

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

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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. © 2001 by the U.S. Secretary of Commerce on behalf of the United States. All rights reserved.

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

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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 |

| | | |
|---------------------|--|----------------------|
| <i>p</i> | Pressure | MPa |
| <i>q</i> | Molecular partition function | |
| <i>R</i> | Molar gas constant | J/(mol K) |
| <i>s</i> | Entropy | J/(mol K) |
| <i>T</i> | Temperature | K |
| <i>u</i> | Internal energy | J/mol |
| <i>v</i> | Molar volume | dm ³ /mol |
| <i>w</i> | Speed of sound | m/s |
| <i>Z</i> | 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 |
| <i>r</i> | Residual |
| ' | Saturated liquid state |
| " | Saturated vapor state |

Subscripts

| | |
|----------|-------------------------------------|
| 0 | Reference state property |
| <i>c</i> | 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 |
| <i>t</i> | translational contribution |
| <i>r</i> | rotational contribution |
| <i>v</i> | vibrational contribution |
| anc | anharmonicity correction |

Physical Constants and Characteristic Properties of Nitrogen

| Symbol | Quantity | Value |
|------------------------|----------------------------------|------------------------------|
| <i>R</i> | Molar gas constant | 8.314 510 J/(mol K) |
| <i>M</i> | Molar mass | 28.013 48 g/mol |
| <i>T_c</i> | Critical temperature | 126.192 K |
| <i>p_c</i> | Critical pressure | 3.3958 MPa |
| ρ_c | Critical density | 11.1839 mol/dm ³ |
| <i>T_{tp}</i> | Triple point temperature | 63.151 K |
| <i>p_{tp}</i> | 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 |
| <i>T_{nbp}</i> | 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_v), 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 Ja-

cobsen *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 ni-

trogen (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

TABLE 1. Summary of critical point measurements

| Author | Critical temp. (K) | Critical pressure (MPa) | Critical density (mol/dm ³) |
|--|-----------------------|----------------------------|--|
| Mathias <i>et al.</i> (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 <i>et al.</i> (1951) | 126.2599 | 3.398 44 | |
| Hirschfelder <i>et al.</i> (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 <i>et al.</i> (1975) | 126.2135 | 3.394 39 | |
| Zozulya and Blagoi (1975) | 126.2059 | 3.397 81 | 11.1768 |
| Haynes <i>et al.</i> (1976) | 126.2135 | | 11.21 |
| Levett Sengers <i>et al.</i> (1976) | 126.2535 | 3.398 | 11.2053 |
| Pestak and Chan (1984) | 126.2278 | | |
| Nowak <i>et al.</i> (1997b) ^a | 126.1920 | 3.3958 | 11.1839 |

^aValues selected in this work.

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.

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

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

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 $T_c - T \approx 22$ 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 $T_c - T \approx 22$ mK. The reported critical values are

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

$$p_c = 3.3958 \pm 0.0017 \text{ MPa, and} \quad (2)$$

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

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

$$\begin{aligned} T_{\text{tr}} &= 63.151 \pm 0.003 \text{ K and} \\ p_{\text{tr}} &= 12.523 \pm 0.010 \text{ kPa} \end{aligned} \quad (3)$$

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 <i>et al.</i> (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 <i>et al.</i> (1984) | 63.1502–63.1508 | |
| Nowak <i>et al.</i> (1997b) ^a | 63.151 | 0.012 523 |

^aValues 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 <i>et al.</i> (1953) | 10 | 97–125 | 0.288 |
| Armstrong (1954) | 74 | 64–78 | 0.275 |
| Jones (1961) | 5 | 119–124 | 0.148 |
| Moussa <i>et al.</i> (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 <i>et al.</i> (1997b) | 58 | 63–126 | 0.003 |
| <i>Overall</i> | 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/dm³.

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 | |

^aAt 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

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 | |

^aDeviations for temperatures between 63.11 and 63.21 K were not included in the comparisons.

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

$$N_1 = -6.12445284,$$

$$N_2 = 1.26327220,$$

$$N_3 = -0.765910082,$$

$$N_4 = -1.77570564,$$

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

$$N_1 = 1.48654237,$$

$$N_2 = -0.280476066,$$

$$N_3 = 0.0894143085,$$

$$N_4 = -0.119879866,$$

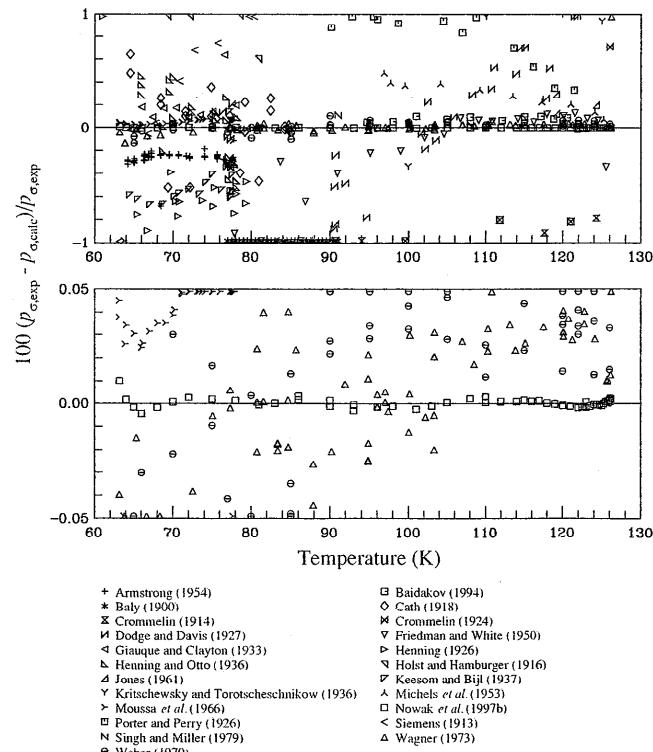


FIG. 1. Comparisons of vapor pressures calculated with the ancillary equations to experimental data.

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

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

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

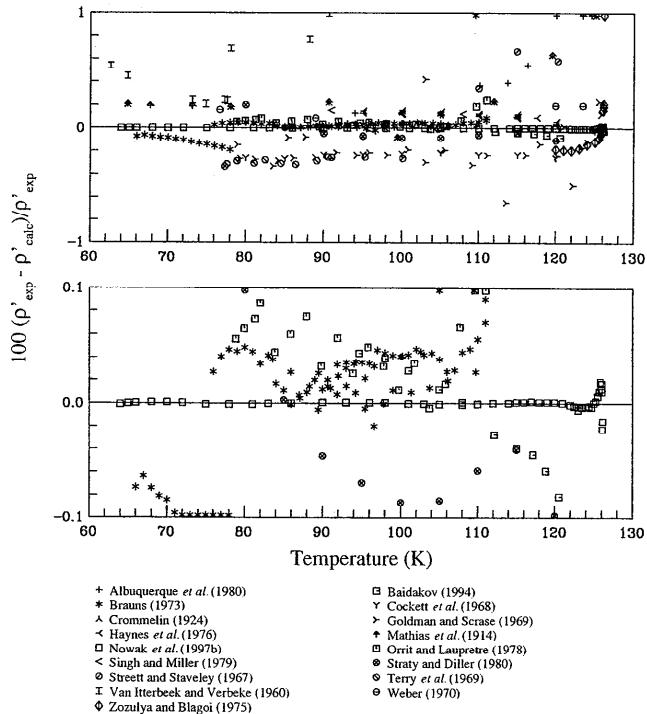


FIG. 2. Comparisons of saturated liquid densities calculated with the ancillary equations to experimental data.

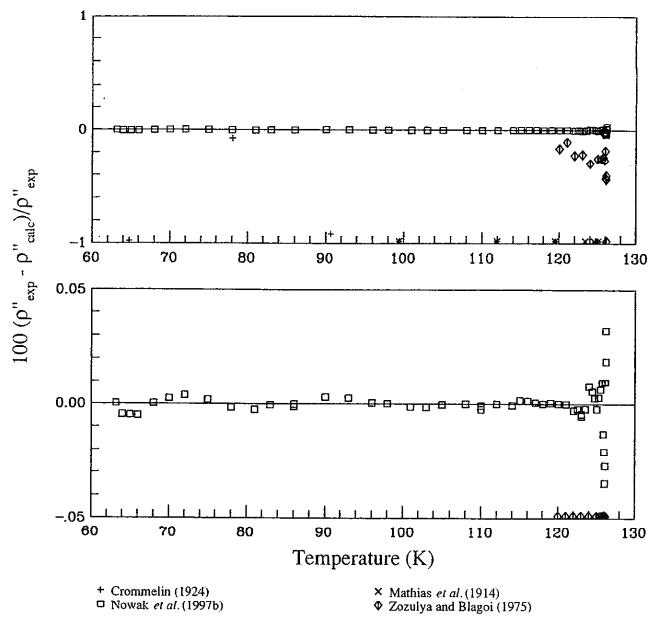


FIG. 3. Comparisons of saturated vapor densities calculated with the ancillary equations to experimental data.

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

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.

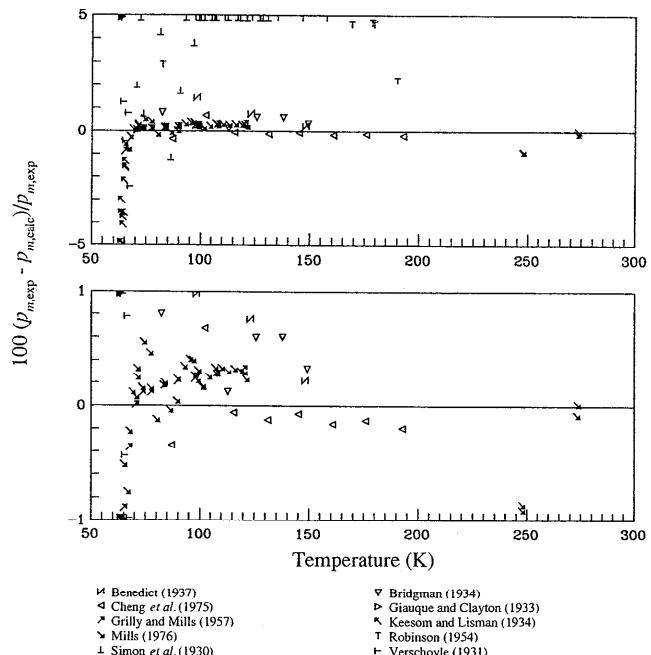


FIG. 4. Comparisons of melting pressures calculated with the ancillary equation to experimental data.

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 <i>et al.</i> (1934) | 56 | 273–423 | 1.93–8.58 | 0.85–2.37 | 0.016 |
| Otto <i>et al.</i> (1934) | 63 | 273–423 | 4.62–42.0 | 2.06–9.59 | 0.020 |
| Michels <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (1986) | 35 | 323 | 1.07–28.7 | 0.40–9.37 | 0.019 |
| Duscheck <i>et al.</i> (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 <i>et al.</i> (1991) | 124 | 273–323 | 0.10–12.1 | 0.04–5.37 | 0.003 |
| Fenghour <i>et al.</i> (1993) | 50 | 290–680 | 3.54–37.0 | 1.43–5.71 | 0.077 |
| Nowak <i>et al.</i> (1997a) | 920 | 66–340 | 0.10–12.0 | 0.07–31.3 | 0.004 ^a |
| Nowak <i>et al.</i> (1997b) | 172 | 125–126 | 3.20–3.39 | 7.25–14.9 | 0.030 ^a |
| Klimeck <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (1961) | 88 | 273–373 | 2.81–109.0 | 0.90–22.2 | 0.123 |
| Miller <i>et al.</i> (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 <i>et al.</i> (1962) | 9 | 143–273 | 5.07–40.5 | 2.26–17.2 | 0.092 |
| Canfield <i>et al.</i> (1965) | 152 | 133–273 | 0.20–54.8 | 0.11–26.6 | 0.051 |
| Golubev and Dobrovolskii (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 <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (1987) | 10 | 295 | 394.0–2220.0 | 31.5–47.5 | 1.171 |
| Blanke <i>et al.</i> (1988) | 104 | 280–360 | 1.02–12.7 | 0.44–4.08 | 0.006 |
| Kortbeek <i>et al.</i> (1988) | 17 | 298 | 200–1000 | 25.9–38.9 | 0.122 |
| Brugge <i>et al.</i> (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 <i>et al.</i> (1990) | 12 | 293–293 | 0.60–6.99 | 0.25–2.88 | 0.013 |
| Ricardo <i>et al.</i> (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 |
| <i>Overall</i> | 8187 | 65–1800 | 0.02–2200 | 0.01–58.5 | |

^aExcluding the region 126.12–126.4 K and 9–13 mol/dm³.

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.

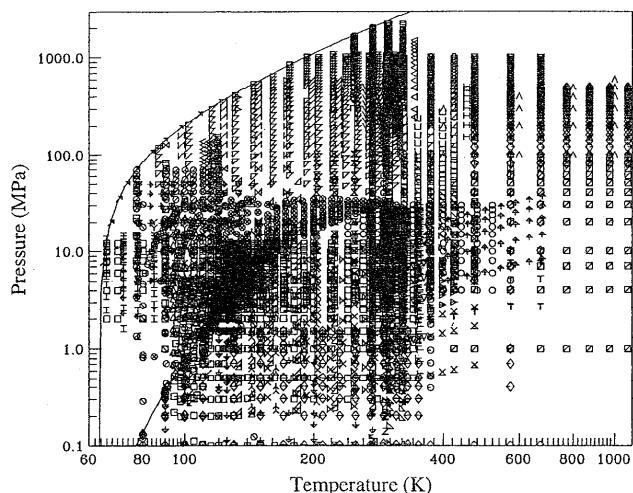
3.2. Caloric Data

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-

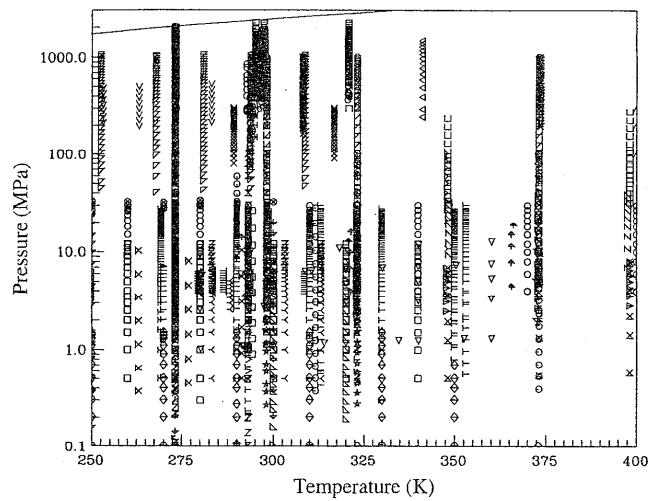
TABLE 7. Uncertainties of experimental data published since 1986 as claimed by the authors of the data

| Source | Uncertainty in temperature | Uncertainty in pressure | Uncertainty in density | Total uncertainty in density ^a | Purity |
|---|--------------------------------------|--|--|--|-----------|
| <i>pρT</i> | | | | | |
| Achtermann <i>et al.</i> (1986) | | 0.005% | | | 0.999 995 |
| Baidakov (1994) | 15 mK | 0.005 MPa | 0.05% | | 0.999 96 |
| Blanke <i>et al.</i> (1988) | 1 mK | $p < 0.2 \text{ MPa}$: 0.01%; $p > 0.2 \text{ MPa}$: 0.005% | 0.03% | 0.03% | 0.999 999 |
| Brugge <i>et al.</i> (1989) | 5 mK | $p < 4 \text{ MPa}$: 0.015%; $p > 4 \text{ MPa}$: 0.005% | | | 0.999 995 |
| Duschek <i>et al.</i> (1988) | 3 mK | larger of 0.007% or 30 Pa | larger of 0.02% or 0.002 kg/m ³ | | 0.999 995 |
| Fenghour <i>et al.</i> (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 <i>et al.</i> (1990) | 50 mK | | | | |
| Kimura <i>et al.</i> (1987) | 300 mK | | | | 0.9999 |
| Klimeck <i>et al.</i> (1998) | 4–10 mK | 0.006% | 0.012% | | 0.999 999 |
| Kortbeek <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (1992) | 10 mK | 0.01 MPa | | 0.1% | 0.999 98 |
| Nowak <i>et al.</i> (1997a, b) | 250–340 K: 1.5 mK, 60–250 K: 3 mK | greater of $4 \times 10^{-5} p$ or 30 Pa | greater of $1 \times 10^{-4} \rho$ or $1.5 \times 10^{-3} \text{ kg/m}^3$ | 0.01% to 0.015% | 0.999 999 |
| Sound Speed | | | | | |
| Kimura <i>et al.</i> (1987) | 300 mK | | | | 0.9999 |
| Kortbeek <i>et al.</i> (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 |
| Isochoric Heat Capacity | | | | | |
| Magee (1991) | 30 mK | 0.2% | | liquid: 0.5%; vapor: 2% | |
| Isobaric Heat Capacity | | | | | |
| Perkins <i>et al.</i> (1991) ^b | | | | 10% | 0.999 99 |
| Vapor Pressure | | | | | |
| Baidakov (1994) | 15 mK | 0.005 MPa | | | 0.999 96 |
| Nowak <i>et al.</i> (1997b) | c | c | | 0.015% | 0.999 999 |
| Saturated Liquid Density | | | | | |
| Baidakov (1994) | 15 mK | | 0.05% | | 0.999 96 |
| Nowak <i>et al.</i> (1997b) | c | | c | 0.012% | 0.999 999 |
| Saturated Vapor Density | | | | | |
| Nowak <i>et al.</i> (1997b) | c | | c | 0.025% | 0.999 999 |

^aExcept for data in the critical region.^bDerived from measurements of the thermal conductivity.cSame as given for Nowak *et al.* (1997) in *pρT* section.



- + Achiermann *et al.* (1986)
- Δ Antonovich and Plotnikov (1976)
- * Bartlett (1927)
- \times Bartlett *et al.* (1930)
- \square Benedict (1937b)
- \triangle Bridgman (1924)
- \blacktriangleleft Brugge *et al.* (1989)
- \blacktriangleright Canfield *et al.* (1965)
- \blacktriangleright Cockett *et al.* (1968)
- \times Date *et al.* (1961)
- \blacktriangleright Fenghour *et al.* (1993)
- \blacktriangleright Gibbons (1969)
- \blacktriangleright Grilly and Mills (1957)
- \blacktriangleright Heuse and Otto (1929)
- \square Holborn and Otto (1924a)
- \square Jaeschke and Hinze (1991)
- \times Jing *et al.* (1990)
- \square Kimura *et al.* (1987)
- \circ Kortbeek *et al.* (1988)
- \diamond Ku and Dodge (1967)
- \diamond Liebenberg *et al.* (1976)
- \diamond Luft (1957)
- \blacktriangleleft Malbrunot and Vodar (1969)
- \blacktriangleleft Maron and Turnbull (1942)
- \square Michels *et al.* (1936)
- \square Miller *et al.* (1961)
- \square Morris and Wylie (1983)
- \square Nowak *et al.* (1997b)
- \square Otto *et al.* (1934)
- \square Pieperbeck *et al.* (1991)
- \times Rivkin (1975)
- \blacktriangleleft Rodosevich and Müller (1973)
- \square Sauler (1958)
- \square Smith and Taylor (1923)
- \square Street and Staveley (1967)
- * Townsend (1956)
- \square Tsiklis and Polyakov (1968)
- \square Van Itterbeek and Verbeke (1961)
- \square Weber (1970)
- \diamond Younglove and McCarty (1980)
- \times Amagat (1893)
- \square Bairdakov (1994)
- \diamond Bartlett *et al.* (1928)
- \times Benedict (1937a)
- ∇ Blanke *et al.* (1988)
- \triangleright Bridgman (1935)
- \square Canfield *et al.* (1962)
- ∇ Cheng (1972)
- \times Crain and Sonntag (1966)
- \blacktriangleleft Duschek *et al.* (1988)
- \downarrow Friedman (1950)
- \triangleright Golubev and Dobrovolskii (1965)
- \square Hall and Canfield (1970)
- \times Holborn and Otto (1922)
- \square Holborn and Otto (1924b)
- \square Jaeschke and Humphreys (1990)
- \square Kamerling Onnes and Van Uit (1924)
- \square Klimeck *et al.* (1998)
- \circ Kosov and Brovko (1979)
- \diamond Liebenberg (1975)
- \diamond Liu and Miller (1972)
- \diamond Malbrunot (1970)
- ∇ Manedov (1969)
- \square Michels *et al.* (1934)
- \square Miller *et al.* (1960)
- \square Mills *et al.* (1975)
- \square Nowak *et al.* (1997a)
- \square Nunes da Ponte *et al.* (1978)
- \square Palavra (1979)
- \square Ricardo *et al.* (1992)
- \times Robertson and Babb (1969)
- \times Roe (1972)
- \square Sharif and Groves (1989)
- \diamond Straty and Diller (1980)
- \circ Timrot *et al.* (1972)
- \diamond Tsiklis (1951)
- \square Van Itterbeek and Verbeke (1960)
- \square Verschoyle (1926)
- \square Wiebe and Gaddy (1938)
- \diamond Zozulya and Blagoi (1975)

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 uncertain-

tion 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-

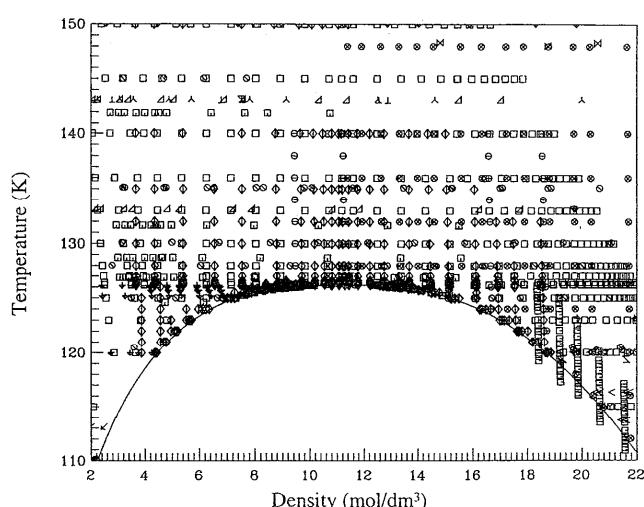
FIG. 7. Critical region $p\rho T$ data. (Author labels are given in Fig. 5.)

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 <i>et al.</i> (1934) | 7 | 273–423 | 0.231 |
| Claitor and Crawford (1949) | 16 | 127–323 | 0.468 |
| Bird <i>et al.</i> (1950) | 7 | 273–423 | 0.350 |
| Friedman (1950) | 12 | 80–300 | 3.659 |
| Van Itterbeek <i>et al.</i> (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 <i>et al.</i> (1962) | 6 | 133–273 | 0.325 |
| Pool <i>et al.</i> (1962) | 1 | 90 | 5.664 |
| Witonsky and Miller (1963) | 5 | 448–748 | 0.469 |
| Hoover <i>et al.</i> (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 |
| Levett Sengers <i>et al.</i> (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 <i>et al.</i> (1988) | 6 | 273–323 | 0.032 |
| Boyes (1992) | 6 | 250–325 | 0.065 |
| Ewing and Trusler (1992) | 14 | 75–700 | 0.195 |
| Nowak <i>et al.</i> (1997a) | 29 | 98–340 | 0.086 |
| <i>Overall</i> | 308 | 70–1400 | |

^aAverage absolute difference in the second virial coefficient (cm³/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

$$a(\rho, T) = a^0(\rho, T) + a^r(\rho, T), \quad (8)$$

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 influ-

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 |
| <i>Overall</i> | | | |
| 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 <i>et al.</i> (1968) | 180 | 10–6000 | 0.329 |

^a0.009%, 0.003%, and 0.002%, respectively, when correcting for the influence of nonexcited vibrational modes, see Sec. 4.1.2.

ence of intermolecular forces. All thermodynamic properties can be calculated as derivatives of the Helmholtz energy. For example, the pressure derived from this expression is

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

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

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

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/dm³. 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

$$a^0 = h^0 - RT - Ts^0, \quad (11)$$

where the ideal gas enthalpy is given by

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

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

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

where $s_0^0 = 191.5$ J/(mol K) is the value for entropy at $T_0 = 298.15$ K and $\rho_0 = 0.101325$ 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 <i>et al.</i> (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 <i>et al.</i> (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 |
| <i>Saturated Liquid</i> | | | | |
| Van Itterbeek and Van Dael (1962) | 13 | 69–91 | | 0.453 |
| Van Dael <i>et al.</i> (1966) | 37 | 65–126 | | 0.324 |
| Data sets not used in developing the equation of state | | | | |
| Dixon <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (1967) | 13 | 77–112 | 0.10–1.65 | 0.765 |
| Singer and Lunsford (1967) | 31 | 74–114 | 0.16–13.9 | 0.743 |
| Voronov <i>et al.</i> (1969) | 113 | 298–448 | 20.3–405.0 | 0.520 |
| Liebenberg (1975) | 533 | 248–321 | 69.2–2039.0 | 0.561 |
| Liebenberg <i>et al.</i> (1976) | 9 | 273 | 300.0–1800.0 | 0.602 |
| Kimura <i>et al.</i> (1987) | 8 | 295 | 291.0–2291.0 | 0.606 |
| <i>Saturated Liquid</i> | | | | |
| Liepmann (1939) | 12 | 69–77 | | 0.704 |
| Van Itterbeek <i>et al.</i> (1949) | 8 | 65–78 | | 2.363 |
| Blagoi <i>et al.</i> (1967) | 8 | 77–110 | | 0.650 |
| Pine (1969) | 17 | 63–77 | | 0.240 |
| <i>Saturated Vapor</i> | | | | |
| Van Itterbeek <i>et al.</i> (1958) | 9 | 77–79 | | 2.585 |
| <i>Overall</i> | | 2389 | 63–1273 | 0.00–2291.0 |

$$a^0 = h_0^0 + \int_{T_0}^T c_p^0 dT - RT$$

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

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

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

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 $p_0 = 0.101325$ MPa.

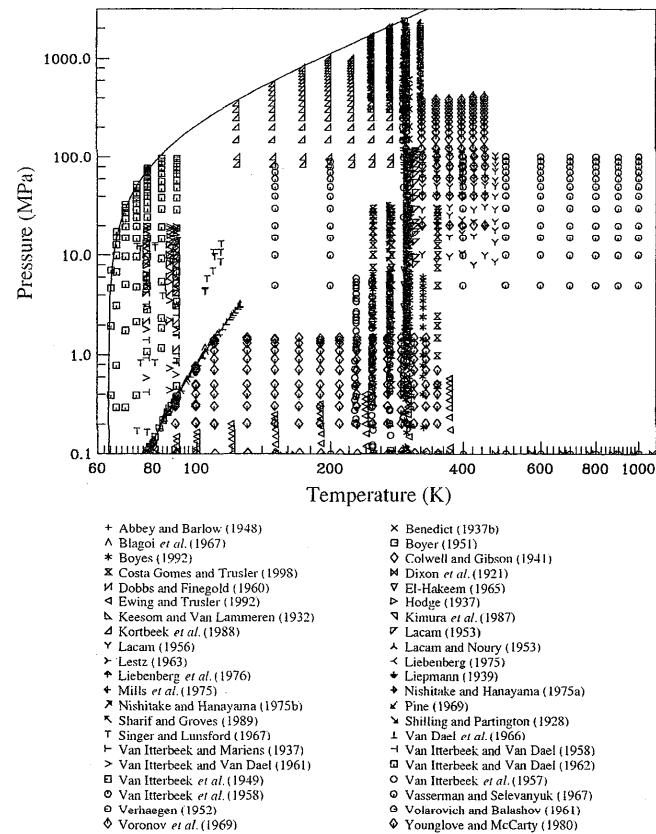


FIG. 8. Speed of sound data.

4.1.1. Ideal Gas Heat Capacity

In the calculation of the thermodynamic properties of nitrogen using an equation of state explicit in Helmholtz en-

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 |
| <i>Overall</i> | 351 | 66–307 | 6.09–34.7 | |

^aIsochoric heat capacity data along the saturated vapor line.

ergy, 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 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 Kruse (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 Zeldnerust (1979) | 33 | 100–270 | 5.07–5.07 | 1.58 |
| Perkins et al. (1991) | 377 | 81–303 | 0.33–71.1 | 7.22 |
| <i>Isobaric Heat Capacity of the Saturated Liquid (c_p)</i> | | | | |
| 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 |
| <i>Saturated Liquid Heat Capacity (c_σ)</i> | | | | |
| Magee (1991) | 102 | 65–121 | | 0.316 |
| <i>Overall</i> | 907 | 64–1273 | 0.00–608.0 | |

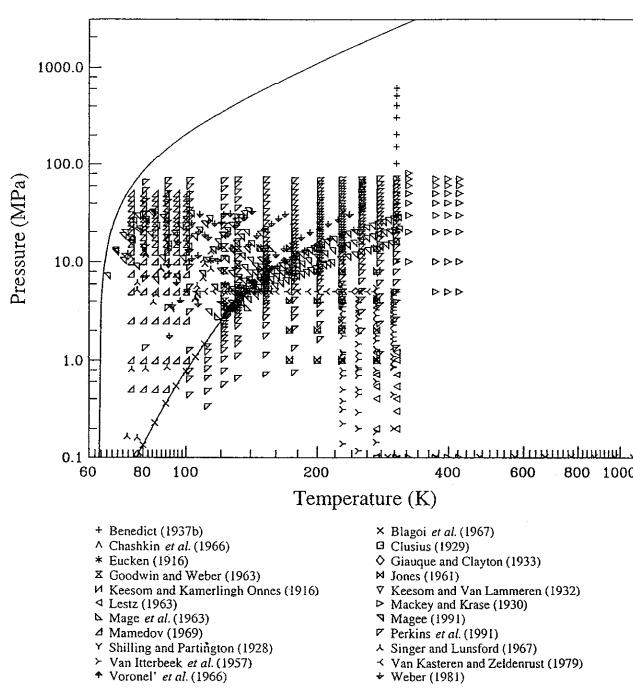


FIG. 9. Isobaric and isochoric heat capacity data.

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 tem-

peratures). 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 $^{14}\text{N}_2$. 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),

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

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 Zeldenerust (1979) | 32 | 100–270 | 5.07 | 2.418 |
| Grini and Owren (1997) | 19 | 160–270 | 0.29–15.0 | 0.128 |
| <i>Overall</i> | 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 |
| <i>Overall</i> | 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 ($^{14}\text{N}_2$) 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 $^{14}\text{N}_2$, $^{14}\text{N}^{15}\text{N}$, and $^{15}\text{N}_2$ 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,

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

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:

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

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

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

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):

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

$$\begin{aligned} G(v) &= \omega_e(v + \frac{1}{2}) - \omega_e x_e(v + \frac{1}{2})^2 + \omega_e y_e(v + \frac{1}{2})^3 \\ &+ \omega_e z_e(v + \frac{1}{2})^4 + \dots \end{aligned} \quad (22)$$

$$\begin{aligned} F(v, j) &= [B_e - \alpha_e(v + \frac{1}{2}) + \dots] j(j+1) \\ &- [D_e + \beta_e(v + \frac{1}{2}) + \dots] j^2(j+1)^2 + \dots \end{aligned} \quad (23)$$

$E(e)$ 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 $^{14}\text{N}^{14}\text{N}$:

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

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

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

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

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

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

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

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 $^{14}\text{N}_2$) + 1/3 (para $^{14}\text{N}_2$) for $^{14}\text{N}_2$, or similarly, 3/4 (ortho $^{15}\text{N}_2$) + 1/4 (para $^{15}\text{N}_2$) for $^{15}\text{N}_2$. For the heteronuclear diatomic $^{14}\text{N}^{15}\text{N}$, there is neither such complication nor requirement.

The calculations must first be made for pure ortho $^{14}\text{N}_2$ and $^{15}\text{N}_2$, pure para $^{14}\text{N}_2$ and $^{15}\text{N}_2$, and $^{14}\text{N}^{15}\text{N}$ separately,

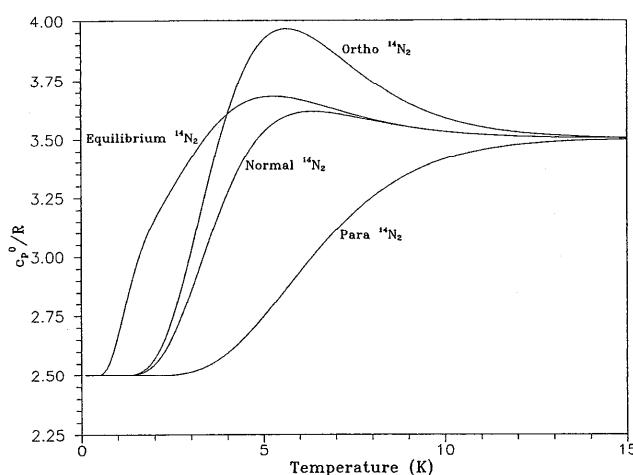


FIG. 10. Low temperature ideal gas heat capacity of $^{14}\text{N}_2$. The curves for normal $^{14}\text{N}_2$ and naturally occurring nitrogen are nearly identical.

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% $^{14}\text{N}_2$, 0.727% $^{14}\text{N}^{15}\text{N}$, and 0.002% $^{15}\text{N}_2$. The results are summarized in Figs. 10 and 11. Differences between normal $^{14}\text{N}_2$ 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 $^{14}\text{N}_2$ in Eqs. (22) and (23) have been adopted (Herzberg, 1950; Huber and Herzberg, 1979; Laher and Gilmore, 1991):

$$\omega_e = 2358.57 \text{ cm}^{-1} \quad (29)$$

$$\omega_e x_e = 14.324 \text{ cm}^{-1} \quad (30)$$

$$B_e = 1.99824 \text{ cm}^{-1} \quad (31)$$

$$\alpha_e = 0.017318 \text{ cm}^{-1} \quad (32)$$

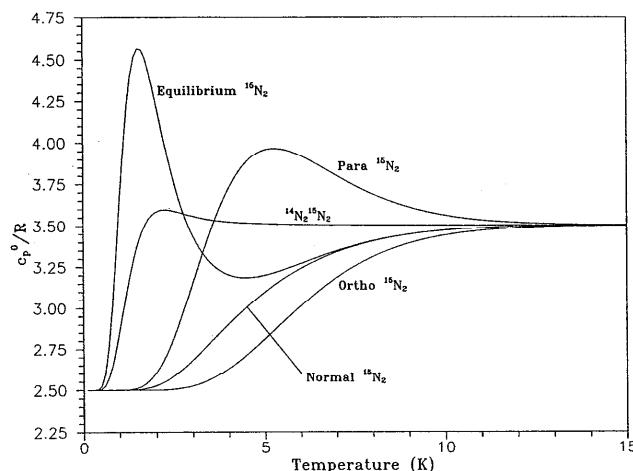


FIG. 11. Low temperature ideal gas heat capacity of $^{15}\text{N}_2$ and $^{14}\text{N}^{15}\text{N}$.

$$D_e = \frac{4B_e^3}{\omega_e^2} \quad (33)$$

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

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):

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

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

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

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

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

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

The value of m is the square root of the reduced mass of $^{14}\text{N}_2$ divided by the reduced mass of the other isotope; $m = 0.983192$ for $^{14}\text{N}^{15}\text{N}$ and $m = 0.966092$ for $^{15}\text{N}_2$. 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 $^{14}\text{N}^{14}\text{N}$, $g_{nj} = 3$ 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):

$$E(e=1) = 50203.0 \text{ cm}^{-1} \quad (41)$$

$$\omega_e = 1460.37 \text{ cm}^{-1} \quad (42)$$

$$\omega_e x_e = 13.891 \text{ cm}^{-1} \quad (43)$$

$$B_e = 1.440 \text{ cm}^{-1} \quad (44)$$

$$\alpha_e = 0.013 \text{ cm}^{-1} \quad (45)$$

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 0.00001%. 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)],

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

and

$$\begin{aligned} \frac{c_{p,\text{anh}}^0}{R} = & \frac{16\gamma}{u} - \frac{\delta u^2 e^u}{(e^u - 1)^2} + \frac{u^2 e^u (2\delta e^u - 4Xu - 8X)}{(e^u - 1)^3} \\ & + \frac{12Xu^3 e^{2u}}{(e^u - 1)^4}, \end{aligned} \quad (47)$$

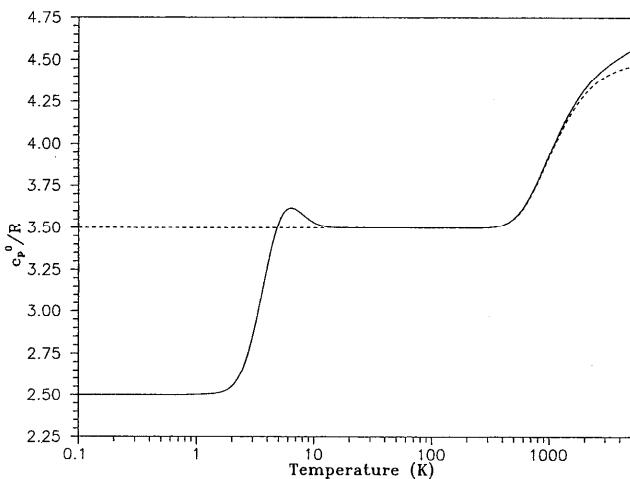


FIG. 12. Ideal gas heat capacity of naturally occurring nitrogen (solid line) and calculations from the RRHO model without electronic states or quantum mechanical corrections (dashed line).

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, $\text{N}_2 \leftrightarrow \text{N} + \text{N}$, and the equilibrium constant $K_p(T)$ can be calculated by the following statistical thermodynamics equation (Landau and Lifshitz, 1980),

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

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,

$$\frac{c_p^0}{R} = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + a_4 \frac{u^2 \exp(u)}{[\exp(u) - 1]^2}, \quad (49)$$

where the ideal gas constant, R , is 8.314 510 J/(mol K) (Cohen and Taylor, 1988), T is in kelvins, $a_0 = 3.5$, $a_1 = 3.066 469 \times 10^{-6}$, $a_2 = 4.701 240 \times 10^{-9}$, $a_3 = -3.987 984 \times 10^{-13}$, $a_4 = 1.012 941$, and $u = 3364.011 K/T$. 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 |

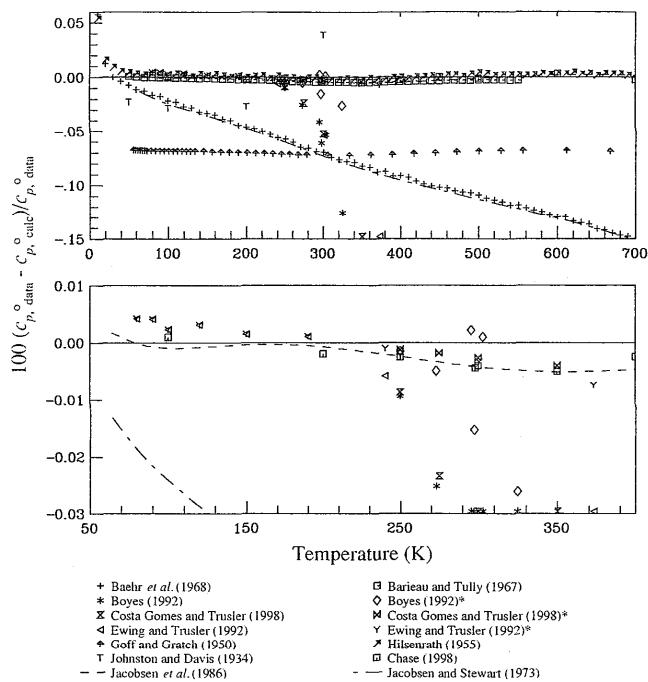


FIG. 13. Comparisons of ideal gas heat capacities calculated with the ancillary equation to experimental data. The data marked with an asterisk have been corrected to account for the vibrational contribution.

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,

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

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

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

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

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

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,

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

where

$$\begin{aligned} a_1 &= 2.5, \\ a_2 &= -12.769\,527\,08, \\ a_3 &= -0.007\,841\,63, \\ a_4 &= -1.934\,819 \times 10^{-4}, \\ a_5 &= -1.247\,742 \times 10^{-5}, \\ a_6 &= 6.678\,326 \times 10^{-8}, \\ a_7 &= 1.012\,941, \end{aligned}$$

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

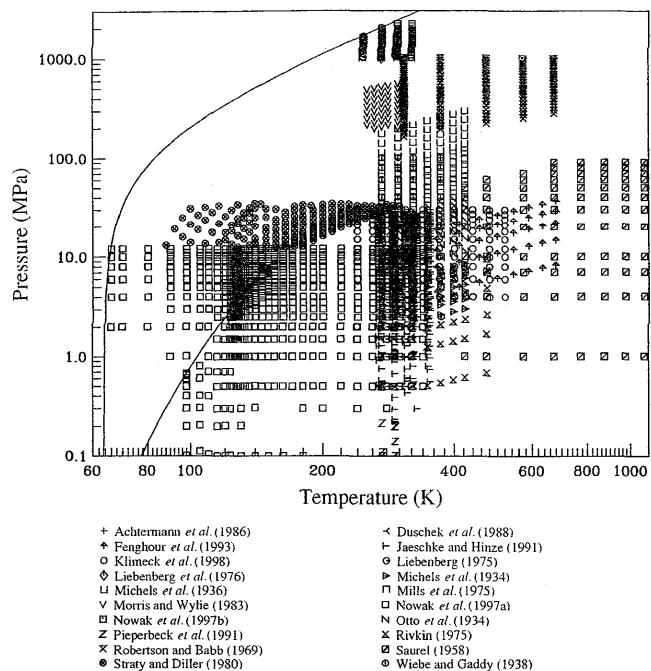


FIG. 14. Selected $p\rho T$ data used in determining the coefficients of the equation of state.

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.

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 % | | | | | |
|--|------------------|-----------------|----------------------|--|--------|---------------------------|----------------------|-----------------|-----------------|
| | | | | Gas | Liquid | Crit. region ^a | Supercritical fluid | | |
| | | | | | | | LD ^b | MD ^b | HD ^b |
| <i>ppt data^c</i> | | | | | | | | | |
| Michels <i>et al.</i> (1934) | 56 | 273–423 | 1.93–8.58 | — | — | — | 0.016 | — | — |
| Otto <i>et al.</i> (1934) | 63 | 273–423 | 4.62–42.0 | — | — | — | 0.016 | 0.025 | — |
| Michels <i>et al.</i> (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 <i>et al.</i> (1975) | 43 | 248–321 | 1000.0–2200.0 | — | — | — | — | — | 0.615 |
| Rivkin (1975) | 24 | 373–473 | 0.60–9.63 | — | — | — | 0.032 | — | — |
| Liebenberg <i>et al.</i> (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 <i>et al.</i> (1986) | 35 | 323 | 1.07–28.7 | — | — | — | 0.010 | 0.042 | — |
| Duschek <i>et al.</i> (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 <i>et al.</i> (1991) | 124 | 273–323 | 0.10–12.1 | — | — | — | 0.003 | — | — |
| Fenghour <i>et al.</i> (1993) | 50 | 290–680 | 3.54–37.0 | — | — | — | 0.077 | — | — |
| Nowak <i>et al.</i> (1997a) | 920 | 66–340 | 0.10–12.0 | 0.003 | 0.002 | 0.004 | 0.003 | 0.004 | 0.001 |
| Nowak <i>et al.</i> (1997b) | 172 | 125–126 | 3.20–3.39 | 0.020 | — | 0.002 | — | — | — |
| Klimeck <i>et al.</i> (1998) | 197 | 240–520 | 1.11–30.1 | — | — | — | 0.001 | 0.001 | — |
| <i>Isochoric heat capacities</i> | | | | | | | | | |
| 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 |
| <i>Speeds of sound</i> | | | | | | | | | |
| 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 <i>et al.</i> (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 <i>et al.</i> (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 <i>et al.</i> (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 | — |
| <i>Isobaric and saturated liquid heat capacities</i> | | | | | | | | | |
| Benedict (1937b) | 8 | 303 | 0.10–608.0 | — | — | — | 0.178 | — | 1.434 |
| Mage <i>et al.</i> (1963) | 28 | 118–274 | 1.01–13.8 | — | — | — | 3.439 | 0.319 | 0.483 |
| Magee (1991) | 102 | 65–121 | sat. liquid | — | 0.300 | — | — | — | — |
| <i>Enthalpy differences</i> | | | | | | | | | |
| 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 <i>et al.</i> (1963) | 5 | 119–124 | vaporization | — | 0.439 | 3.556 | — | — | — |
| Grini and Owren (1997) | 19 | 160–270 | 0.29–15.0 | — | — | — | 0.139 | 0.085 | — |
| <i>Second virial coefficients</i> | | | | | | | | | |
| Duschek <i>et al.</i> (1988) | 6 | 273–323 | — | 0.363 ^h | — | — | — | — | — |
| Ewing and Trusler (1992) | 14 | 75–700 | — | 0.400 | — | — | — | — | — |
| Nowak <i>et al.</i> (1997a) | 29 | 98–340 | — | 0.186 ^h | — | — | — | — | — |
| Nowak <i>et al.</i> (1997a) | 29 | 98–340 | — | 3.784 | — | — | — | — | — |

^aCorresponds to an extended critical region with $0.98 \leq T/T_c \leq 1.1$ and $0.7 \leq \rho/\rho_c \leq 1.4$.^bThe supercritical fluid is divided into three subregions (LD: $\rho/\rho_c \leq 0.6$; MD: $0.6 < \rho/\rho_c < 1.5$; HD: $\rho/\rho_c \geq 1.5$).^cDeviations in pressure are given in place of deviations in density in the critical region.^dBurnett measurements.^eRefractive index measurements.^fData corrected for missing vibrational contribution, see Sec. 4.1.2.^gAverage absolute deviation of temperature differences calculated for near isenthalpic expansions.^hThe 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 | | Nonlinear optimization used directly |
|--|---------------------|-----------------|---|
| | used directly | used linearized | |
| $p\rho T$ | × | | × |
| 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,

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

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 $1 \leq d_i \leq 3$, $0 \leq t_i \leq 3$, $15 \leq \phi_i \leq 25$, $275 \leq \beta_i \leq 325$, and $1.13 \leq \gamma_i \leq 1.25$. 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

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

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

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

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

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

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

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

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

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

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

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

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

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).

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

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

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

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 ($\partial p / \partial T$)_ρ, the Joule–Thomson coefficient (μ_J), the isentro-

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

| <i>k</i> | 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).

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

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

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

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

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

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

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

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

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

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

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

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

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

and

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

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).

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

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

$$\delta^3 \left(\frac{\partial^3 \alpha^r}{\partial \delta^3}\right)_T = \sum_{k=1}^6 i_k (i_k - 1)(i_k - 2) N_k \delta^{i_k} \tau^{j_k} + \sum_{k=7}^{32} N_k \delta^{i_k} \tau^{j_k} \exp(-\delta^{l_k}) \{i_k(i_k - 1)(i_k - 2) + \delta^{l_k}[-2l_k + 6i_k l_k - 3i_k^2 l_k - 3i_k l_k^2$$

$$\begin{aligned} &+ 3l_k^2 - l_k^3] + \delta^{2l_k}[3i_k l_k^2 - 3l_k^2 + 3l_k^3] - l_k^3 \delta^{3l_k}\} + \sum_{k=33}^{36} N_k \delta^{i_k} \tau^{j_k} \exp(-\varphi_k(\delta - 1)^2 - \beta_k(\tau - \gamma_k)^2) \\ &\times \left\{ \begin{aligned} &[-2\varphi_k(\delta - 1)\delta]^3 + i_k(2 - 3i_k + i_k^2) + 3(2\varphi_k \delta)^2(\delta - 1)[-i_k + \delta(1 + i_k)] \\ &- 2\varphi_k \delta[(3i_k^2 - 3i_k)(\delta - 1) + 3\delta i_k] \end{aligned} \right\} \end{aligned} \quad (83)$$

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

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

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

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 $\pm 0.01\%$. At temperatures below 70 K, the differences increase up to 0.026% at T_{tp} .

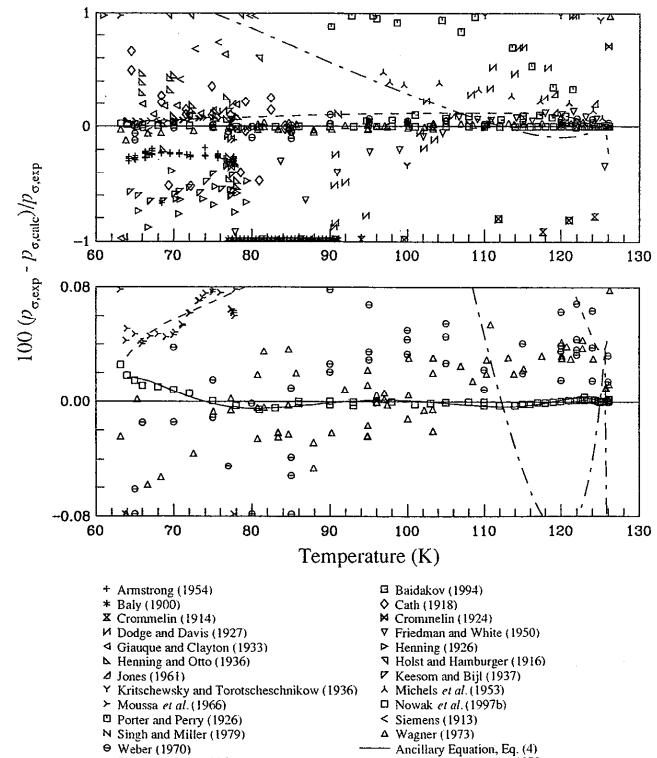


FIG. 15. Comparisons of vapor pressures calculated with the equation of state to experimental data.

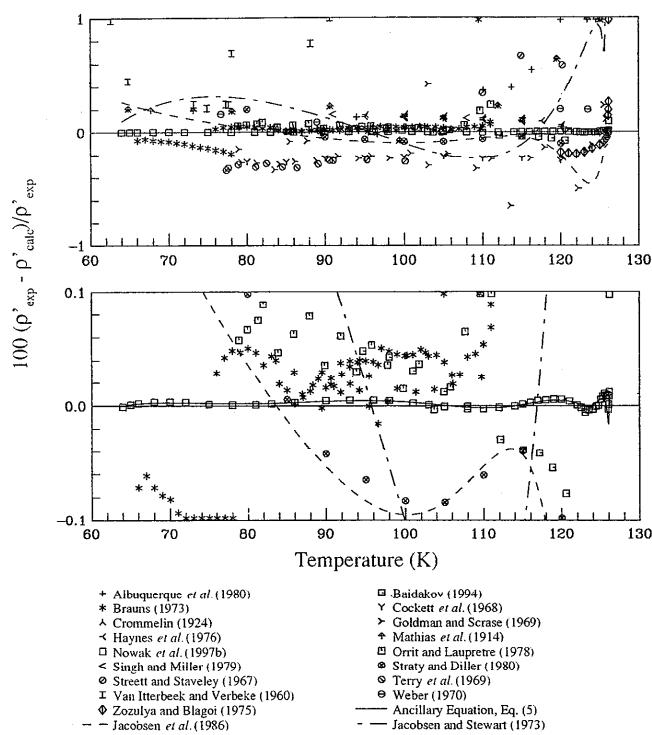


FIG. 16. Comparisons of saturated liquid densities calculated with the equation of state to experimental data.

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 de-

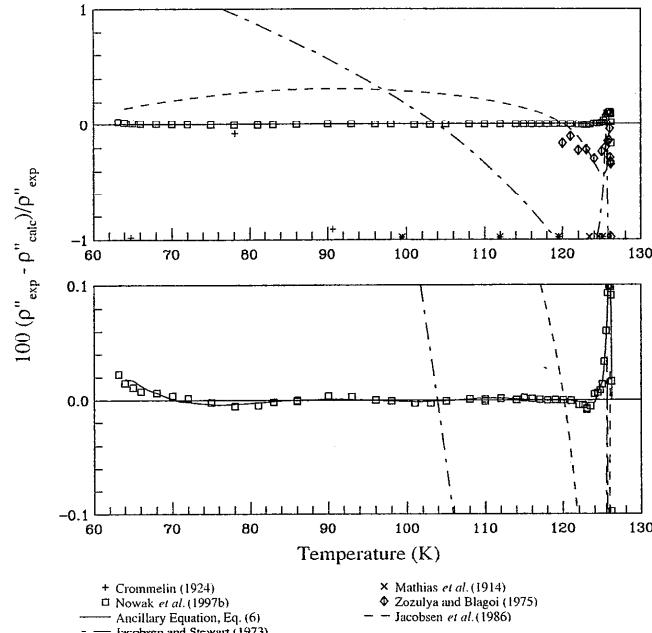


FIG. 17. Comparisons of saturated vapor densities calculated with the equation of state to experimental data.

viations 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.

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 Lauprêtre (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

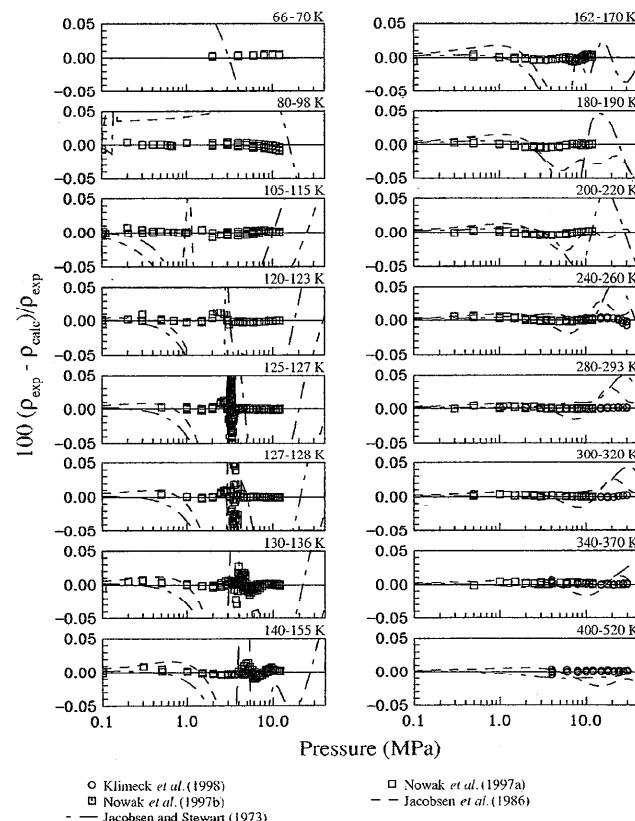


FIG. 18. Comparisons of densities calculated with the equation of state to the experimental data of Klimeck *et al.* (1998) and Nowak *et al.* (1997a,b).

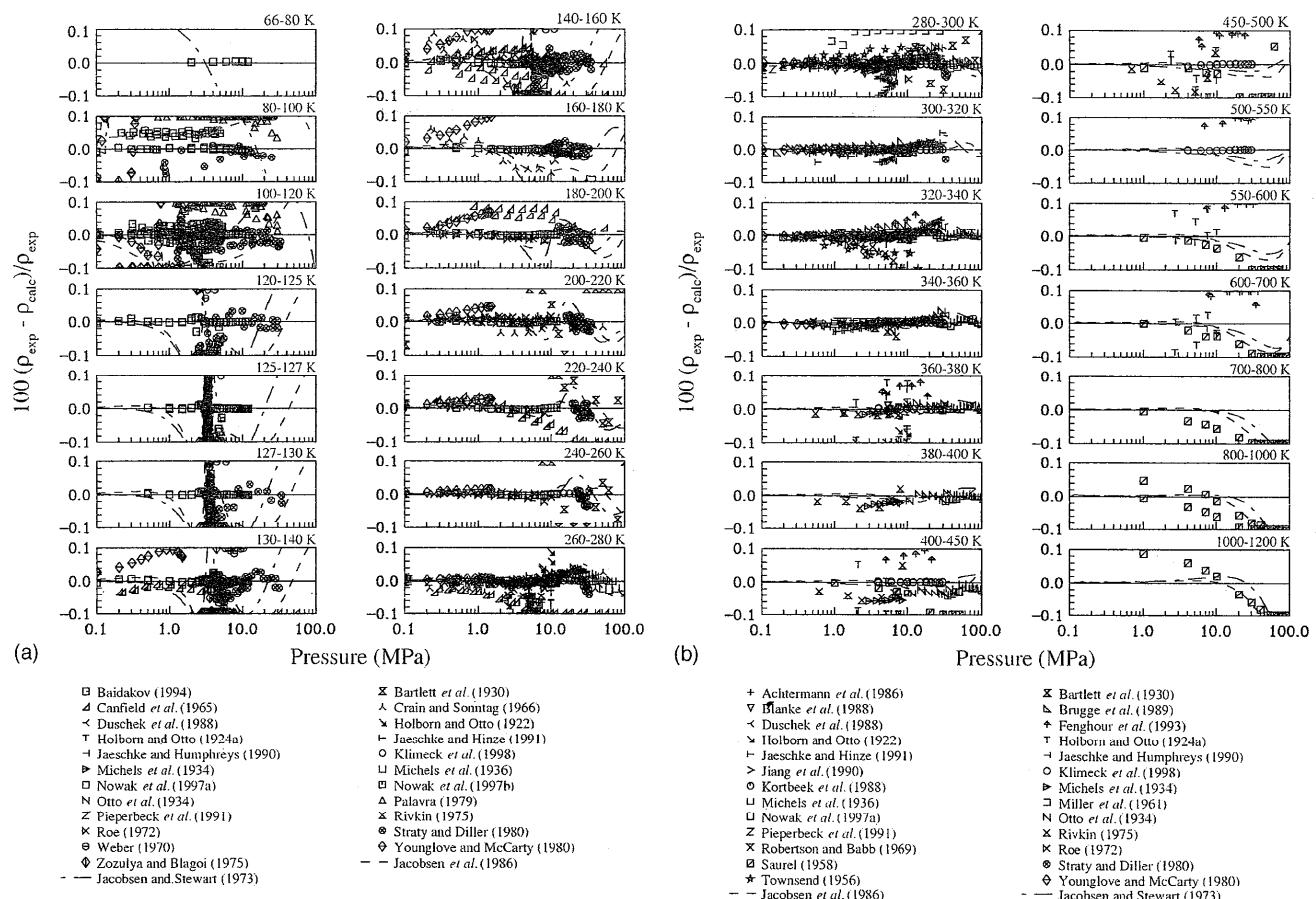


FIG. 19. Comparisons of densities calculated with the equation of state to accurate experimental data.

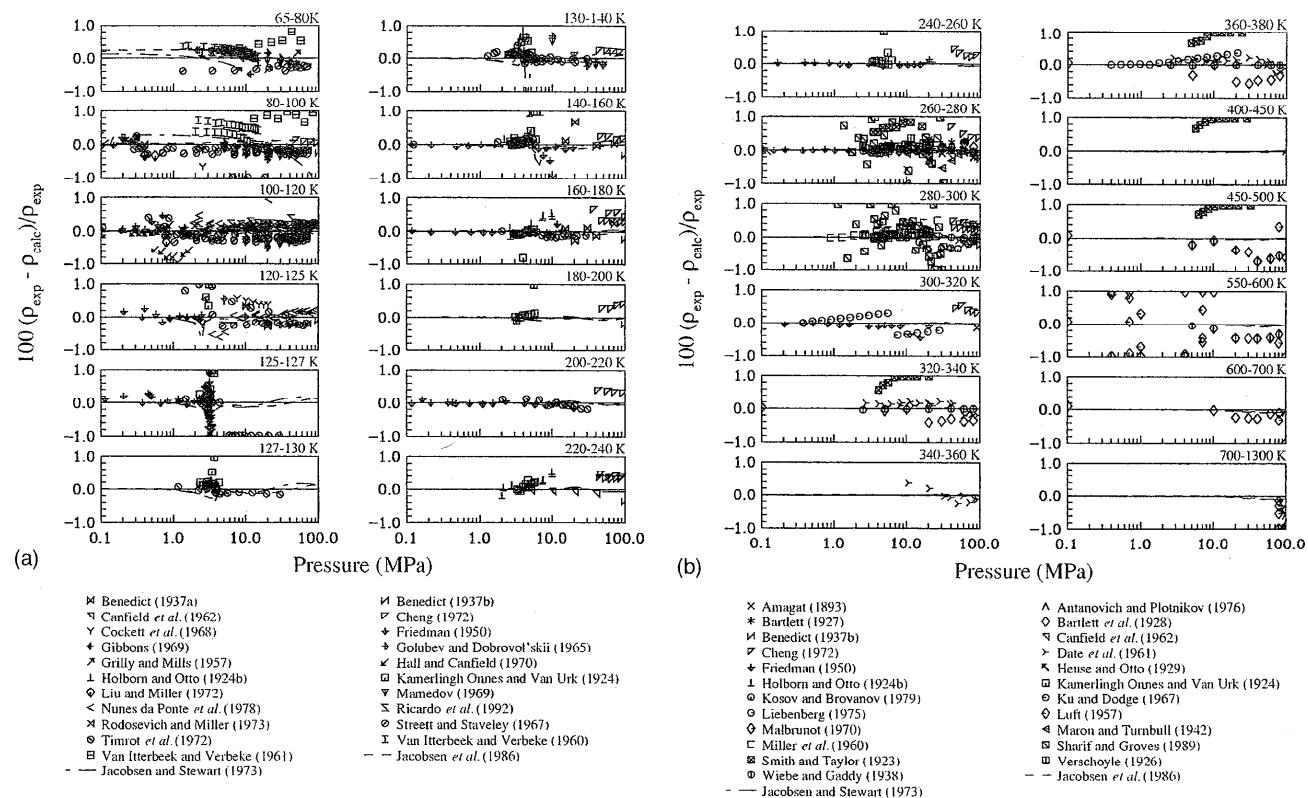


FIG. 20. Comparisons of densities calculated with the equation of state to experimental data with higher uncertainties.

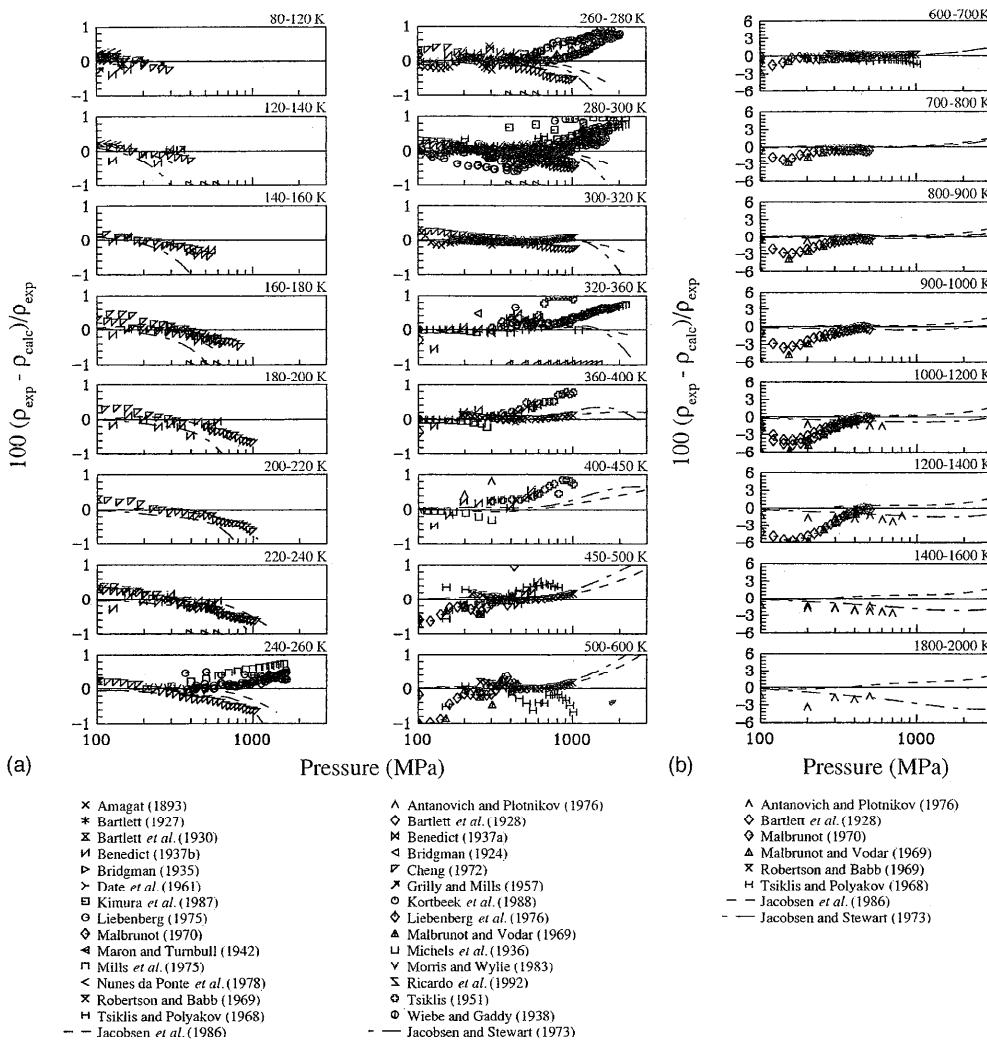


FIG. 21. Comparisons of densities calculated with the equation of state to experimental data at pressures greater than 100 MPa.

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 va-

porization 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

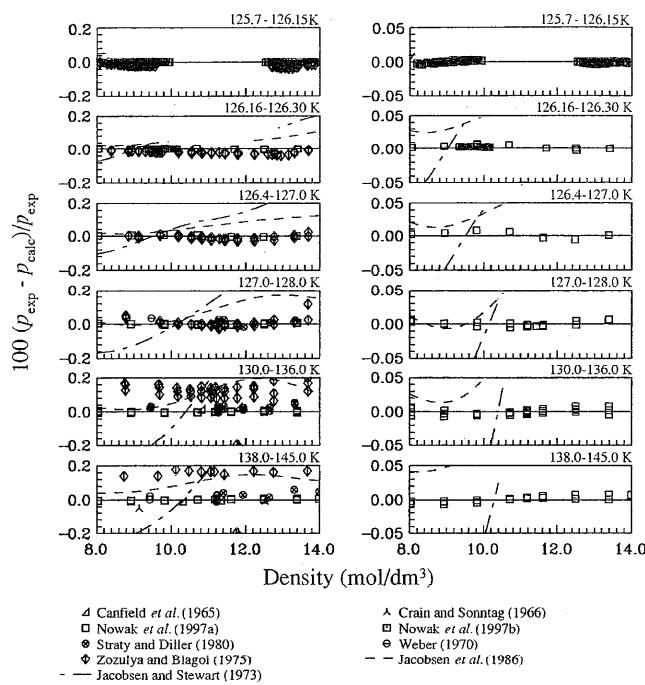


FIG. 22. Comparisons of pressures calculated with the equation of state to experimental data in the critical region.

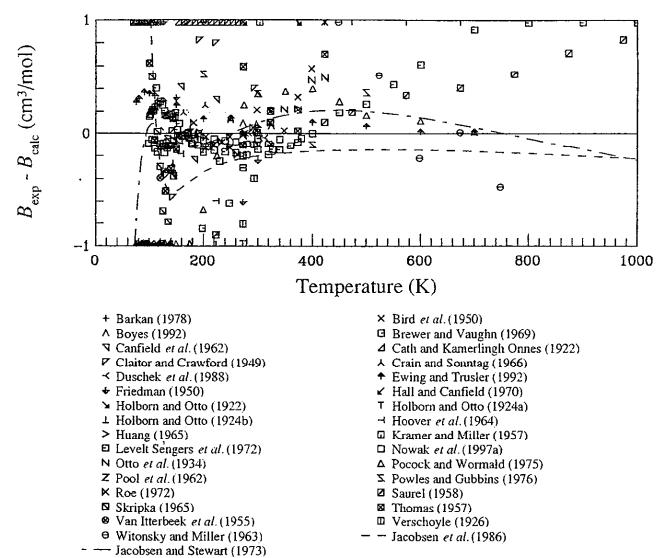
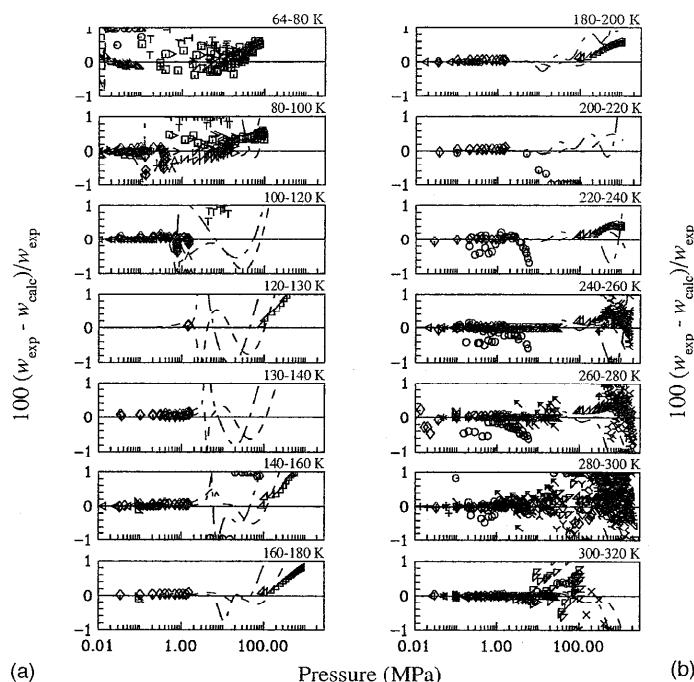


FIG. 23. Comparisons of second virial coefficients calculated with the equation of state to experimental data.



(a)

(b)

- + Abbey and Barlow (1948)
- Δ Blagoi et al. (1967)
- \diamond Colwell and Gibson (1941)
- \boxplus Dixon et al. (1921)
- ∇ El-Hakeem (1965)
- \triangleright Hodge (1937)
- \blacktriangleleft Kimura et al. (1987)
- \square Lacam (1953)
- \wedge Lacam and Nouy (1953)
- \leftarrow Liebenberg (1975)
- \leftarrow Mills et al. (1975)
- \nearrow Nishitake and Hanayama (1975b)
- \times Nishitake and Hanayama (1975b)
- \times Shilling and Partington (1928)
- \leftarrow Van Itterbeek and Marien (1937)
- \rightarrow Van Itterbeek and Van Dael (1961)
- \circ Van Itterbeek et al. (1957)
- \diamond Verhaegen (1952)
- \heartsuit Voronov et al. (1969)
- \dashv Voronov et al. (1969)
- \dashv Jacobson et al. (1986)

- \wedge Benedict (1937b)
- * Boyes (1992)
- \boxtimes Costa Gomes and Trusler (1998)
- \triangleleft Costa Gomes and Trusler (1998)
- \boxplus Dobbs and Finegold (1960)
- \leftarrow Ewing and Trusler (1992)
- \blacktriangleleft Ewing and Trusler (1992)
- \square Keenan and Van Lameren (1932)
- \triangleright Kortbeek et al. (1988)
- \vee Lacam (1956)
- \triangleright Lestz (1963)
- \triangleright Liebenberg et al. (1976)
- \triangleright Nishitake and Hanayama (1975a)
- \blacktriangleleft Sharif and Groves (1989)
- \square Singer and Lunsford (1967)
- \leftarrow Van Itterbeek and Van Dael (1958)
- \boxplus Van Itterbeek and Van Dael (1962)
- \circ Vasserman and Selevanyuk (1967)
- \diamond Volarovich and Balashov (1961)
- \heartsuit Younglove and McCarty (1980)
- \dashv Younglove and McCarty (1980)
- \dashv Jacobson et al. (1986)

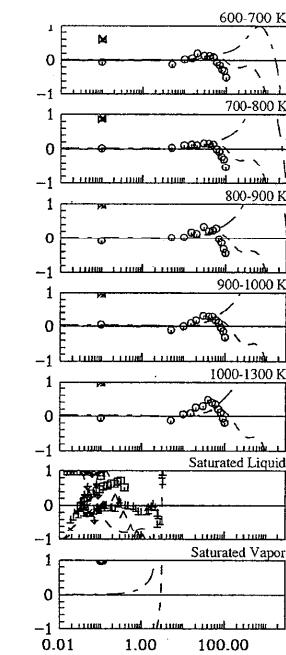


FIG. 24. Comparisons of sound speeds calculated with the equation of state to experimental data.

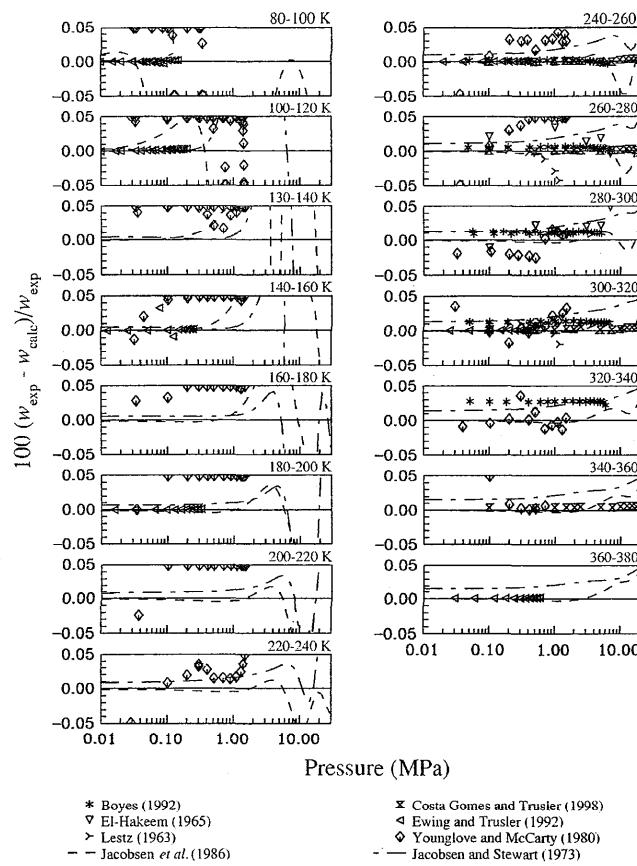


FIG. 25. Comparisons of sound speeds calculated with the equation of state to experimental data and corrected experimental data in the vapor phase.

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

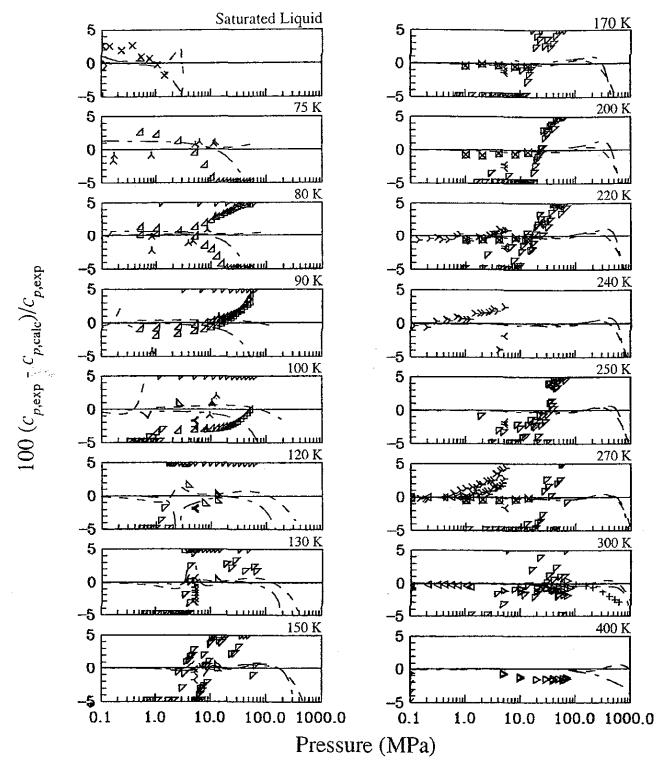


FIG. 26. Comparisons of isobaric heat capacities calculated with the equation of state to experimental data.

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

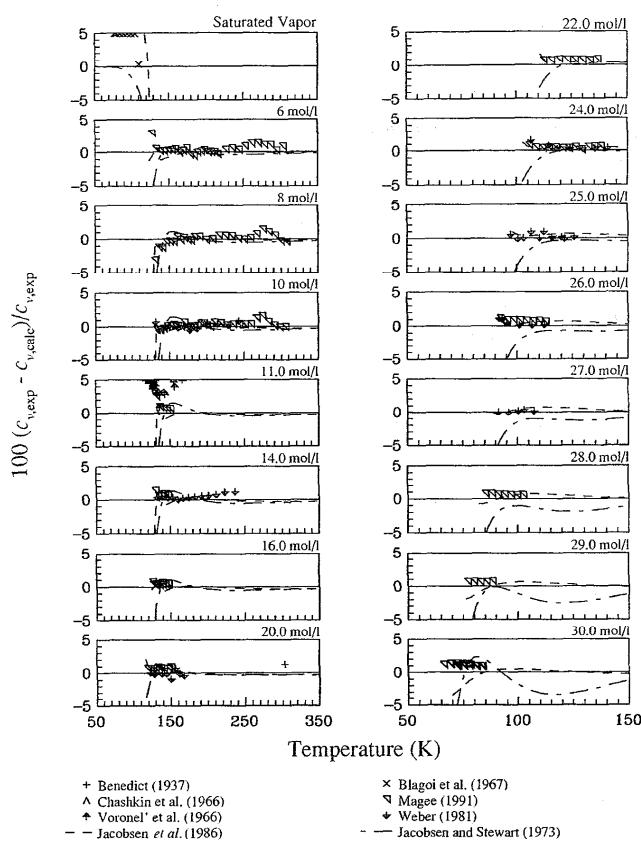


FIG. 27. Comparisons of isochoric heat capacities calculated with the equation of state to experimental data.

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 Slevanyuk (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

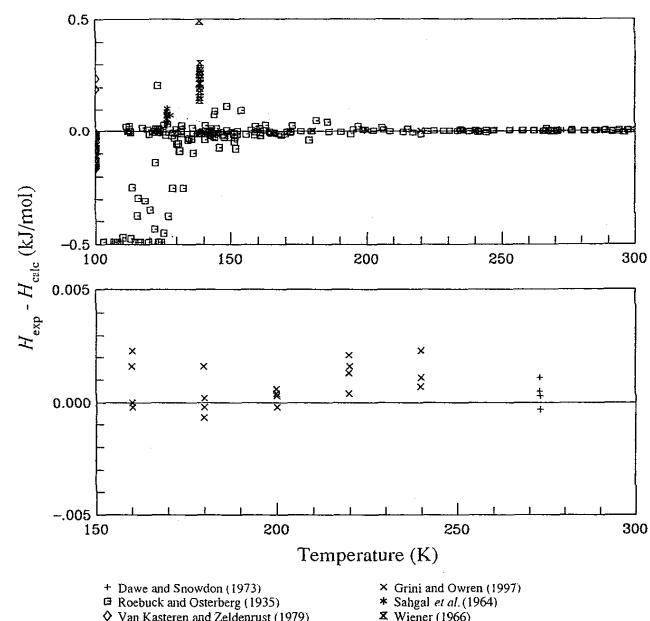


FIG. 29. Comparisons of enthalpy differences calculated with the equation of state to experimental data.

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

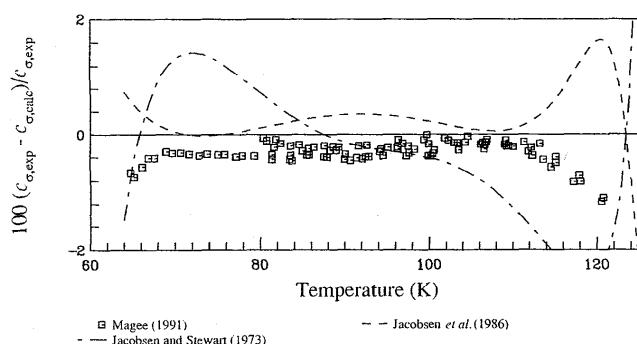


FIG. 28. Comparisons of saturated liquid heat capacities calculated with the equation of state to experimental data.

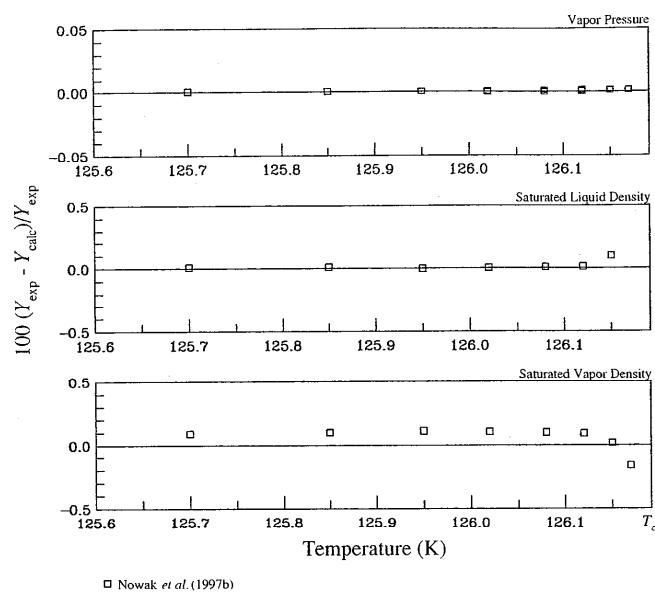


FIG. 30. Comparisons of saturation properties in the critical region calculated with the equation of state to experimental data.

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 $T > T_c + 2.5$ K. The new equation gives reliable results for $T > T_c + 0.5$ 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 ($T \approx T_c + 8.8$ K), while the mBWR equation of state predicts values that are too high. On the 128 K isotherm ($T \approx T_c + 1.8$ 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

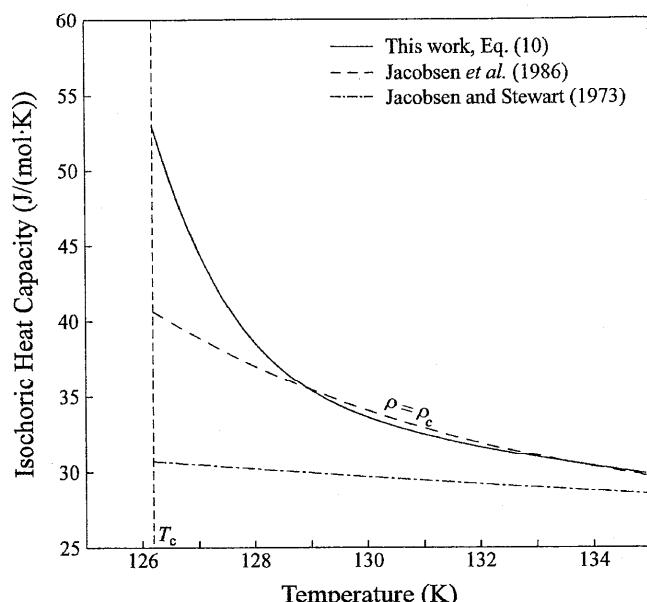


FIG. 31. Comparisons of the isochoric heat capacity on the critical isochore between calculations from the new equation of state and from the equations of Jacobsen *et al.* (1986) and Jacobsen and Stewart (1973).

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 ($|T - T_c| < 0.5$ K and $|\rho - \rho_c| < 2$ mol/dm³), 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

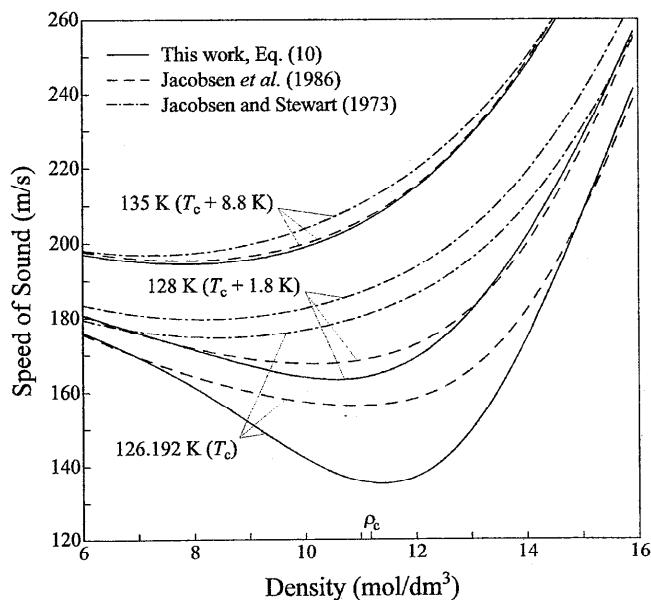


FIG. 32. Comparisons of the speed of sound in the critical region between calculations from the new equation of state and from the equations of Jacobsen *et al.* (1986) and Jacobsen and Stewart (1973).

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

$$Z=1, \quad (89)$$

the Boyle curve,

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

the Joule–Thomson inversion curve,

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

and the Joule inversion curve,

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

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).

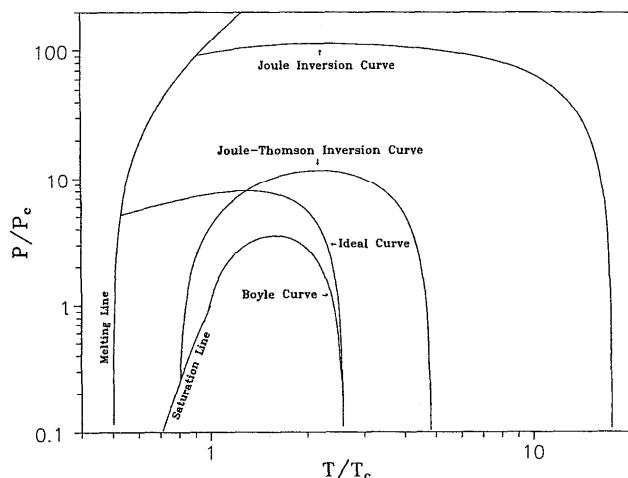


FIG. 33. Characteristic curves.

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

$$p - p_o = \rho_o(w_s - w_o)(w_p - w_o), \quad (93)$$

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

and

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

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

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

Rearrangement of Eq. (95) results in

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

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 v 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

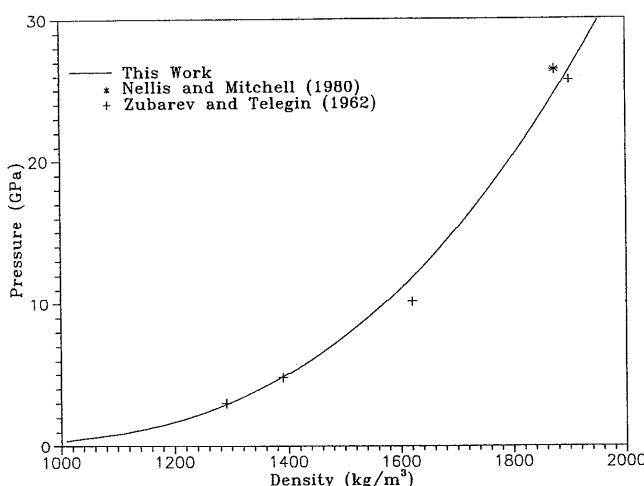


FIG. 34. Calculated Hugoniot curve.

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.

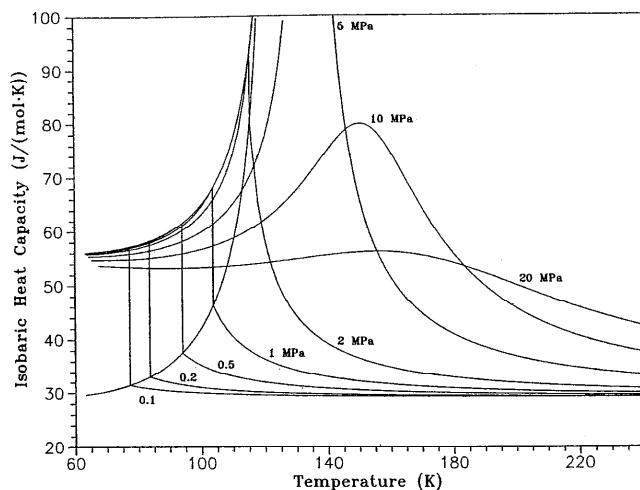


FIG. 36. Isobaric heat capacity versus temperature diagram.

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.

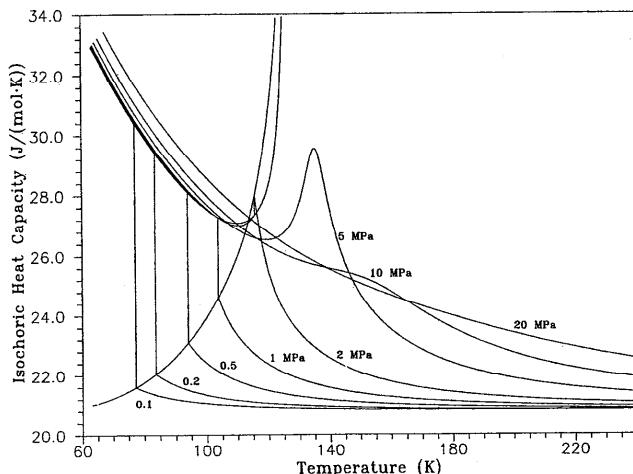


FIG. 35. Isochoric heat capacity versus temperature diagram.

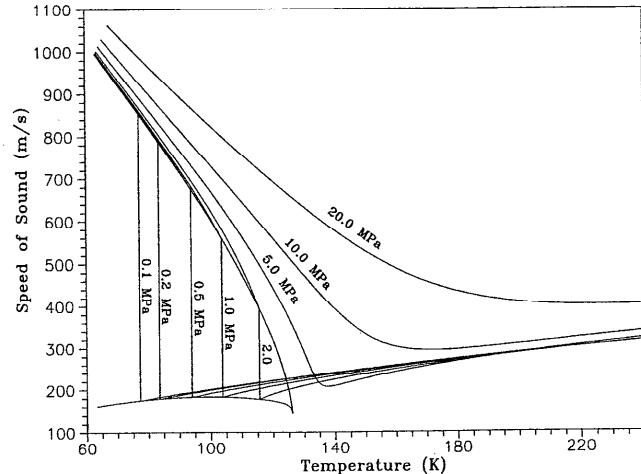


FIG. 37. Speed of sound versus temperature diagram.

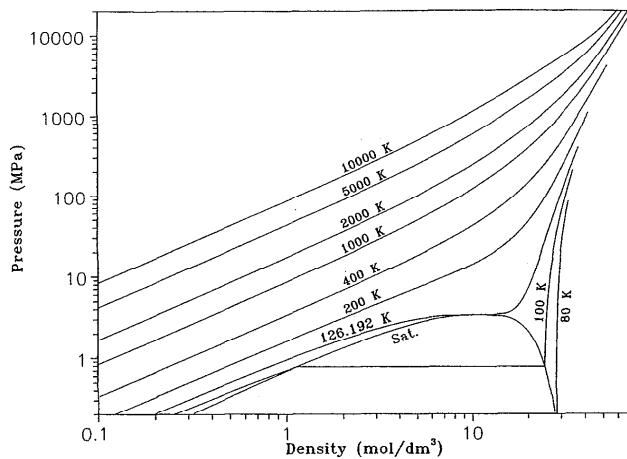


FIG. 38. Pressure versus density diagram.

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

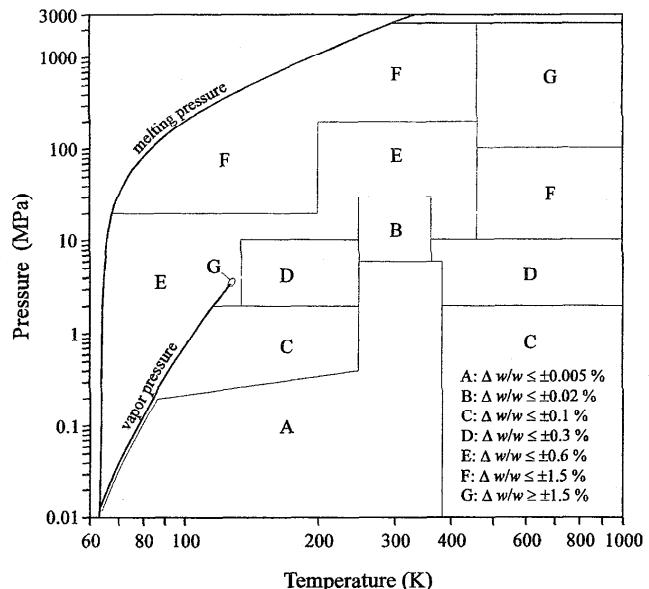


FIG. 40. Estimated uncertainties in the speed of sound for the new equation of state.

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-

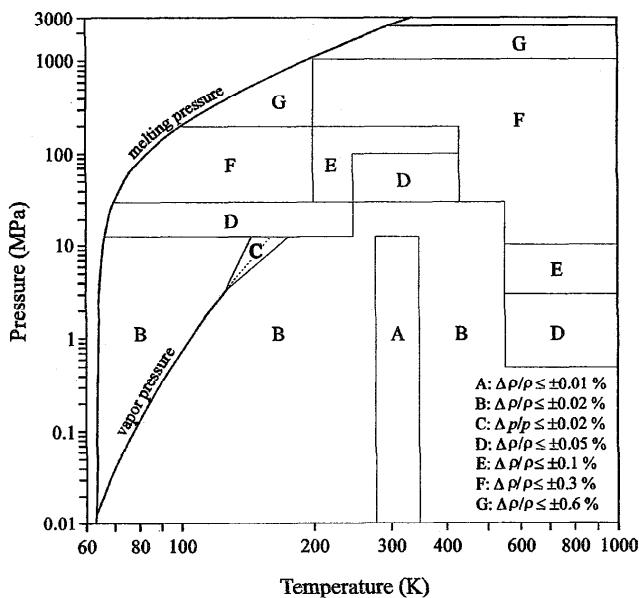


FIG. 39. Estimated uncertainties in density for the new equation of state.

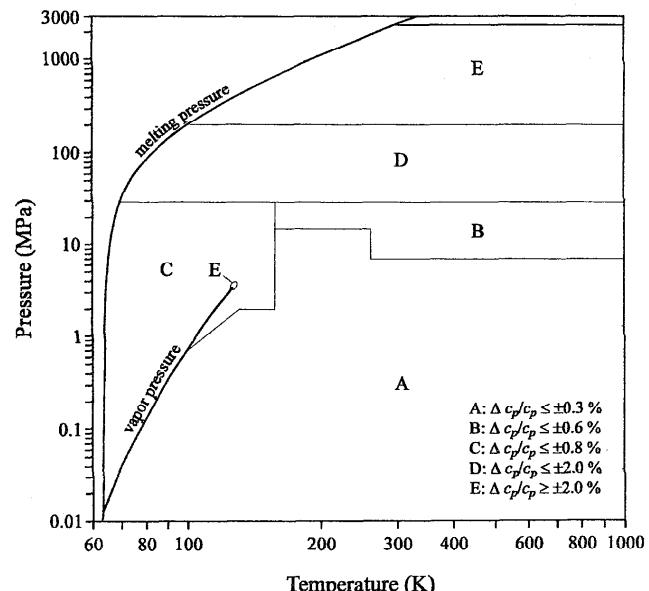


FIG. 41. Estimated uncertainties in the isobaric heat capacity for the new equation of state.

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 $\times 10^{-1}$ | 3.0 | 0.0 |
| 2 | 0.583 733 818 214 | 1.0 | -0.875 | 7 | -0.604 379 290 033 $\times 10^{-1}$ | 3.0 | 2.875 |
| 3 | -0.132 040 812 535 $\times 10^1$ | 1.0 | 1.625 | 8 | 0.567 224 683 248 $\times 10^{-2}$ | 4.0 | -0.125 |
| 4 | 0.854 602 646 673 $\times 10^{-1}$ | 2.0 | 0.125 | 9 | -0.496 167 879 044 $\times 10^{-2}$ | 6.0 | -1.0 |
| 5 | 0.207 794 266 769 | 2.0 | 3.5 | 10 | 0.572 786 635 566 $\times 10^{-2}$ | 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

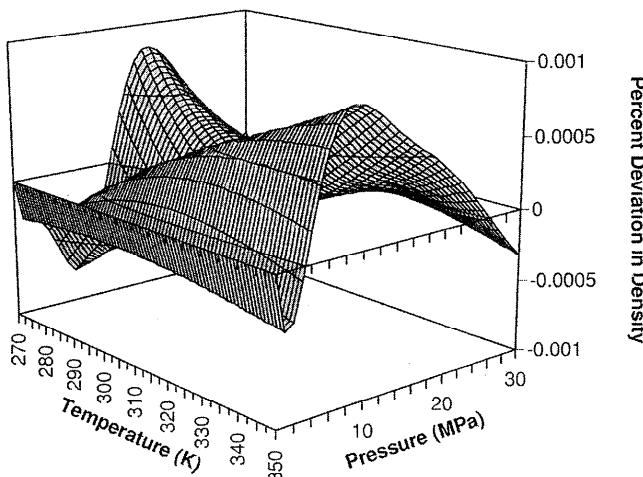


FIG. 42. Comparisons of densities calculated with the calibration equation to densities calculated with the reference equation of state.

$$\frac{c_p^0}{R} = 3.500 571 + 1.115 488 \times 10^{-20} T^7 \quad (98)$$

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

$$\alpha^0 = \ln(\delta) + 2.500 571 \ln(\tau) - 12.769 41 - 0.008 137 875 \tau - 1.015 078 5 \times 10^{-7} \tau^{-7}. \quad (99)$$

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

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

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

$$p = \rho R T \left[1 + \sum_{k=1}^{10} i_k N_k \delta^k \tau^{j_k} \right]. \quad (101)$$

The maximum deviation between values calculated from Eqs. (100) or (101) and those from Eq. (10) is $\pm 0.001\%$ in density in the specified range as shown in Fig. 42. The accompanying maximum deviation in the speed of sound is $\pm 0.002\%$ at pressures less than 7 MPa and $\pm 0.006\%$ 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.

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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

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

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

THERMODYNAMIC PROPERTIES OF NITROGEN

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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 2.6543 | -1157.9 2356.7 | 102.59 133.80 | 27.13 26.79 | 82.87 65.92 | 439.0 179.4 |
| 113.646 | 1.80 | 21.103 2.8441 | -1075.1 2332.2 | 103.28 133.27 | 27.18 27.16 | 85.93 70.18 | 423.5 178.7 |
| 114.641 | 1.90 | 20.779 3.0412 | -993.40 2305.2 | 103.96 132.73 | 27.26 27.56 | 89.38 75.03 | 408.3 178.0 |
| 115.599 | 2.00 | 20.452 3.2462 | -912.52 2275.7 | 104.62 132.20 | 27.35 28.00 | 93.29 80.62 | 393.2 177.3 |
| 116.521 | 2.10 | 20.121 3.4604 | -832.16 2243.5 | 105.27 131.66 | 27.47 28.46 | 97.77 87.11 | 378.3 176.5 |
| 117.412 | 2.20 | 19.785 3.6847 | -752.00 2208.4 | 105.91 131.12 | 27.62 28.96 | 103.0 94.72 | 363.5 175.6 |
| 118.274 | 2.30 | 19.441 3.9209 | -671.73 2170.1 | 106.55 130.58 | 27.80 29.50 | 109.1 103.8 | 348.7 174.7 |
| 119.108 | 2.40 | 19.087 4.1705 | -590.98 2128.5 | 107.18 130.02 | 28.01 30.08 | 116.3 114.7 | 333.9 173.7 |
| 119.916 | 2.50 | 18.722 4.4361 | -509.32 2082.9 | 107.82 129.44 | 28.28 30.70 | 125.2 128.1 | 318.9 172.7 |
| 120.700 | 2.60 | 18.341 4.7207 | -426.24 2032.9 | 108.47 128.84 | 28.61 31.39 | 136.3 145.1 | 303.7 171.6 |
| 121.461 | 2.70 | 17.940 5.0283 | -341.09 1977.6 | 109.13 128.22 | 29.02 32.16 | 150.5 167.0 | 288.2 170.4 |
| 122.200 | 2.80 | 17.514 5.3647 | -252.99 1916.0 | 109.80 127.55 | 29.54 33.03 | 169.6 196.7 | 272.1 169.1 |
| 122.918 | 2.90 | 17.053 5.7382 | -160.69 1846.3 | 110.51 126.84 | 30.22 34.05 | 196.4 238.8 | 255.3 167.6 |
| 123.616 | 3.00 | 16.545 6.1621 | -62.249 1766.0 | 111.26 126.05 | 31.15 35.29 | 237.3 303.2 | 237.6 165.9 |
| 124.295 | 3.10 | 15.964 6.6591 | 45.692 1670.7 | 112.08 125.16 | 32.47 36.87 | 307.0 413.0 | 218.4 163.6 |
| 124.955 | 3.20 | 15.265 7.2755 | 169.91 1551.2 | 113.03 124.08 | 34.50 39.09 | 452.4 640.3 | 197.1 160.5 |
| 125.597 | 3.30 | 14.313 8.1402 | 329.32 1382.8 | 114.25 122.63 | 38.18 42.74 | 930.9 1370. | 171.9 155.4 |
| 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 | δ 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/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 | 1.0573 | 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/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 | 1.2324 | 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 | δ 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 | μ 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. |