3078.9	4311.6	165.64	20.90	29.64	248.4
160	0.151 77	3289.8	4607.6	167.55	20.88	29.55	256.8
170	0.142 59	3500.2	4902.8	169.34	20.86	29.49	265.0
180	0.134 48	3710.2	5197.4	171.02	20.85	29.43	272.9
190	0.127 26	3919.9	5491.5	172.61	20.84	29.39	280.5
200	0.120 79	4129.4	5785.2	174.12	20.84	29.35	287.9
210	0.114 95	4338.7	6078.6	175.55	20.83	29.33	295.2
220	0.109 66	4547.9	6371.7	176.92	20.83	29.30	302.2
230	0.104 83	4756.9	6664.7	178.22	20.82	29.28	309.1
240	0.100 42	4965.8	6957.4	179.46	20.82	29.27	315.8
250	0.096369	5174.6	7250.0	180.66	20.82	29.25	322.4
260	0.092632	5383.4	7542.5	181.81	20.82	29.24	328.8
270	0.089177	5592.1	7834.8	182.91	20.82	29.23	335.1
280	0.085972	5800.8	8127.1	183.97	20.82	29.23	341.3
290	0.082990	6009.4	8419.3	185.00	20.82	29.22	347.4
300	0.080210	6218.1	8711.5	185.99	20.83	29.22	353.3
310	0.077610	6426.7	9003.7	186.95	20.83	29.22	359.2
320	0.075175	6635.4	9295.8	187.87	20.84	29.22	364.9
330	0.072888	6844.1	9588.0	188.77	20.84	29.22	370.6
340	0.070737	7052.8	9880.2	189.65	20.85	29.22	376.1
350	0.068710	7261.7	10 172	190.49	20.86	29.23	381.6
400	0.060103	8307.7	11 635	194.40	20.94	29.30	407.7
450	0.053416	9358.8	13 103	197.86	21.08	29.42	432.1
500	0.048070	10 418	14 579	200.97	21.27	29.61	454.9
550	0.043699	11 488	16 065	203.80	21.51	29.85	476.3
600	0.040057	12 571	17 564	206.41	21.80	30.13	496.5
700	0.034335	14 783	20 608	211.10	22.44	30.77	534.1
800	0.030044	17 062	23 718	215.25	23.12	31.44	568.7
900	0.026707	19 407	26 896	218.99	23.78	32.10	600.9

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
1000	0.024038	21 816.	30 137.	222.41	24.39	32.71	631.3
			0.5 MPa				
63.258	30.971	-4221.7	-4205.6	67.972	32.97	55.96	997.1
65	30.716	-4124.3	-4108.0	69.493	32.63	56.04	979.4
70	29.967	-3843.8	-3827.1	73.656	31.68	56.34	929.0
75	29.189	-3561.5	-3544.4	77.557	30.79	56.78	878.7
80	28.378	-3276.6	-3258.9	81.242	29.97	57.45	827.7
85	27.524	-2987.6	-2969.4	84.752	29.23	58.43	775.4
90	26.615	-2692.7	-2673.9	88.130	28.57	59.87	720.8
93.995	25.837	-2450.9	-2431.6	90.764	28.11	61.52	674.9
93.995	0.737 01	1745.4	2423.8	142.42	23.09	37.55	182.8
95	0.725 18	1771.8	2461.3	142.82	22.94	37.06	184.4
100	0.673 19	1898.9	2641.7	144.67	22.40	35.23	191.8
105	0.629 94	2020.9	2814.6	146.35	22.05	34.02	198.5
110	0.593 04	2139.4	2982.5	147.92	21.80	33.16	204.8
115	0.560 98	2255.3	3146.6	149.38	21.62	32.52	210.8
120	0.532 72	2369.3	3307.9	150.75	21.48	32.02	216.5
125	0.507 55	2481.9	3467.0	152.05	21.37	31.63	221.9
130	0.484 92	2593.3	3624.4	153.28	21.29	31.32	227.1
135	0.464 44	2703.7	3780.3	154.46	21.22	31.06	232.2
140	0.445 78	2813.4	3935.0	155.59	21.16	30.85	237.0
145	0.428 69	2922.5	4088.8	156.66	21.12	30.67	241.8
150	0.412 96	3031.0	4241.7	157.70	21.08	30.51	246.4
160	0.384 94	3246.7	4545.6	159.66	21.02	30.27	255.3
170	0.360 68	3461.0	4847.3	161.49	20.98	30.08	263.8
180	0.339 44	3674.4	5147.4	163.21	20.94	29.94	272.0
190	0.320 66	3886.9	5446.2	164.82	20.92	29.83	279.9
200	0.303 93	4098.9	5744.0	166.35	20.90	29.73	287.5
210	0.288 90	4310.3	6041.0	167.80	20.89	29.66	294.9
220	0.275 34	4521.3	6337.2	169.18	20.87	29.60	302.1
230	0.263 02	4731.9	6632.9	170.49	20.87	29.55	309.1
240	0.251 78	4942.3	6928.2	171.75	20.86	29.50	315.9
250	0.241 48	5152.4	7223.0	172.95	20.85	29.47	322.6
260	0.232 01	5362.4	7517.5	174.11	20.85	29.43	329.1
270	0.223 26	5572.2	7811.7	175.22	20.85	29.41	335.4
280	0.215 16	5781.8	8105.7	176.29	20.85	29.39	341.7
290	0.207 63	5991.4	8399.5	177.32	20.85	29.37	347.8
300	0.200 62	6200.8	8693.1	178.31	20.85	29.35	353.8
310	0.194 08	6410.2	8986.5	179.27	20.85	29.34	359.7
320	0.187 95	6619.6	9279.9	180.21	20.85	29.33	365.5
330	0.182 20	6829.0	9573.2	181.11	20.86	29.33	371.1
340	0.176 80	7038.3	9866.4	181.98	20.87	29.32	376.7
350	0.171 71	7247.7	10 160	182.83	20.88	29.32	382.2
400	0.150 13	8296.1	11 627	186.75	20.95	29.36	408.5
450	0.133 40	9349.0	13 097	190.22	21.09	29.47	432.9
500	0.120 03	10 409	14 575	193.33	21.28	29.65	455.7
550	0.109 11	11 480	16 063	196.17	21.52	29.88	477.1
600	0.100 01	12 564	17 564	198.78	21.80	30.15	497.3
700	0.085731	14 778	20 610	203.47	22.45	30.79	534.9

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
800	0.075 022	17 057.	23 722.	207.63	23.13	31.46	569.4
900	0.066 694	19 404.	26 901.	211.37	23.78	32.11	601.7
1000	0.060 032	21 814.	30 143.	214.78	24.39	32.71	632.0
				1.0 MPa			
63.368	30.986	-4220.3	-4188.1	67.993	32.98	55.89	998.9
65	30.748	-4129.3	-4096.8	69.415	32.66	55.96	982.5
70	30.003	-3849.7	-3816.4	73.572	31.72	56.23	932.5
75	29.232	-3568.4	-3534.2	77.465	30.83	56.65	882.7
80	28.427	-3284.7	-3249.5	81.139	30.01	57.27	832.3
85	27.583	-2997.3	-2961.0	84.637	29.27	58.19	780.7
90	26.686	-2704.4	-2666.9	87.998	28.60	59.52	727.1
95	25.721	-2403.6	-2364.7	91.266	28.02	61.51	670.5
100	24.658	-2090.7	-2050.1	94.493	27.55	64.56	609.4
103.747	23.768	-1844.1	-1802.0	96.928	27.28	68.11	559.2
103.747	1.4754	1780.0	2457.7	137.99	24.61	46.27	182.8
105	1.4391	1819.8	2514.7	138.53	24.26	44.69	185.3
110	1.3184	1968.1	2726.6	140.51	23.31	40.49	194.1
115	1.2236	2105.1	2922.3	142.25	22.74	38.00	201.9
120	1.1457	2235.1	3107.9	143.83	22.36	36.33	208.9
125	1.0798	2360.3	3286.4	145.28	22.08	35.14	215.4
130	1.0228	2482.1	3459.8	146.64	21.87	34.24	221.5
135	0.972 78	2601.1	3629.1	147.92	21.70	33.54	227.3
140	0.928 31	2718.2	3795.4	149.13	21.57	32.98	232.8
145	0.888 40	2833.5	3959.1	150.28	21.47	32.53	238.1
150	0.852 30	2947.6	4120.8	151.38	21.39	32.16	243.2
160	0.789 30	3172.4	4439.4	153.43	21.26	31.58	252.9
170	0.735 92	3394.1	4753.0	155.33	21.17	31.16	262.0
180	0.689 94	3613.5	5062.9	157.11	21.10	30.84	270.6
190	0.649 81	3831.1	5370.0	158.77	21.05	30.59	278.9
200	0.614 41	4047.3	5674.9	160.33	21.01	30.39	286.9
210	0.582 89	4262.4	5978.0	161.81	20.98	30.23	294.5
220	0.554 62	4476.6	6279.6	163.21	20.96	30.10	301.9
230	0.529 10	4690.1	6580.1	164.55	20.94	29.99	309.1
240	0.505 92	4903.0	6879.6	165.82	20.92	29.90	316.1
250	0.484 77	5115.4	7178.2	167.04	20.91	29.83	322.9
260	0.465 38	5327.3	7476.1	168.21	20.90	29.76	329.5
270	0.447 53	5539.0	7773.4	169.33	20.89	29.70	336.0
280	0.431 04	5750.3	8070.2	170.41	20.89	29.66	342.4
290	0.415 76	5961.3	8366.6	171.45	20.88	29.61	348.6
300	0.401 55	6172.2	8662.5	172.45	20.88	29.58	354.6
310	0.388 30	6382.9	8958.2	173.42	20.88	29.55	360.6
320	0.375 92	6593.4	9253.6	174.36	20.88	29.53	366.4
330	0.364 32	6803.9	9548.7	175.27	20.89	29.51	372.2
340	0.353 42	7014.2	9843.7	176.15	20.89	29.49	377.8
350	0.343 18	7224.6	10 139	177.01	20.90	29.48	383.3
400	0.299 83	8276.9	11 612	180.94	20.97	29.48	409.7
450	0.266 30	9332.6	13 088	184.42	21.10	29.56	434.1
500	0.239 58	10 395	14 569	187.54	21.29	29.72	457.0
550	0.217 76	11 468	16 060	190.38	21.53	29.93	478.4

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
600	0.199 60	12 554	17 564	193.00	21.81	30.20	498.7
700	0.171 11	14 769	20 614	197.70	22.45	30.82	536.2
800	0.149 75	17 051	23 728	201.86	23.13	31.48	570.7
900	0.133 14	19 398	26 909	205.60	23.79	32.13	602.9
1000	0.119 86	21 809	30 152	209.02	24.39	32.73	633.2
			1.5 MPa				
63.478	31.000	-4219.0	-4170.6	68.015	33.00	55.83	1001.
65	30.779	-4134.3	-4085.6	69.338	32.70	55.88	985.5
70	30.039	-3855.5	-3805.6	73.488	31.75	56.13	936.0
75	29.273	-3575.2	-3524.0	77.373	30.86	56.52	886.6
80	28.476	-3292.7	-3240.0	81.038	30.04	57.10	836.8
85	27.640	-3006.8	-2952.5	84.524	29.30	57.96	785.9
90	26.756	-2715.9	-2659.8	87.870	28.63	59.20	733.2
95	25.807	-2417.7	-2359.6	91.116	28.05	61.02	677.8
100	24.769	-2108.6	-2048.1	94.311	27.56	63.79	618.6
105	23.597	-1782.5	-1718.9	97.522	27.20	68.27	553.3
110	22.199	-1426.7	-1359.1	100.87	27.08	76.65	477.6
110.399	22.073	-1396.3	-1328.3	101.15	27.08	77.64	470.8
110.399	2.2934	1744.3	2398.4	134.90	26.11	58.82	180.6
115	2.0610	1914.9	2642.7	137.07	24.50	48.77	191.0
120	1.8816	2074.7	2871.9	139.03	23.55	43.47	200.3
125	1.7433	2220.4	3080.9	140.73	22.96	40.35	208.3
130	1.6310	2357.4	3277.1	142.27	22.56	38.27	215.6
135	1.5367	2488.4	3464.6	143.69	22.26	36.78	222.3
140	1.4556	2615.1	3645.6	145.00	22.04	35.67	228.6
145	1.3848	2738.4	3821.7	146.24	21.86	34.80	234.5
150	1.3220	2859.2	3993.8	147.41	21.72	34.10	240.0
160	1.2151	3094.9	4329.4	149.57	21.51	33.07	250.5
170	1.1268	3325.0	4656.3	151.55	21.36	32.34	260.3
180	1.0520	3551.1	4976.9	153.39	21.26	31.81	269.4
190	0.987 66	3774.2	5292.9	155.10	21.18	31.40	278.1
200	0.931 50	3995.0	5605.3	156.70	21.12	31.08	286.3
210	0.881 94	4214.0	5914.8	158.21	21.07	30.83	294.3
220	0.837 79	4431.6	6222.0	159.64	21.04	30.62	301.9
230	0.798 15	4648.0	6527.3	161.00	21.01	30.45	309.3
240	0.762 33	4863.5	6831.1	162.29	20.98	30.31	316.4
250	0.729 78	5078.2	7133.6	163.52	20.96	30.19	323.4
260	0.700 03	5292.2	7435.0	164.71	20.95	30.09	330.1
270	0.672 73	5505.7	7735.4	165.84	20.94	30.00	336.7
280	0.647 57	5718.7	8035.1	166.93	20.93	29.93	343.1
290	0.624 30	5931.3	8334.0	167.98	20.92	29.86	349.4
300	0.602 70	6143.5	8632.3	168.99	20.91	29.81	355.5
310	0.582 61	6355.5	8930.2	169.97	20.91	29.76	361.5
320	0.563 85	6567.3	9227.5	170.91	20.91	29.72	367.4
330	0.546 30	6778.8	9524.6	171.82	20.91	29.69	373.2
340	0.529 83	6990.2	9821.3	172.71	20.92	29.66	378.9
350	0.514 36	7201.5	10 118	173.57	20.92	29.64	384.5
400	0.449 07	8257.7	11 598	177.52	20.99	29.59	410.9
450	0.398 71	9316.4	13 079	181.01	21.12	29.65	435.5
500	0.358 63	10 381	14 564	184.14	21.30	29.78	458.3

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
550	0.325 95	11 456	16 058	186.99	21.54	29.99	479.8
600	0.298 76	12 543	17 564	189.61	21.82	30.24	500.0
700	0.256 13	14 761	20 617	194.31	22.46	30.85	537.5
800	0.224 18	17 044	23 735	198.48	23.14	31.50	572.0
900	0.199 35	19 393	26 917	202.22	23.79	32.14	604.1
1000	0.179 48	21 804	30 162	205.64	24.40	32.74	634.4
			2.0 MPa				
63.587	31.014	-4217.6	-4153.1	68.036	33.01	55.76	1003.
65	30.811	-4139.2	-4074.3	69.262	32.74	55.81	988.6
70	30.075	-3861.2	-3794.7	73.405	31.79	56.04	939.4
75	29.315	-3582.0	-3513.7	77.282	30.90	56.39	890.5
80	28.524	-3300.6	-3230.5	80.938	30.08	56.94	841.2
85	27.697	-3016.1	-2943.9	84.412	29.33	57.74	791.0
90	26.824	-2727.1	-2652.5	87.743	28.67	58.89	739.1
95	25.890	-2431.4	-2354.2	90.969	28.08	60.57	684.9
100	24.874	-2125.9	-2045.5	94.136	27.57	63.08	627.3
105	23.739	-1805.2	-1721.0	97.301	27.19	67.04	564.5
110	22.410	-1459.5	-1370.2	100.56	27.00	74.01	493.4
115	20.704	-1063.9	-967.29	104.14	27.25	89.82	405.8
115.599	20.452	-1010.3	-912.52	104.62	27.35	93.29	393.2
115.599	3.2462	1659.6	2275.7	132.20	28.00	80.62	177.3
120	2.8387	1867.3	2571.8	134.71	25.45	58.41	189.7
125	2.5477	2052.6	2837.6	136.89	24.15	49.09	200.4
130	2.3376	2214.3	3069.8	138.71	23.41	44.24	209.3
135	2.1733	2362.7	3282.9	140.32	22.91	41.21	217.1
140	2.0387	2502.4	3483.5	141.78	22.55	39.12	224.2
145	1.9250	2636.1	3675.0	143.12	22.28	37.59	230.8
150	1.8270	2765.3	3860.0	144.37	22.07	36.43	237.0
160	1.6647	3013.9	4215.4	146.67	21.77	34.77	248.3
170	1.5343	3253.6	4557.1	148.74	21.56	33.65	258.7
180	1.4261	3487.1	4889.5	150.64	21.42	32.86	268.3
190	1.3344	3716.1	5214.9	152.40	21.31	32.26	277.4
200	1.2552	3941.8	5535.2	154.04	21.23	31.81	286.0
210	1.1860	4165.0	5851.4	155.59	21.16	31.45	294.1
220	1.1247	4386.1	6164.3	157.04	21.11	31.16	302.0
230	1.0701	4605.7	6474.7	158.42	21.08	30.92	309.5
240	1.0209	4823.8	6782.9	159.73	21.04	30.72	316.8
250	0.976 38	5040.9	7089.3	160.98	21.02	30.56	323.9
260	0.935 85	5257.0	7394.1	162.18	21.00	30.42	330.8
270	0.898 75	5472.4	7697.7	163.33	20.98	30.30	337.4
280	0.864 65	5687.1	8000.2	164.43	20.97	30.20	343.9
290	0.833 17	5901.3	8301.7	165.48	20.96	30.11	350.3
300	0.804 02	6114.9	8602.4	166.50	20.95	30.03	356.5
310	0.776 93	6328.2	8902.5	167.49	20.94	29.97	362.5
320	0.751 68	6541.2	9201.9	168.44	20.94	29.91	368.5
330	0.728 09	6753.8	9500.7	169.36	20.94	29.86	374.3
340	0.705 99	6966.3	9799.2	170.25	20.94	29.82	380.0
350	0.685 23	7178.5	10 097	171.11	20.95	29.79	385.6
400	0.597 83	8238.6	11 584	175.08	21.01	29.70	412.2

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
450	0.530 61	9300.2	13 069	178.58	21.13	29.73	436.8
500	0.477 19	10 367	14 559	181.72	21.31	29.85	459.7
550	0.433 67	11 444	16 056	184.57	21.55	30.04	481.1
600	0.397 50	12 532	17 564	187.20	21.83	30.29	501.4
700	0.340 79	14 752	20 621	191.91	22.47	30.88	538.8
800	0.298 32	17 037	23 741	196.07	23.14	31.53	573.2
900	0.265 30	19 387	26 926	199.83	23.80	32.16	605.3
1000	0.238 89	21 800	30 172	203.24	24.40	32.75	635.5
			2.5 MPa				
63.697	31.029	-4216.2	-4135.6	68.057	33.03	55.69	1004.
65	30.842	-4144.1	-4063.0	69.186	32.77	55.73	991.6
70	30.111	-3866.9	-3783.9	73.323	31.83	55.94	942.8
75	29.356	-3588.6	-3503.4	77.193	30.93	56.27	894.3
80	28.572	-3308.4	-3220.9	80.840	30.12	56.78	845.6
85	27.753	-3025.3	-2935.2	84.303	29.37	57.52	795.9
90	26.890	-2738.1	-2645.1	87.619	28.70	58.60	744.9
95	25.971	-2444.7	-2348.5	90.826	28.10	60.15	691.8
100	24.976	-2142.5	-2042.4	93.966	27.59	62.43	635.7
105	23.873	-1826.8	-1722.1	97.090	27.19	65.95	575.1
110	22.603	-1489.6	-1379.0	100.28	26.95	71.86	507.8
115	21.031	-1112.9	-994.04	103.70	27.02	83.78	428.3
119.916	18.722	-642.85	-509.32	107.82	28.28	125.2	318.9
119.916	4.4361	1519.4	2082.9	129.44	30.70	128.1	172.7
120	4.4128	1527.0	2093.6	129.53	30.52	125.1	173.2
125	3.6090	1834.3	2527.0	133.08	26.01	67.55	190.9
130	3.1944	2043.4	2826.0	135.42	24.52	54.05	202.4
135	2.9097	2219.3	3078.5	137.33	23.69	47.59	211.8
140	2.6930	2377.7	3306.1	138.99	23.14	43.71	220.0
145	2.5186	2525.1	3517.7	140.47	22.75	41.11	227.3
150	2.3731	2664.9	3718.3	141.83	22.45	39.23	234.1
160	2.1406	2929.1	4097.0	144.28	22.04	36.71	246.3
170	1.9596	3179.7	4455.4	146.45	21.77	35.10	257.3
180	1.8128	3421.5	4800.5	148.42	21.58	33.98	267.4
190	1.6902	3657.0	5136.1	150.24	21.44	33.17	276.8
200	1.5856	3888.0	5464.7	151.92	21.33	32.56	285.7
210	1.4950	4115.5	5787.8	153.50	21.26	32.09	294.1
220	1.4154	4340.4	6106.7	154.98	21.19	31.71	302.2
230	1.3447	4563.1	6422.2	156.38	21.14	31.40	309.9
240	1.2815	4784.0	6734.8	157.72	21.10	31.14	317.3
250	1.2245	5003.5	7045.2	158.98	21.07	30.93	324.5
260	1.1727	5221.8	7353.6	160.19	21.04	30.75	331.5
270	1.1255	5439.1	7660.3	161.35	21.02	30.60	338.2
280	1.0822	5655.6	7965.7	162.46	21.01	30.47	344.8
290	1.0423	5871.3	8269.8	163.53	20.99	30.36	351.2
300	1.0054	6086.4	8572.9	164.56	20.98	30.26	357.5
310	0.971 21	6301.0	8875.1	165.55	20.97	30.18	363.6
320	0.939 37	6515.1	9176.5	166.50	20.97	30.11	369.6
330	0.909 65	6728.9	9477.2	167.43	20.97	30.04	375.5
340	0.881 83	6942.4	9777.4	168.32	20.97	29.99	381.2

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
350	0.855 74	7155.6	10 077	169.19	20.97	29.94	386.8
400	0.746 10	8219.6	11 570	173.18	21.02	29.81	413.5
450	0.661 98	9284.1	13 061	176.69	21.14	29.82	438.1
500	0.595 24	10 354	14 554	179.84	21.32	29.92	461.0
550	0.540 92	11 432	16 053	182.70	21.56	30.09	482.5
600	0.495 80	12 522	17 564	185.32	21.84	30.33	502.7
700	0.425 10	14 744	20 625	190.04	22.47	30.91	540.2
800	0.372 17	17 030	23 748	194.21	23.15	31.55	574.5
900	0.331 02	19 382	26 934	197.96	23.80	32.18	606.5
1000	0.298 10	21 795	30 182	201.38	24.41	32.77	636.7
			3.0 MPa				
63.806	31.043	-4214.8	-4118.2	68.079	33.04	55.62	1006.
65	30.872	-4148.9	-4051.7	69.110	32.81	55.66	994.5
70	30.146	-3872.5	-3773.0	73.241	31.86	55.85	946.1
75	29.396	-3595.1	-3493.1	77.104	30.97	56.15	898.1
80	28.618	-3316.0	-3211.2	80.742	30.15	56.63	849.8
85	27.807	-3034.3	-2926.4	84.195	29.40	57.32	800.8
90	26.955	-2748.8	-2637.5	87.498	28.73	58.32	750.6
95	26.050	-2457.7	-2342.5	90.687	28.13	59.75	698.5
100	25.074	-2158.5	-2038.9	93.801	27.61	61.84	643.7
105	24.001	-1847.4	-1722.4	96.889	27.19	64.98	585.2
110	22.780	-1517.6	-1385.9	100.02	26.91	70.06	521.0
115	21.313	-1155.6	-1014.8	103.32	26.87	79.47	447.6
120	19.312	-723.85	-568.50	107.11	27.49	104.0	355.0
123.616	16.545	-243.58	-62.25	111.26	31.15	237.3	237.6
123.616	6.1621	1279.2	1766.0	126.05	35.29	303.2	165.9
125	5.3780	1479.3	2037.1	128.23	30.16	143.5	177.1
130	4.3137	1825.1	2520.6	132.03	26.12	73.49	194.8
135	3.7920	2051.0	2842.1	134.46	24.65	57.55	206.3
140	3.4415	2237.6	3109.3	136.41	23.82	50.06	215.8
145	3.1781	2403.7	3347.6	138.08	23.26	45.61	224.0
150	2.9679	2557.0	3567.9	139.57	22.86	42.65	231.4
160	2.6455	2840.0	3974.0	142.20	22.32	38.93	244.5
170	2.4039	3103.3	4351.3	144.48	21.98	36.69	256.2
180	2.2124	3354.2	4710.2	146.53	21.74	35.19	266.7
190	2.0551	3596.8	5056.6	148.41	21.57	34.14	276.5
200	1.9226	3833.4	5393.8	150.14	21.44	33.35	285.6
210	1.8088	4065.6	5724.2	151.75	21.35	32.74	294.3
220	1.7095	4294.3	6049.1	153.26	21.27	32.27	302.5
230	1.6220	4520.3	6369.8	154.69	21.21	31.88	310.4
240	1.5440	4744.1	6687.1	156.04	21.16	31.57	317.9
250	1.4739	4966.1	7001.4	157.32	21.12	31.31	325.2
260	1.4106	5186.6	7313.4	158.54	21.09	31.09	332.3
270	1.3529	5405.8	7623.3	159.71	21.07	30.90	339.1
280	1.3001	5624.0	7931.5	160.83	21.04	30.74	345.8
290	1.2516	5841.4	8238.3	161.91	21.03	30.61	352.3
300	1.2069	6057.9	8543.7	162.95	21.01	30.49	358.6
310	1.1654	6273.8	8848.1	163.94	21.00	30.39	364.7
320	1.1269	6489.2	9151.5	164.91	21.00	30.30	370.7
330	1.0909	6704.1	9454.0	165.84	20.99	30.22	376.6

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm³	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
340	1.0573	6918.6	9755.9	166.74	20.99	30.15	382.4
350	1.0259	7132.8	10 057	167.61	20.99	30.10	388.1
400	0.893 85	8200.7	11 557	171.62	21.04	29.92	414.9
450	0.792 82	9268.0	13 052	175.14	21.16	29.90	439.5
500	0.712 78	10 340	14 549	178.29	21.34	29.98	462.4
550	0.647 70	11 420	16 051	181.16	21.57	30.15	483.9
600	0.593 67	12 511	17 564	183.79	21.85	30.37	504.1
700	0.509 05	14 736	20 629	188.51	22.48	30.94	541.5
800	0.445 72	17 023	23 754	192.69	23.15	31.57	575.8
900	0.396 49	19 376	26 942	196.44	23.81	32.20	607.7
1000	0.357 10	21 791	30 192	199.86	24.41	32.78	637.9
				3.5 MPa			
63.915	31.057	-4213.4	-4100.7	68.100	33.06	55.56	1008.
65	30.903	-4153.7	-4040.4	69.035	32.85	55.59	997.5
70	30.181	-3878.1	-3762.1	73.160	31.90	55.76	949.4
75	29.436	-3601.5	-3482.6	77.016	31.01	56.04	901.8
80	28.664	-3323.5	-3201.4	80.646	30.19	56.48	854.1
85	27.861	-3043.1	-2917.5	84.088	29.44	57.12	805.7
90	27.019	-2759.2	-2629.7	87.378	28.76	58.05	756.1
95	26.127	-2470.3	-2336.3	90.550	28.16	59.38	705.0
100	25.169	-2174.0	-2034.9	93.642	27.64	61.29	651.5
105	24.122	-1867.0	-1721.9	96.696	27.20	64.12	594.7
110	22.946	-1543.7	-1391.2	99.772	26.89	68.53	533.3
115	21.561	-1193.6	-1031.3	102.97	26.77	76.20	464.6
120	19.782	-792.10	-615.18	106.51	27.06	92.85	383.1
125	16.765	-230.88	-22.11	111.34	29.23	174.4	265.0
130	6.0392	1501.5	2081.1	127.89	28.88	130.8	185.7
135	4.9075	1844.0	2557.2	131.49	25.90	75.02	200.9
140	4.3189	2076.9	2887.3	133.89	24.60	59.25	211.9
145	3.9202	2269.6	3162.4	135.82	23.83	51.52	221.0
150	3.6201	2440.7	3407.5	137.49	23.30	46.87	229.0
160	3.1826	2746.5	3846.3	140.32	22.61	41.47	243.1
170	2.8681	3024.2	4244.6	142.74	22.19	38.44	255.3
180	2.6252	3285.4	4618.6	144.87	21.90	36.49	266.2
190	2.4292	3535.6	4976.4	146.81	21.70	35.15	276.3
200	2.2660	3778.2	5322.7	148.59	21.55	34.17	285.7
210	2.1272	4015.2	5660.5	150.23	21.44	33.42	294.6
220	2.0071	4247.9	5991.7	151.77	21.35	32.84	303.0
230	1.9017	4477.3	6317.8	153.22	21.28	32.38	311.0
240	1.8082	4704.0	6639.6	154.59	21.22	32.00	318.7
250	1.7246	4928.6	6958.0	155.89	21.18	31.69	326.0
260	1.6492	5151.3	7273.5	157.13	21.14	31.43	333.2
270	1.5808	5372.6	7586.7	158.31	21.11	31.21	340.1
280	1.5183	5592.6	7897.7	159.44	21.08	31.02	346.8
290	1.4610	5811.5	8207.1	160.53	21.06	30.85	353.3
300	1.4082	6029.5	8514.9	161.57	21.05	30.71	359.7
310	1.3594	6246.8	8821.4	162.58	21.03	30.59	365.9
320	1.3141	6463.3	9126.8	163.55	21.02	30.49	371.9
330	1.2719	6679.4	9431.2	164.48	21.02	30.40	377.9

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm³	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
340	1.2324	6894.9	9734.8	165.39	21.02	30.32	383.7
350	1.1955	7110.0	10 038	166.27	21.02	30.25	389.4
400	1.0411	8181.8	11 544	170.29	21.06	30.03	416.2
450	0.923 11	9252.1	13 044	173.82	21.17	29.98	440.9
500	0.829 81	10 326	14 544	176.99	21.35	30.05	463.8
550	0.754 00	11 408	16 050	179.86	21.58	30.20	485.3
600	0.691 12	12 500	17 565	182.49	21.86	30.41	505.4
700	0.592 65	14 727	20 633	187.22	22.49	30.97	542.8
800	0.518 98	17 017	23 761	191.40	23.16	31.59	577.0
900	0.461 72	19 371	26 951	195.15	23.81	32.21	609.0
1000	0.415 90	21 786	30 202	198.58	24.42	32.79	639.1
			4.0 MPa				
64.024	31.071	-4212.0	-4083.2	68.121	33.07	55.49	1010.
65	30.933	-4158.4	-4029.1	68.961	32.88	55.52	1000.
70	30.215	-3883.5	-3751.1	73.080	31.93	55.67	952.7
75	29.475	-3607.9	-3472.2	76.929	31.04	55.93	905.5
80	28.710	-3330.9	-3191.6	80.551	30.22	56.33	858.2
85	27.914	-3051.8	-2908.5	83.983	29.47	56.94	810.4
90	27.081	-2769.5	-2621.8	87.260	28.79	57.80	761.6
95	26.201	-2482.6	-2329.9	90.417	28.19	59.03	711.3
100	25.261	-2189.0	-2030.6	93.486	27.66	60.78	659.0
105	24.239	-1885.8	-1720.8	96.510	27.22	63.33	603.8
110	23.101	-1568.3	-1395.1	99.539	26.88	67.21	544.7
115	21.785	-1228.2	-1044.6	102.65	26.70	73.60	479.9
120	20.161	-848.13	-649.73	106.01	26.81	85.90	406.0
125	17.829	-376.19	-151.83	110.07	27.71	121.1	313.7
130	10.707	735.44	1109.0	119.91	33.80	515.3	179.6
135	6.4463	1570.3	2190.8	128.11	27.59	110.9	196.1
140	5.3797	1888.2	2631.7	131.32	25.51	73.25	208.6
145	4.7669	2119.9	2959.1	133.62	24.44	59.40	218.6
150	4.3403	2314.6	3236.1	135.50	23.76	52.08	227.2
160	3.7546	2648.3	3713.7	138.59	22.91	44.38	242.0
170	3.3531	2942.6	4135.5	141.15	22.40	40.35	254.7
180	3.0514	3214.9	4525.8	143.38	22.07	37.88	266.0
190	2.8123	3473.3	4895.7	145.38	21.83	36.21	276.4
200	2.6158	3722.3	5251.5	147.20	21.66	35.01	286.0
210	2.4501	3964.4	5596.9	148.89	21.52	34.12	295.0
220	2.3078	4201.3	5934.5	150.46	21.42	33.43	303.6
230	2.1836	4434.2	6266.0	151.93	21.34	32.88	311.7
240	2.0741	4663.9	6592.5	153.32	21.28	32.44	319.5
250	1.9764	4891.0	6914.9	154.64	21.23	32.07	327.0
260	1.8886	5116.1	7234.1	155.89	21.18	31.77	334.2
270	1.8091	5339.3	7550.4	157.08	21.15	31.51	341.1
280	1.7367	5561.1	7864.3	158.23	21.12	31.29	347.9
290	1.6704	5781.7	8176.3	159.32	21.10	31.10	354.5
300	1.6095	6001.2	8486.5	160.37	21.08	30.94	360.9
310	1.5532	6219.8	8795.1	161.38	21.06	30.80	367.1
320	1.5010	6437.6	9102.5	162.36	21.05	30.68	373.2
330	1.4524	6654.7	9408.7	163.30	21.04	30.57	379.2

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
340	1.4071	6871.3	9713.9	164.21	21.04	30.48	385.0
350	1.3647	7087.4	10 018	165.10	21.04	30.40	390.7
400	1.1877	8163.1	11 531	169.14	21.08	30.14	417.6
450	1.0529	9236.2	13 035	172.68	21.19	30.06	442.3
500	0.946 32	10 312	14 539	175.85	21.36	30.11	465.2
550	0.859 83	11 396	16 048	178.73	21.59	30.25	486.7
600	0.788 12	12 490	17 565	181.37	21.86	30.46	506.8
700	0.675 90	14 719	20 637	186.10	22.50	31.00	544.1
800	0.591 95	17 010	23 767	190.28	23.17	31.61	578.3
900	0.526 71	19 365	26 959	194.04	23.82	32.23	610.2
1000	0.474 50	21 782	30 212	197.46	24.42	32.81	640.2
			5.0 MPa				
64.242	31.099	-4209.1	-4048.3	68.164	33.10	55.37	1013.
65	30.993	-4167.6	-4006.3	68.814	32.95	55.38	1006.
70	30.283	-3894.3	-3729.2	72.922	32.00	55.50	959.2
75	29.553	-3620.4	-3451.2	76.758	31.11	55.71	912.7
80	28.799	-3345.4	-3171.8	80.364	30.29	56.06	866.4
85	28.018	-3068.7	-2890.3	83.777	29.54	56.58	819.6
90	27.202	-2789.4	-2605.6	87.031	28.86	57.33	772.1
95	26.346	-2506.2	-2316.4	90.158	28.25	58.39	723.5
100	25.436	-2217.6	-2021.0	93.188	27.71	59.87	673.2
105	24.458	-1921.2	-1716.7	96.157	27.25	61.97	620.9
110	23.385	-1613.6	-1399.8	99.105	26.88	65.02	565.8
115	22.179	-1289.3	-1063.9	102.09	26.62	69.68	506.9
120	20.765	-938.81	-698.02	105.20	26.53	77.38	442.9
125	18.991	-541.97	-278.69	108.63	26.76	92.20	371.5
130	16.433	-43.87	260.39	112.85	27.73	130.5	288.8
135	11.950	715.33	1133.7	119.43	29.55	211.9	214.3
140	8.3870	1388.7	1984.9	125.63	27.50	125.1	208.8
145	6.8842	1762.5	2488.8	129.17	25.74	83.49	217.5
150	6.0294	2028.8	2858.0	131.68	24.70	66.26	226.1
160	5.0134	2437.1	3434.4	135.40	23.51	51.37	241.4
170	4.3874	2771.4	3911.0	138.29	22.83	44.68	254.7
180	3.9436	3069.5	4337.3	140.73	22.39	40.89	266.5
190	3.6045	3346.1	4733.3	142.87	22.08	38.46	277.2
200	3.3329	3608.8	5109.0	144.80	21.86	36.78	287.2
210	3.1081	3861.7	5470.4	146.56	21.70	35.55	296.5
220	2.9177	4107.4	5821.1	148.20	21.57	34.62	305.2
230	2.7534	4347.6	6163.5	149.72	21.47	33.89	313.5
240	2.6097	4583.5	6499.4	151.15	21.39	33.31	321.5
250	2.4825	4816.0	6830.1	152.50	21.33	32.84	329.1
260	2.3689	5045.7	7156.4	153.78	21.27	32.44	336.4
270	2.2665	5273.1	7479.1	155.00	21.23	32.11	343.5
280	2.1737	5498.5	7798.8	156.16	21.19	31.83	350.3
290	2.0890	5722.4	8115.9	157.27	21.16	31.59	357.0
300	2.0113	5944.8	8430.7	158.34	21.14	31.38	363.4
310	1.9398	6166.1	8743.7	159.36	21.12	31.21	369.7
320	1.8737	6386.3	9054.9	160.35	21.11	31.05	375.8
330	1.8122	6605.7	9364.7	161.31	21.09	30.92	381.8

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
340	1.7550	6824.4	9673.3	162.23	21.09	30.80	387.7
350	1.7016	7042.4	9980.7	163.12	21.08	30.69	393.4
400	1.4793	8125.9	11 506	167.19	21.11	30.35	420.4
450	1.3106	9204.7	13 020	170.76	21.21	30.22	445.2
500	1.1778	10 285	14 531	173.94	21.38	30.23	468.1
550	1.0701	11 372	16 045	176.83	21.61	30.35	489.5
600	0.980 84	12 469	17 567	179.48	21.88	30.54	509.6
700	0.841 33	14 702	20 645	184.22	22.51	31.06	546.8
800	0.737 03	16 997	23 781	188.41	23.18	31.66	580.9
900	0.655 96	19 354	26 977	192.17	23.83	32.26	612.6
1000	0.591 09	21 773	30 232	195.60	24.43	32.83	642.6
			6.0 MPa				
64.459	31.127	-4206.2	-4013.4	68.207	33.13	55.24	1017.
65	31.052	-4176.7	-3983.5	68.669	33.03	55.25	1012.
70	30.350	-3904.8	-3707.1	72.766	32.07	55.34	965.5
75	29.629	-3632.5	-3430.0	76.590	31.18	55.51	919.8
80	28.886	-3359.5	-3151.7	80.181	30.36	55.81	874.3
85	28.118	-3085.1	-2871.7	83.577	29.61	56.25	828.5
90	27.319	-2808.5	-2588.9	86.809	28.93	56.90	782.2
95	26.484	-2528.8	-2302.2	89.909	28.31	57.81	735.1
100	25.602	-2244.6	-2010.2	92.904	27.77	59.07	686.7
105	24.661	-1954.0	-1710.7	95.826	27.29	60.82	636.7
110	23.643	-1654.7	-1400.9	98.709	26.90	63.27	584.8
115	22.519	-1342.7	-1076.2	101.59	26.59	66.82	530.3
120	21.245	-1012.1	-729.69	104.54	26.40	72.18	472.8
125	19.744	-652.96	-349.07	107.65	26.39	80.82	411.7
130	17.870	-246.30	89.46	111.09	26.65	96.18	346.7
135	15.351	243.85	634.69	115.20	27.30	124.3	281.8
140	12.164	827.48	1320.7	120.19	27.60	142.1	238.0
145	9.6047	1337.0	1961.7	124.69	26.60	111.0	228.2
150	8.0794	1700.5	2443.1	127.96	25.49	84.02	231.4
160	6.4290	2207.6	3140.9	132.47	24.05	59.65	244.0
170	5.5052	2591.0	3680.8	135.74	23.23	49.55	256.7
180	4.8856	2918.9	4147.0	138.41	22.69	44.16	268.4
190	4.4284	3215.9	4570.8	140.70	22.33	40.85	279.2
200	4.0709	3493.6	4967.5	142.74	22.06	38.62	289.2
210	3.7801	3758.0	5345.3	144.58	21.86	37.03	298.6
220	3.5370	4013.0	5709.3	146.27	21.71	35.84	307.5
230	3.3295	4260.8	6062.9	147.85	21.59	34.92	315.9
240	3.1493	4503.1	6408.3	149.32	21.50	34.19	323.9
250	2.9910	4741.1	6747.1	150.70	21.42	33.60	331.6
260	2.8503	4975.6	7080.6	152.01	21.36	33.11	339.0
270	2.7241	5207.1	7409.7	153.25	21.31	32.71	346.1
280	2.6102	5436.3	7735.0	154.43	21.27	32.37	353.0
290	2.5065	5663.4	8057.2	155.56	21.23	32.07	359.7
300	2.4118	5888.9	8376.6	156.65	21.20	31.82	366.2
310	2.3247	6112.8	8693.8	157.69	21.18	31.61	372.5
320	2.2444	6335.5	9008.9	158.69	21.16	31.42	378.7
330	2.1700	6557.2	9322.2	159.65	21.14	31.25	384.7

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
340	2.1008	6777.9	9634.0	160.58	21.13	31.11	390.6
350	2.0362	6997.8	9944.5	161.48	21.13	30.99	396.3
400	1.7684	8089.1	11 482	165.59	21.14	30.56	423.4
450	1.5661	9173.6	13 005	169.18	21.24	30.38	448.1
500	1.4071	10 258	14 523	172.37	21.40	30.36	471.0
550	1.2783	11 349	16 042	175.27	21.63	30.45	492.3
600	1.1718	12 448	17 569	177.93	21.90	30.62	512.4
700	1.0054	14 686	20 654	182.68	22.52	31.11	549.5
800	0.880 95	16 983	23 794	186.87	23.19	31.70	583.4
900	0.784 26	19 344	26 994	190.64	23.84	32.29	615.1
1000	0.706 88	21 764	30 252	194.07	24.44	32.86	644.9
			8.0 MPa				
64.891	31.181	-4200.2	-3943.7	68.293	33.19	55.00	1024.
65	31.167	-4194.3	-3937.6	68.386	33.16	55.00	1023.
70	30.480	-3925.1	-3662.6	72.462	32.21	55.03	977.8
75	29.776	-3655.9	-3387.2	76.262	31.32	55.14	933.5
80	29.054	-3386.4	-3111.1	79.827	30.49	55.34	889.5
85	28.310	-3116.2	-2833.6	83.190	29.74	55.66	845.6
90	27.541	-2844.7	-2554.2	86.385	29.06	56.14	801.4
95	26.743	-2571.1	-2271.9	89.437	28.44	56.81	756.8
100	25.908	-2294.5	-1985.7	92.373	27.88	57.73	711.5
105	25.030	-2013.7	-1694.1	95.218	27.39	58.97	665.4
110	24.096	-1727.3	-1395.3	97.998	26.96	60.63	618.3
115	23.092	-1433.3	-1086.8	100.74	26.60	62.87	570.1
120	21.999	-1129.0	-765.32	103.48	26.32	65.90	520.9
125	20.788	-810.83	-426.00	106.25	26.12	70.04	470.7
130	19.424	-474.19	-62.31	109.10	26.01	75.73	420.4
135	17.861	-113.47	334.43	112.09	26.01	83.29	371.4
140	16.073	274.88	772.61	115.28	26.05	91.95	327.1
145	14.128	682.44	1248.7	118.62	26.00	97.36	293.1
150	12.264	1078.4	1730.7	121.89	25.71	93.88	273.1
160	9.5312	1730.8	2570.1	127.31	24.72	73.68	263.3
170	7.9146	2216.6	3227.4	131.30	23.84	59.12	268.7
180	6.8764	2609.7	3773.1	134.42	23.21	50.76	277.5
190	6.1433	2951.1	4253.3	137.02	22.75	45.67	287.0
200	5.5896	3260.9	4692.1	139.27	22.42	42.31	296.3
210	5.1514	3549.9	5102.9	141.28	22.17	39.96	305.3
220	4.7926	3824.3	5493.5	143.09	21.98	38.24	314.0
230	4.4914	4087.9	5869.1	144.76	21.82	36.94	322.3
240	4.2334	4343.4	6233.1	146.31	21.70	35.91	330.2
250	4.0092	4592.6	6588.0	147.76	21.61	35.09	337.9
260	3.8117	4836.7	6935.5	149.12	21.52	34.43	345.2
270	3.6361	5076.7	7276.9	150.41	21.46	33.87	352.3
280	3.4784	5313.4	7613.2	151.64	21.40	33.41	359.2
290	3.3359	5547.1	7945.3	152.80	21.36	33.01	365.9
300	3.2062	5778.5	8273.6	153.91	21.32	32.67	372.4
310	3.0876	6007.9	8598.9	154.98	21.29	32.38	378.7
320	2.9785	6235.5	8921.4	156.01	21.26	32.13	384.9
330	2.8777	6461.6	9241.6	156.99	21.24	31.91	390.9

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
340	2.7843	6686.4	9559.7	157.94	21.22	31.72	396.8
350	2.6974	6910.1	9876.0	158.86	21.21	31.55	402.5
400	2.3389	8016.7	11 437	163.03	21.21	30.96	429.5
450	2.0698	9112.3	12 977	166.66	21.29	30.68	454.2
500	1.8591	10 206	14 509	169.88	21.45	30.59	476.9
550	1.6891	11 303	16 039	172.80	21.67	30.64	498.2
600	1.5485	12 408	17 574	175.47	21.93	30.78	518.1
700	1.3292	14 654	20 673	180.25	22.55	31.22	554.9
800	1.1654	16 958	23 822	184.45	23.21	31.78	588.6
900	1.0380	19 322	27 029	188.23	23.86	32.36	620.0
1000	0.936 09	21 746	30 293	191.67	24.45	32.91	649.6
			10 MPa				
65.321	31.235	-4194.1	-3874.0	68.379	33.24	54.77	1031.
70	30.605	-3944.5	-3617.7	72.168	32.34	54.75	989.6
75	29.917	-3678.1	-3343.9	75.946	31.45	54.80	946.6
80	29.214	-3411.9	-3069.6	79.486	30.63	54.92	904.1
85	28.492	-3145.5	-2794.5	82.822	29.87	55.14	861.8
90	27.749	-2878.4	-2518.0	85.983	29.19	55.48	819.4
95	26.983	-2610.1	-2239.4	88.995	28.57	55.98	777.0
100	26.188	-2339.8	-1958.0	91.882	28.00	56.65	734.2
105	25.359	-2067.0	-1672.6	94.667	27.50	57.54	691.1
110	24.489	-1790.5	-1382.1	97.369	27.06	58.70	647.6
115	23.571	-1509.3	-1085.0	100.01	26.67	60.21	603.7
120	22.593	-1222.0	-779.38	102.61	26.34	62.13	559.6
125	21.543	-927.09	-462.90	105.20	26.06	64.55	515.7
130	20.408	-622.88	-132.88	107.78	25.85	67.55	472.3
135	19.176	-307.91	213.58	110.40	25.69	71.11	430.6
140	17.841	18.26	578.75	113.05	25.57	74.96	392.0
145	16.420	353.45	962.46	115.75	25.45	78.35	358.2
150	14.963	690.91	1359.2	118.44	25.30	79.94	331.2
160	12.286	1327.4	2141.3	123.49	24.79	74.74	300.8
170	10.280	1864.2	2837.0	127.71	24.14	64.36	292.7
180	8.8794	2309.0	3435.2	131.13	23.55	55.76	294.7
190	7.8747	2691.1	3961.0	133.97	23.08	49.76	300.5
200	7.1194	3032.0	4436.6	136.41	22.71	45.61	307.7
210	6.5276	3345.1	4877.1	138.56	22.43	42.65	315.4
220	6.0481	3638.8	5292.2	140.49	22.20	40.47	323.2
230	5.6494	3918.2	5688.3	142.25	22.03	38.82	330.9
240	5.3109	4186.8	6069.7	143.88	21.89	37.53	338.4
250	5.0187	4447.1	6439.7	145.39	21.77	36.50	345.8
260	4.7631	4700.8	6800.3	146.80	21.67	35.66	352.9
270	4.5370	4949.2	7153.3	148.14	21.60	34.96	359.8
280	4.3350	5193.1	7499.9	149.40	21.53	34.38	366.6
290	4.1532	5433.5	7841.3	150.59	21.47	33.89	373.1
300	3.9883	5670.7	8178.1	151.74	21.43	33.47	379.5
310	3.8379	5905.3	8510.9	152.83	21.39	33.11	385.8
320	3.7000	6137.8	8840.5	153.87	21.35	32.80	391.8
330	3.5729	6368.2	9167.1	154.88	21.33	32.53	397.8
340	3.4554	6597.1	9491.1	155.85	21.31	32.29	403.6

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
350	3.3463	6824.5	9812.9	156.78	21.29	32.08	409.3
400	2.8981	7946.0	11 397	161.01	21.27	31.35	436.0
450	2.5635	9052.4	12 953	164.68	21.34	30.97	460.5
500	2.3024	10 154	14 497	167.93	21.49	30.82	483.1
550	2.0920	11 258	16 038	170.87	21.70	30.82	504.1
600	1.9183	12 368	17 581	173.55	21.96	30.93	523.9
700	1.6475	14 623	20 692	178.35	22.58	31.33	560.4
800	1.4452	16 932	23 851	182.57	23.23	31.86	593.8
900	1.2881	19 301	27 065	186.35	23.88	32.42	625.0
1000	1.1622	21 729	30 334	189.79	24.47	32.95	654.4
			15 MPa				
66.386	31.367	-4178.3	-3700.1	68.594	33.36	54.23	1047.
70	30.902	-3989.7	-3504.2	71.466	32.67	54.15	1018.
75	30.249	-3729.6	-3233.7	75.199	31.77	54.07	977.3
80	29.586	-3470.4	-2963.4	78.688	30.94	54.04	937.8
85	28.911	-3212.0	-2693.2	81.965	30.19	54.08	898.8
90	28.222	-2954.0	-2422.5	85.059	29.50	54.19	860.3
95	27.519	-2696.2	-2151.1	87.993	28.87	54.38	822.0
100	26.799	-2438.3	-1878.6	90.789	28.31	54.66	784.0
105	26.061	-2179.9	-1604.4	93.465	27.79	55.04	746.2
110	25.302	-1920.8	-1328.0	96.037	27.32	55.54	708.8
115	24.520	-1660.5	-1048.8	98.519	26.90	56.15	671.8
120	23.712	-1398.8	-766.21	100.92	26.53	56.90	635.3
125	22.876	-1135.3	-479.63	103.26	26.19	57.76	599.6
130	22.011	-869.94	-188.46	105.55	25.89	58.73	565.1
135	21.115	-602.64	107.75	107.78	25.63	59.76	532.0
140	20.191	-333.72	409.18	109.98	25.39	60.80	500.9
145	19.243	-63.88	715.62	112.13	25.18	61.75	472.2
150	18.280	205.69	1026.3	114.23	24.98	62.46	446.3
160	16.361	736.75	1653.6	118.28	24.61	62.68	404.7
170	14.563	1242.8	2272.9	122.04	24.23	60.85	376.9
180	12.990	1710.6	2865.3	125.42	23.85	57.47	361.2
190	11.680	2136.3	3420.6	128.43	23.49	53.58	354.1
200	10.608	2523.8	3937.8	131.08	23.16	49.96	352.4
210	9.7303	2880.0	4421.6	133.44	22.87	46.89	353.8
220	9.0039	3211.5	4877.4	135.56	22.63	44.37	357.2
230	8.3943	3523.6	5310.6	137.49	22.43	42.33	361.6
240	7.8754	3820.6	5725.3	139.25	22.26	40.67	366.7
250	7.4278	4105.5	6124.9	140.88	22.12	39.31	372.1
260	7.0373	4380.7	6512.3	142.40	22.00	38.19	377.8
270	6.6928	4648.1	6889.3	143.83	21.89	37.25	383.5
280	6.3863	4908.9	7257.7	145.17	21.81	36.45	389.3
290	6.1113	5164.3	7618.7	146.43	21.73	35.78	395.0
300	5.8629	5415.1	7973.5	147.64	21.67	35.20	400.7
310	5.6370	5662.0	8322.9	148.78	21.62	34.70	406.4
320	5.4306	5905.5	8667.7	149.88	21.57	34.26	412.0
330	5.2410	6146.3	9008.3	150.92	21.53	33.88	417.5
340	5.0660	6384.5	9345.4	151.93	21.50	33.54	422.9

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
350	4.9040	6620.6	9679.3	152.90	21.48	33.25	428.2
400	4.2423	7777.1	11 313	157.26	21.42	32.20	453.7
450	3.7519	8909.1	12 907	161.02	21.47	31.63	477.2
500	3.3709	10 030	14 480	164.33	21.60	31.34	499.0
550	3.0647	11 150	16 044	167.32	21.80	31.24	519.4
600	2.8124	12 273	17 606	170.03	22.05	31.27	538.7
700	2.4192	14 547	20 747	174.88	22.64	31.58	574.3
800	2.1256	16 871	23 928	179.12	23.29	32.04	606.9
900	1.8972	19 251	27 158	182.93	23.92	32.56	637.4
1000	1.7140	21 688	30 439	186.38	24.51	33.07	666.2
			20 MPa				
67.437	31.494	-4161.8	-3526.7	68.807	33.46	53.74	1064.
70	31.178	-4030.6	-3389.1	70.810	32.97	53.64	1044.
75	30.555	-3775.9	-3121.3	74.505	32.07	53.48	1006.
80	29.925	-3522.6	-2854.3	77.953	31.25	53.35	968.6
85	29.287	-3270.6	-2587.7	81.184	30.49	53.26	932.2
90	28.641	-3019.8	-2321.5	84.227	29.80	53.22	896.5
95	27.985	-2770.1	-2055.4	87.105	29.17	53.23	861.3
100	27.321	-2521.2	-1789.1	89.837	28.60	53.29	826.7
105	26.646	-2273.0	-1522.4	92.440	28.08	53.41	792.5
110	25.960	-2025.3	-1254.9	94.928	27.60	53.58	759.0
115	25.262	-1778.2	-986.44	97.315	27.17	53.81	726.2
120	24.551	-1531.3	-716.69	99.611	26.78	54.09	694.1
125	23.829	-1284.8	-445.43	101.83	26.42	54.42	663.0
130	23.093	-1038.5	-172.46	103.97	26.10	54.77	633.0
135	22.346	-792.69	102.33	106.04	25.80	55.14	604.3
140	21.588	-547.50	378.93	108.05	25.54	55.50	577.1
145	20.823	-303.28	657.21	110.01	25.29	55.80	551.7
150	20.053	-60.53	936.84	111.90	25.07	56.03	528.1
160	18.520	417.97	1497.9	115.52	24.66	56.07	487.5
170	17.037	881.99	2055.9	118.91	24.30	55.41	456.0
180	15.651	1325.7	2603.6	122.04	23.97	54.02	433.1
190	14.396	1745.3	3134.6	124.91	23.67	52.11	417.7
200	13.287	2139.8	3645.0	127.53	23.38	49.94	408.2
210	12.321	2510.2	4133.4	129.91	23.13	47.76	403.0
220	11.484	2859.2	4600.7	132.08	22.90	45.73	401.0
230	10.758	3189.6	5048.8	134.08	22.70	43.92	401.2
240	10.125	3504.5	5479.8	135.91	22.53	42.33	402.8
250	9.5702	3806.4	5896.2	137.61	22.38	40.97	405.5
260	9.0806	4097.3	6299.8	139.19	22.25	39.79	408.9
270	8.6453	4379.1	6692.5	140.68	22.14	38.77	412.7
280	8.2557	4653.2	7075.7	142.07	22.04	37.90	416.9
290	7.9049	4920.7	7450.8	143.39	21.96	37.14	421.4
300	7.5870	5182.7	7818.8	144.63	21.88	36.48	426.0
310	7.2974	5439.9	8180.6	145.82	21.82	35.90	430.6
320	7.0324	5693.0	8537.0	146.95	21.76	35.39	435.4
330	6.7887	5942.5	8888.5	148.03	21.72	34.94	440.1
340	6.5637	6188.8	9235.9	149.07	21.68	34.54	444.9
350	6.3552	6432.4	9579.5	150.07	21.64	34.19	449.7

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
400	5.5036	7619.9	11 254	154.54	21.56	32.91	472.9
450	4.8725	8774.9	12 880	158.37	21.58	32.18	495.0
500	4.3823	9914.0	14 478	161.74	21.70	31.79	515.8
550	3.9884	11 048	16 062	164.76	21.88	31.61	535.4
600	3.6638	12 183	17 641	167.51	22.12	31.58	553.9
700	3.1577	14 475	20 809	172.39	22.71	31.80	588.4
800	2.7792	16 812	24 009	176.66	23.34	32.22	620.1
900	2.4843	19 203	27 254	180.48	23.97	32.69	649.9
1000	2.2475	21 648	30 547	183.95	24.55	33.17	678.0
			25 MPa				
68.476	31.617	-4144.6	-3353.9	69.019	33.55	53.29	1079.
70	31.436	-4068.0	-3272.7	70.192	33.26	53.22	1068.
75	30.839	-3817.8	-3007.2	73.855	32.36	52.99	1032.
80	30.238	-3569.5	-2742.8	77.269	31.53	52.79	996.9
85	29.631	-3323.0	-2479.3	80.464	30.77	52.62	962.7
90	29.019	-3078.1	-2216.5	83.467	30.08	52.47	929.3
95	28.401	-2834.7	-1954.5	86.301	29.45	52.37	896.6
100	27.779	-2592.8	-1692.8	88.985	28.88	52.29	864.5
105	27.151	-2352.3	-1431.5	91.535	28.35	52.25	833.0
110	26.518	-2113.0	-1170.3	93.966	27.87	52.24	802.3
115	25.879	-1875.0	-909.00	96.288	27.44	52.27	772.4
120	25.234	-1638.3	-647.55	98.514	27.04	52.32	743.3
125	24.584	-1402.7	-385.81	100.65	26.67	52.39	715.2
130	23.929	-1168.5	-123.68	102.71	26.33	52.47	688.1
135	23.269	-935.51	138.87	104.69	26.03	52.55	662.2
140	22.607	-704.05	401.83	106.60	25.75	52.63	637.6
145	21.942	-474.24	665.10	108.45	25.49	52.68	614.3
150	21.279	-246.36	928.52	110.24	25.25	52.68	592.6
160	19.963	202.43	1454.8	113.63	24.82	52.52	554.0
170	18.681	639.55	1977.8	116.80	24.45	52.03	522.2
180	17.459	1062.2	2494.1	119.75	24.12	51.17	497.0
190	16.317	1468.1	3000.2	122.49	23.83	50.01	477.9
200	15.267	1856.2	3493.7	125.02	23.56	48.64	463.9
210	14.316	2226.5	3972.8	127.36	23.32	47.17	454.2
220	13.461	2579.8	4436.9	129.52	23.11	45.68	448.0
230	12.697	2917.4	4886.5	131.52	22.92	44.24	444.4
240	12.013	3241.2	5322.2	133.37	22.74	42.91	442.7
250	11.402	3552.6	5745.1	135.10	22.59	41.70	442.5
260	10.854	3853.3	6156.6	136.71	22.46	40.61	443.5
270	10.360	4144.8	6557.8	138.23	22.34	39.64	445.3
280	9.9143	4428.2	6949.8	139.65	22.24	38.78	447.7
290	9.5091	4704.7	7333.8	141.00	22.15	38.02	450.6
300	9.1397	4975.2	7710.5	142.28	22.07	37.34	453.8
310	8.8015	5240.4	8080.8	143.49	22.00	36.74	457.4
320	8.4905	5501.0	8445.5	144.65	21.94	36.20	461.1
330	8.2037	5757.6	8805.0	145.76	21.88	35.72	464.9
340	7.9381	6010.6	9160.0	146.82	21.84	35.29	468.9
350	7.6913	6260.6	9511.0	147.83	21.80	34.91	472.9
400	6.6787	7474.6	11 218	152.39	21.69	33.49	493.4

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
450	5.9246	8649.9	12 870	156.29	21.70	32.65	513.7
500	5.3371	9805.1	14 489	159.70	21.80	32.18	533.1
550	4.8642	10 952	16 091	162.75	21.97	31.94	551.7
600	4.4739	12 098	17 686	165.53	22.20	31.86	569.4
700	3.8641	14 407	20 876	170.45	22.77	32.01	602.6
800	3.4072	16 757	24 094	174.74	23.40	32.37	633.4
900	3.0504	19 158	27 353	178.58	24.02	32.82	662.4
1000	2.7633	21 611	30 658	182.06	24.59	33.27	689.9
			50 MPa				
73.495	32.183	-4051.3	-2497.7	70.042	33.86	51.51	1151.
75	32.031	-3981.3	-2420.3	71.085	33.59	51.40	1142.
80	31.526	-3750.2	-2164.2	74.390	32.75	51.03	1114.
85	31.023	-3521.7	-1910.0	77.473	31.99	50.67	1087.
90	30.521	-3295.7	-1657.5	80.359	31.30	50.33	1061.
95	30.021	-3072.2	-1406.7	83.071	30.66	49.99	1036.
100	29.524	-2851.1	-1157.6	85.627	30.09	49.67	1011.
105	29.029	-2632.4	-910.01	88.043	29.56	49.35	987.0
110	28.538	-2416.1	-664.02	90.332	29.07	49.05	963.9
115	28.050	-2202.1	-419.54	92.505	28.62	48.75	941.4
120	27.566	-1990.4	-176.52	94.574	28.21	48.46	919.8
125	27.086	-1780.9	65.08	96.546	27.83	48.18	898.9
130	26.610	-1573.7	305.28	98.431	27.48	47.90	878.8
135	26.139	-1368.7	544.13	100.23	27.15	47.63	859.6
140	25.673	-1166.0	781.64	101.96	26.85	47.37	841.1
145	25.212	-965.39	1017.8	103.62	26.56	47.11	823.4
150	24.756	-767.01	1252.7	105.21	26.30	46.85	806.6
160	23.862	-376.80	1718.6	108.22	25.83	46.32	775.4
170	22.994	4.72	2179.2	111.01	25.42	45.80	747.5
180	22.155	377.57	2634.4	113.61	25.05	45.25	722.7
190	21.346	741.79	3084.2	116.04	24.73	44.69	701.0
200	20.570	1097.5	3528.2	118.32	24.45	44.11	682.1
210	19.829	1444.8	3966.4	120.46	24.20	43.52	665.9
220	19.123	1783.9	4398.5	122.47	23.97	42.92	652.1
230	18.453	2115.0	4824.7	124.37	23.77	42.31	640.4
240	17.818	2438.7	5244.7	126.15	23.59	41.71	630.7
250	17.219	2755.1	5658.8	127.84	23.42	41.11	622.6
260	16.653	3064.7	6067.1	129.44	23.27	40.54	616.0
270	16.120	3367.9	6469.6	130.96	23.14	39.98	610.7
280	15.617	3665.2	6866.8	132.41	23.02	39.45	606.5
290	15.144	3957.0	7258.7	133.78	22.91	38.94	603.2
300	14.697	4243.7	7645.6	135.10	22.81	38.46	600.8
310	14.276	4525.6	8027.9	136.35	22.72	38.00	599.1
320	13.879	4803.2	8405.7	137.55	22.64	37.57	598.0
330	13.504	5076.8	8779.4	138.70	22.57	37.17	597.4
340	13.149	5346.7	9149.1	139.80	22.50	36.79	597.2
350	12.814	5613.2	9515.2	140.86	22.44	36.44	597.5
400	11.378	6904.7	11 299	145.63	22.25	35.01	603.0
450	10.251	8146.4	13 024	149.69	22.19	34.04	612.6
500	9.3434	9357.8	14 709	153.25	22.23	33.41	624.2
550	8.5954	10 552	16 369	156.41	22.36	33.03	636.6

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
600	7.9671	11 739	18 015	159.28	22.56	32.83	649.4
700	6.9671	14 115	21 292	164.33	23.07	32.77	675.1
800	6.2032	16 517	24 578	168.71	23.65	32.98	700.3
900	5.5979	18 960	27 892	172.62	24.24	33.31	724.9
1000	5.1051	21 447	31 241	176.14	24.79	33.68	748.9
			75 MPa				
78.256	32.688	-3949.9	-1655.5	70.985	34.02	50.23	1215.
80	32.533	-3873.4	-1568.0	72.090	33.74	50.09	1207.
85	32.090	-3655.7	-1318.6	75.115	32.97	49.69	1184.
90	31.651	-3440.7	-1071.1	77.944	32.28	49.30	1162.
95	31.215	-3228.2	-825.54	80.600	31.64	48.92	1140.
100	30.784	-3018.2	-581.88	83.099	31.06	48.54	1119.
105	30.357	-2810.7	-340.09	85.459	30.53	48.18	1099.
110	29.935	-2605.6	-100.12	87.692	30.04	47.81	1080.
115	29.517	-2402.8	138.06	89.809	29.59	47.46	1061.
120	29.105	-2202.4	374.49	91.822	29.18	47.11	1043.
125	28.698	-2004.2	609.20	93.738	28.79	46.77	1025.
130	28.297	-1808.3	842.23	95.566	28.43	46.44	1008.
135	27.901	-1614.5	1073.6	97.313	28.10	46.12	992.1
140	27.510	-1422.9	1303.4	98.984	27.79	45.80	976.4
145	27.125	-1233.3	1531.6	100.59	27.50	45.49	961.3
150	26.746	-1045.8	1758.3	102.12	27.22	45.19	946.8
160	26.005	-676.82	2207.2	105.02	26.73	44.60	919.6
170	25.288	-315.49	2650.4	107.71	26.30	44.04	894.8
180	24.594	38.49	3088.1	110.21	25.91	43.50	872.2
190	23.923	385.41	3520.5	112.55	25.57	42.98	851.7
200	23.276	725.57	3947.8	114.74	25.26	42.48	833.2
210	22.653	1059.3	4370.1	116.80	24.99	41.99	816.6
220	22.053	1386.8	4787.7	118.74	24.74	41.52	801.8
230	21.477	1708.4	5200.6	120.58	24.52	41.06	788.5
240	20.923	2024.4	5608.9	122.32	24.31	40.62	776.8
250	20.392	2335.1	6012.9	123.96	24.13	40.18	766.4
260	19.883	2640.7	6412.7	125.53	23.96	39.77	757.3
270	19.396	2941.5	6808.3	127.03	23.81	39.36	749.3
280	18.929	3237.7	7199.9	128.45	23.67	38.97	742.3
290	18.482	3529.7	7587.7	129.81	23.54	38.60	736.3
300	18.054	3817.6	7971.9	131.11	23.43	38.24	731.0
310	17.644	4101.7	8352.5	132.36	23.32	37.89	726.5
320	17.251	4382.3	8729.8	133.56	23.23	37.56	722.7
330	16.876	4659.6	9103.9	134.71	23.14	37.25	719.5
340	16.516	4933.7	9474.8	135.82	23.06	36.95	716.8
350	16.171	5205.0	9842.9	136.88	22.99	36.67	714.5
400	14.646	6524.0	11 645	141.70	22.73	35.47	709.0
450	13.394	7796.0	13 395	145.82	22.62	34.60	709.7
500	12.352	9037.0	15 109	149.44	22.62	33.99	714.1
550	11.470	10 259	16 798	152.66	22.71	33.60	720.7
600	10.715	11 472	18 471	155.57	22.87	33.37	728.6
700	9.4855	13 892	21 799	160.70	23.34	33.24	746.7
800	8.5250	16 331	25 129	165.14	23.89	33.39	766.2

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
900	7.7514	18 804	28 480	169.09	24.45	33.66	786.3
1000	7.1131	21 318	31 861	172.65	24.98	33.97	806.6
			100 MPa				
82.799	33.147	-3843.5	-826.60	71.848	34.12	49.26	1273.
85	32.971	-3751.3	-718.38	73.138	33.79	49.09	1264.
90	32.574	-3543.8	-473.92	75.933	33.10	48.70	1245.
95	32.182	-3338.8	-231.39	78.555	32.46	48.31	1226.
100	31.793	-3136.1	9.22	81.024	31.89	47.93	1208.
105	31.409	-2935.8	247.96	83.353	31.35	47.56	1190.
110	31.030	-2737.8	484.83	85.557	30.86	47.19	1173.
115	30.656	-2542.1	719.88	87.647	30.41	46.83	1157.
120	30.288	-2348.5	953.14	89.632	29.99	46.47	1141.
125	29.924	-2157.1	1184.6	91.522	29.60	46.12	1125.
130	29.567	-1967.8	1414.4	93.325	29.24	45.78	1110.
135	29.214	-1780.5	1642.4	95.046	28.90	45.44	1096.
140	28.867	-1595.3	1868.8	96.693	28.59	45.12	1082.
145	28.526	-1411.9	2093.6	98.271	28.29	44.80	1068.
150	28.190	-1230.5	2316.8	99.784	28.01	44.49	1055.
160	27.534	-873.16	2758.7	102.64	27.51	43.89	1031.
170	26.900	-522.81	3194.7	105.28	27.06	43.32	1008.
180	26.286	-179.10	3625.1	107.74	26.66	42.78	987.2
190	25.693	158.32	4050.4	110.04	26.30	42.27	968.0
200	25.120	489.79	4470.6	112.19	25.97	41.78	950.3
210	24.567	815.63	4886.2	114.22	25.68	41.32	934.2
220	24.032	1136.1	5297.2	116.13	25.42	40.89	919.5
230	23.516	1451.6	5703.9	117.94	25.18	40.47	906.0
240	23.018	1762.2	6106.6	119.66	24.96	40.07	893.8
250	22.538	2068.4	6505.3	121.28	24.76	39.69	882.7
260	22.074	2370.2	6900.3	122.83	24.57	39.32	872.7
270	21.627	2668.0	7291.8	124.31	24.41	38.97	863.6
280	21.196	2961.9	7679.8	125.72	24.25	38.64	855.5
290	20.780	3252.3	8064.5	127.07	24.11	38.32	848.1
300	20.379	3539.1	8446.2	128.37	23.98	38.01	841.5
310	19.992	3822.8	8824.8	129.61	23.86	37.72	835.6
320	19.619	4103.4	9200.5	130.80	23.75	37.44	830.3
330	19.259	4381.1	9573.5	131.95	23.65	37.17	825.6
340	18.911	4656.1	9943.9	133.05	23.56	36.91	821.4
350	18.576	4928.6	10 312	134.12	23.48	36.67	817.7
400	17.064	6258.0	12 118	138.95	23.16	35.63	805.0
450	15.786	7544.5	13 879	143.10	23.01	34.85	799.4
500	14.694	8801.7	15 607	146.74	22.97	34.30	798.3
550	13.753	10 041	17 312	149.99	23.03	33.92	800.1
600	12.932	11 269	19 002	152.93	23.17	33.70	804.0
700	11.571	13 720	22 362	158.11	23.59	33.56	815.3
800	10.486	16 186	25 722	162.59	24.11	33.67	829.6
900	9.5984	18 682	29 101	166.57	24.64	33.91	845.6
1000	8.8572	21 216	32 506	170.16	25.15	34.20	862.5
			200 MPa				
99.295	34.689	-3392.8	2372.8	74.639	34.29	46.99	1465.
100	34.647	-3366.6	2405.9	74.971	34.21	46.95	1463.

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
105	34.353	-3182.0	2639.9	77.255	33.70	46.65	1451.
110	34.063	-2999.1	2872.4	79.418	33.23	46.35	1439.
115	33.776	-2817.9	3103.4	81.472	32.79	46.05	1428.
120	33.494	-2638.3	3332.9	83.425	32.38	45.75	1417.
125	33.216	-2460.4	3560.9	85.287	31.99	45.45	1406.
130	32.942	-2283.9	3787.4	87.063	31.63	45.14	1395.
135	32.672	-2109.1	4012.3	88.761	31.29	44.84	1384.
140	32.407	-1935.7	4235.8	90.387	30.97	44.55	1374.
145	32.146	-1763.8	4457.8	91.945	30.66	44.25	1364.
150	31.889	-1593.4	4678.3	93.440	30.38	43.96	1355.
160	31.388	-1256.7	5115.1	96.259	29.85	43.39	1336.
170	30.904	-925.39	5546.3	98.873	29.37	42.85	1318.
180	30.435	-599.17	5972.2	101.31	28.93	42.33	1302.
190	29.981	-277.77	6393.0	103.58	28.53	41.84	1286.
200	29.542	39.07	6809.1	105.72	28.17	41.37	1271.
210	29.117	351.60	7220.5	107.72	27.84	40.93	1257.
220	28.704	660.07	7627.7	109.62	27.53	40.51	1244.
230	28.304	964.69	8030.8	111.41	27.25	40.11	1232.
240	27.916	1265.7	8430.0	113.11	26.99	39.74	1220.
250	27.540	1563.3	8825.6	114.73	26.75	39.38	1209.
260	27.174	1857.7	9217.7	116.26	26.52	39.05	1199.
270	26.818	2149.0	9606.6	117.73	26.31	38.73	1189.
280	26.472	2437.4	9992.5	119.13	26.12	38.44	1180.
290	26.136	2723.1	10 375	120.48	25.94	38.15	1172.
300	25.809	3006.3	10 756	121.77	25.77	37.89	1164.
310	25.490	3287.0	11 133	123.01	25.61	37.63	1156.
320	25.180	3565.4	11 508	124.20	25.46	37.40	1149.
330	24.877	3841.7	11 881	125.34	25.33	37.17	1143.
340	24.583	4116.0	12 252	126.45	25.20	36.96	1137.
350	24.295	4388.3	12 620	127.52	25.08	36.75	1131.
400	22.960	5724.7	14 436	132.37	24.62	35.90	1106.
450	21.772	7028.0	16 214	136.56	24.33	35.27	1089.
500	20.709	8308.3	17 966	140.25	24.18	34.83	1076.
550	19.753	9573.7	19 699	143.55	24.14	34.53	1067.
600	18.887	10 831	21 420	146.55	24.20	34.35	1060.
700	17.381	13 341	24 848	151.83	24.48	34.24	1054.
800	16.114	15 864	28 275	156.41	24.89	34.34	1054.
900	15.033	18 415	31 719	160.46	25.34	34.54	1057.
1000	14.098	20 998	35 185	164.12	25.78	34.78	1064.
			400 MPa				
127.083	37.002	-2452.2	8358.1	78.313	34.58	45.38	1750.
130	36.879	-2355.9	8490.4	79.342	34.40	45.29	1746.
135	36.671	-2191.5	8716.4	81.048	34.10	45.11	1739.
140	36.465	-2027.8	8941.5	82.685	33.82	44.92	1733.
145	36.263	-1865.0	9165.6	84.258	33.54	44.73	1726.
150	36.063	-1703.0	9388.7	85.771	33.28	44.52	1720.
160	35.672	-1381.5	9831.8	88.631	32.77	44.09	1707.
170	35.292	-1063.4	10 271	91.291	32.30	43.65	1694.
180	34.924	-748.63	10 705	93.774	31.86	43.21	1682.
190	34.566	-437.14	11 135	96.098	31.45	42.78	1670.

Thermodynamic properties of nitrogen—Continued

T K	*ρ* mol/dm^3	*u* J/mol	*h* J/mol	*s* J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	*w* m/s
200	34.219	-128.86	11 560	98.281	31.06	42.35	1659.
210	33.882	176.29	11 982	100.34	30.70	41.93	1648.
220	33.555	478.41	12 399	102.28	30.36	41.52	1637.
230	33.237	777.63	12 812	104.12	30.05	41.13	1627.
240	32.928	1074.0	13 222	105.86	29.75	40.76	1617.
250	32.627	1367.8	13 627	107.51	29.47	40.40	1608.
260	32.334	1658.9	14 030	109.09	29.20	40.05	1599.
270	32.049	1947.7	14 429	110.60	28.95	39.72	1590.
280	31.771	2234.0	14 824	112.04	28.72	39.41	1582.
290	31.499	2518.2	15 217	113.41	28.49	39.11	1574.
300	31.234	2800.2	15 607	114.74	28.29	38.83	1566.
310	30.976	3080.2	15 994	116.00	28.09	38.56	1559.
320	30.723	3358.3	16 378	117.22	27.90	38.30	1552.
330	30.476	3634.6	16 760	118.40	27.73	38.06	1545.
340	30.234	3909.1	17 139	119.53	27.56	37.83	1539.
350	29.998	4182.0	17 516	120.63	27.41	37.61	1532.
400	28.886	5525.2	19 373	125.58	26.77	36.69	1504.
450	27.876	6840.0	21 189	129.86	26.32	36.01	1481.
500	26.951	8135.2	22 977	133.63	26.03	35.53	1461.
550	26.097	9418.1	24 745	137.00	25.87	35.22	1444.
600	25.306	10 694	26 501	140.06	25.82	35.03	1430.
700	23.880	13 245	29 996	145.45	25.91	34.91	1408.
800	22.627	15 812	33 490	150.11	26.17	35.00	1393.
900	21.513	18 406	36 999	154.25	26.50	35.19	1384.
1000	20.516	21 032	40 530	157.96	26.84	35.42	1379.
			600 MPa				
150.718	38.782	-1503.3	13 968	80.733	35.00	45.04	1970.
160	38.466	-1213.3	14 385	83.418	34.61	44.80	1961.
170	38.134	-902.68	14 831	86.124	34.20	44.49	1952.
180	37.811	-593.93	15 275	88.658	33.80	44.15	1942.
190	37.496	-287.27	15 714	91.035	33.41	43.79	1933.
200	37.191	17.21	16 150	93.272	33.04	43.42	1924.
210	36.893	319.45	16 583	95.381	32.69	43.04	1915.
220	36.604	619.44	17 011	97.375	32.35	42.67	1906.
230	36.322	917.18	17 436	99.263	32.02	42.29	1897.
240	36.048	1212.7	17 857	101.06	31.71	41.93	1889.
250	35.781	1506.0	18 275	102.76	31.42	41.57	1881.
260	35.521	1797.2	18 689	104.38	31.14	41.23	1873.
270	35.267	2086.3	19 099	105.93	30.87	40.89	1865.
280	35.020	2373.4	19 507	107.42	30.62	40.57	1858.
290	34.778	2658.6	19 911	108.83	30.37	40.26	1851.
300	34.542	2941.8	20 312	110.19	30.14	39.96	1844.
310	34.312	3223.3	20 710	111.50	29.92	39.68	1837.
320	34.086	3503.1	21 105	112.75	29.72	39.40	1830.
330	33.866	3781.2	21 498	113.96	29.52	39.14	1824.
340	33.650	4057.7	21 888	115.13	29.33	38.89	1818.
350	33.439	4332.7	22 276	116.25	29.15	38.65	1812.
400	32.442	5687.7	24 182	121.34	28.41	37.63	1784.
450	31.534	7015.7	26 043	125.73	27.86	36.85	1759.
500	30.697	8324.8	27 871	129.58	27.48	36.29	1738.
550	29.920	9621.8	29 675	133.02	27.24	35.90	1719.

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	*u* J/mol	*h* J/mol	*s* J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	*w* m/s
600	29.196	10 912	31 463	136.13	27.11	35.65	1702.
700	27.876	13 491	35 015	141.61	27.08	35.44	1673.
800	26.697	16 084	38 558	146.34	27.23	35.47	1651.
900	25.631	18 703	42 112	150.52	27.46	35.62	1635.
1000	24.661	21 353	45 683	154.29	27.73	35.81	1622.
				800 MPa			
171.727	40.257	-558.35	19 314	82.519	35.48	45.12	2153.
180	40.012	-307.17	19 687	84.637	35.21	44.93	2147.
190	39.724	-4.44	20 135	87.059	34.87	44.66	2140.
200	39.443	297.09	20 580	89.342	34.54	44.35	2132.
210	39.169	597.22	21 022	91.498	34.21	44.03	2125.
220	38.902	895.81	21 460	93.539	33.88	43.70	2117.
230	38.642	1192.8	21 896	95.474	33.57	43.35	2110.
240	38.389	1488.0	22 327	97.312	33.26	43.01	2103.
250	38.142	1781.5	22 756	99.061	32.97	42.67	2096.
260	37.901	2073.3	23 181	100.73	32.68	42.33	2089.
270	37.667	2363.4	23 602	102.32	32.41	42.00	2082.
280	37.438	2651.7	24 021	103.84	32.14	41.67	2075.
290	37.214	2938.3	24 436	105.30	31.89	41.36	2068.
300	36.995	3223.3	24 848	106.69	31.65	41.05	2062.
310	36.781	3506.7	25 257	108.03	31.42	40.75	2056.
320	36.572	3788.5	25 663	109.32	31.19	40.47	2050.
330	36.368	4068.8	26 066	110.57	30.98	40.19	2044.
340	36.168	4347.6	26 467	111.76	30.78	39.93	2038.
350	35.972	4625.0	26 865	112.91	30.59	39.67	2032.
400	35.047	5993.3	28 820	118.14	29.76	38.57	2005.
450	34.203	7335.7	30 726	122.63	29.14	37.71	1981.
500	33.424	8659.4	32 594	126.57	28.70	37.06	1959.
550	32.701	9970.8	34 435	130.07	28.39	36.60	1939.
600	32.025	11 276	36 256	133.24	28.20	36.28	1921.
700	30.789	13 881	39 864	138.81	28.07	35.95	1889.
800	29.677	16 499	43 455	143.60	28.14	35.90	1863.
900	28.666	19 141	47 049	147.83	28.31	35.99	1842.
1000	27.736	21 811	50 654	151.63	28.51	36.14	1825.
				1000 MPa			
190.876	41.528	379.35	24 459	83.929	35.98	45.37	2313.
200	41.287	651.82	24 872	86.043	35.72	45.16	2307.
210	41.030	949.90	25 323	88.240	35.43	44.90	2301.
220	40.778	1247.1	25 770	90.322	35.13	44.61	2295.
230	40.533	1543.3	26 215	92.299	34.84	44.30	2288.
240	40.294	1838.4	26 656	94.177	34.54	43.98	2282.
250	40.060	2132.1	27 094	95.966	34.25	43.66	2276.
260	39.833	2424.5	27 529	97.673	33.97	43.33	2269.
270	39.611	2715.5	27 961	99.302	33.70	43.01	2263.
280	39.394	3005.1	28 390	100.86	33.43	42.69	2257.
290	39.182	3293.2	28 815	102.35	33.18	42.37	2251.
300	38.975	3579.9	29 237	103.78	32.93	42.06	2245.
310	38.773	3865.2	29 656	105.16	32.69	41.76	2239.
320	38.575	4149.0	30 072	106.48	32.46	41.47	2234.
330	38.382	4431.5	30 486	107.75	32.24	41.18	2228.

Thermodynamic properties of nitrogen—Continued

T K	ρ mol/dm^3	u J/mol	h J/mol	s J/(mol K)	c_v J/(mol K)	c_p J/(mol K)	w m/s
340	38.192	4712.7	30 896	108.98	32.03	40.91	2223.
350	38.007	4992.5	31 304	110.16	31.82	40.65	2217.
400	37.131	6374.1	33 306	115.51	30.94	39.47	2191.
450	36.332	7730.7	35 255	120.10	30.26	38.54	2168.
500	35.595	9069.0	37 163	124.12	29.76	37.82	2146.
550	34.910	10 395	39 040	127.70	29.40	37.29	2126.
600	34.270	11 714	40 894	130.93	29.17	36.91	2107.
700	33.098	14 347	44 560	136.58	28.96	36.47	2074.
800	32.042	16 990	48 199	141.44	28.96	36.33	2045.
900	31.078	19 654	51 832	145.72	29.06	36.35	2022.
1000	30.189	22 346	55 471	149.55	29.21	36.45	2002.