An International Standard Equation of State for the Thermodynamic Properties of Refrigerant 123 (2,2-Dichloro-1,1,1-Trifluoroethane)

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A modified Benedict-Webb-Rubin (MBWR) equation of state has been developed for Refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) based on recently measured thermodynamic property data and data available from the literature. Single-phase pressure-volume-temperature (*PVT*), heat capacity, and sound speed data, as well as second virial, vapor pressure, and saturated liquid and saturated vapor density data, were used with multiproperty linear least squares fitting techniques to fit the 32 adjustable coefficients of the MBWR equation. Coefficients for the equation of state and for ancillary equations representing the vapor pressure, saturated liquid and saturated vapor densities, and ideal gas heat capacity are given. While the measurements cover differing ranges of temperature and pressure, the MBWR formulation is applicable along the saturation line and in the liquid, vapor, and supercritical regions at temperatures from 166 to 500 K with pressures to 40 MPa and densities to 11.6 mol/L (1774 kg/m^3). This formulation has been selected as an international standard based on an evaluation of the available equations of state by a group working under the auspices of the International Energy Agency.

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1. Introduction

Refrigerant 123 is a leading candidate to replace the fully halogenated chlorofluorocarbon (CFC) R11, which will be phased out under the Montreal Protocol. R123 is under active worldwide development by several chemical manufacturers working with the refrigeration and air-conditioning industry. It is already seeing widespread commercial use, particularly in large air-conditioning systems.

In this paper we present an equation of state for R123. The thermodynamic properties of a refrigerant have a large influence on the energy efficiency and capacity of refrigeration equipment and are thus essential in evaluating potential alternative refrigerants and for equipment design. An equation of state allows for the correlation and computation of all of the thermodynamic properties in a thermodynamically consistent way, including properties, such as entropy, that cannot be measured directly.

Previous equations of state for R123 include those of McLinden *et al.* (1989), the Japanese Association of Refrigeration (1991), and Piao *et al.* (1992). Since the publication of these formulations, several new data sets for R123 have become available. Most significantly, comprehensive measurements have been completed at the National Institute of Standards and Technology (NIST). These data include the *PVT* measurements of Magee and Howley (1993), the isochoric heat capacities of Magee (1993), the vapor pressures of Weber (1992a), and the speed of sound, ideal gas heat capacity, and virial coefficient data of Goodwin and Moldover (1991). These new data, combined with other work at NIST and elsewhere, prompted us to develop a new formulation for R123.

In view of the importance of R123 and the existence of several competing formulations, it was desirable to settle upon a standard formulation for use by the refrigeration industry. This task has been taken on by a group working under the auspices of the Heat Pump Programme of the International Energy Agency (IEA). The IEA Heat Pump Programme was established in 1978 and is currently supported by fifteen countries. It offers opportunities for international collaboration in research, development, demonstration, and promotion of heat pumping and related technologies. The aim is to accelerate the knowledge, acceptance, and implementation of this energy saving and environmentally important technology. Eight member countries (Austria, Canada, Germany, Japan, Norway, Sweden, the United Kingdom, and the United States) have joined together to form Annex 18—Thermophysical Properties of the Environmentally Acceptable Refrigerants. One of the goals of this Annex (or Programme project) is to provide property formulations that will become de facto international standards for the most important alternative refrigerants.

The comparison and evaluation of the available equations of state for R123 (and also R134a, 1,1,1,2-tetrafluoroethane) was assigned by Annex 18 to two independent groups or *evaluators*: the Center for Applied Thermodynamic Studies (CATS) of the University of Idaho, Moscow, Idaho, USA, under the direction of R.T Jacobsen and S.G. Penoncello, and the IUPAC Thermodynamic Tables Project Centre at Imperial College, London, UK under the direction of M. de Reuck. The CATS and IUPAC groups presented their preliminary evaluations at the July, 1992 meeting of Annex 18. At that meeting, the Annex made recommendations for further comparisons and evaluations and also decided to allow revisions to the equations and additions to the data sets being reviewed, subject to a submission deadline of December, 1992. The final recommendations of the evaluators were presented to the Annex at their April, 1993 meeting. The equation of state presented here was chosen to form the basis for an international properties bulletin for R123. The equation of state of Tillner-Roth and Baehr (1994) was selected for R134a. Details of the evaluation are given by Penoncello *et al.* (1993) and Elhassan *et al.* (1993).

2. Experimental Data

The R123 formulation is based on an extensive set of experimental data. The reported triple point and critical parameters are listed in Table 1. (All temperatures in this work are on the ITS-90; data that were measured on the IPTS-68 have been converted to ITS-90.) The critical temperature and density of Weber and Levelt Sengers (1990), and the critical pressure of Goodwin *et al.* (1992) were chosen for use in the correlations presented here; they are:

$$T_c = 456.831 \text{ K (ITS-90)}, \quad P_c = 36.618 \text{ bar, and}$$
$$\rho_c = 3.596417 \text{ mol/L}.$$

The critical density has been converted from the mass basis of the original source to a molar basis for use in the MBWR equation of state presented below; the accuracy of the measurement does not justify seven significant figures, but it is

important to retain all the digits in the calculations. The triple point is not used directly in any of the correlations but does serve to define their lower temperature limit. The only information that could be located is an undocumented triple-point temperature (166 K) reported by Sukornic (1989).

Saturation data (vapor pressures and saturated-liquid and saturated-vapor densities) and ideal gas heat capacities were used to develop ancillary equations which are described in the next section. The available saturation data are listed in Table 2 and depicted graphically in Figs. 1 and 2. The ancillary equations were used with experimental pressure-volume-temperature (PVT) data, isochoric and isobaric heat capacities, sound speed data, and second virial coefficients, as listed in Table 3 and depicted in Figs. 3 and 4, to develop the equation of state.

Several of the data sets warrant comment. The vapor pressure data listed "calc. from C_σ" in Table 2 are values calculated from the C_σ data of Magee (1993) and an expression for the second virial coefficient based on the data of Goodwin and Moldover (1991) using a variation on a technique described by Weber (1992b). (Weber described how C_σ data could be used to select among conflicting low-temperature vapor pressure data sets: C_σ is calculated from the vapor pressure and its temperature derivative and compared to experimental C_σ data. We start with an initial guess for vapor pressure, calculate C_σ, and use the differences with experimental C_σ data to adjust the vapor pressures; the iteration proceeds until satisfactory agreement is obtained.) The values obtained in this way have an uncertainty of about $\pm1\%$ but are invaluable given the scarcity of accurate experimental vapor pressures significantly below the normal boiling point. The saturated liquid-densities of Magee and Howley (1993) are extrapolations of their single-phase isochoric PVT data to the saturation line; these points were calculated primarily to extend the saturation line to lower temperatures. Finally, the PVT data of Magee (1993) are obtained as a byproduct of his isochoric heat capacity measurements; the uncertainty of these data are

$\pm0.2\%$, compared with the $\pm0.05\%$ uncertainty of the overlapping PVT data measured by Magee and Howley (1993) with an isochoric technique and, thus, were not used in the fit.

3. Ancillary Equations

3.1. Liquid-vapor Saturation Boundary

The MBWR equation of state is expected to accurately represent the vapor pressure and the density of the liquid and vapor at the saturation boundary, and considerable effort is given to reproducing these data. In the development of the equation of state, it is convenient to include the saturation properties by using ancillary equations previously fitted to data. An evaluation of the two-phase data is also part of this process. (The ancillary equations for vapor pressure and saturated liquid and vapor density are used only in the fit. The saturation properties tabulated in the Appendix of this paper are computed directly from the MBWR equation of state.)

The vapor pressure P_σ was fit to the function

$$\ln(P_\sigma/P_c) = \frac{\alpha_1\tau + \alpha_2\tau^{1.5} + \alpha_3\tau^2 + \alpha_4\tau^4 + \alpha_5\tau^{6.5}}{1 - \tau} \tag{1}$$

where $\tau = 1 - T/T_c$, T_c is the critical temperature, and P_c is the critical pressure. The form of Eq. (1) was developed using a simulated annealing technique described by Huber (1994); it was selected from several that were studied. Eq. (1) is applicable from 180 K to the critical temperature. The coefficients of Eq. (1) are given in Table 4.

The deviations of the ancillary function from the vapor pressure data are shown in Fig. 5. The fit is described in terms of two statistics. The bias is defined as:

$$bias = \frac{1}{n} \sum_{i=1}^{n} 100(x_{i,\text{calc}} - x_{i,\text{exp}})/x_{i,\text{exp}} \tag{2a}$$

TABLE 1. Reported critical point parameters and triple point temperature for R123

Source	Temperature[1] (K)	Pressure (MPa)	Density (kg/m³)
Critical point			
Fukushima et al. (1990)	456.901 ± 0.04[2]	3.672 ± 0.005	553 ± 5
Goodwin et al. (1992)	—	3.6618 ± 0.0003	—
Maezawa et al. (1990)	456.82 ± 0.02	—	556
Piao et al. (1991)	—	3.6655 ± 0.003	—
Tanikawa et al. (1990)	456.82 ± 0.02	—	556 ± 3
Weber & Levelt Sengers (1990)[3]	456.831 ± 0.03	3.668 ± 0.004	550 ± 4
Yamashita et al. (1989)	456.92 ± 0.05	3.675 ± 0.005	—
Triple point			
Sukornic (1989)	166.	—	—

[1]The temperatures reported in the source papers were on the IPTS-68; the values listed here have been converted to the ITS-90.
[2]The uncertainties are those reported by the respective authors and represent different measures.
[3]The critical pressure listed in the paper by Weber & Levelt Sengers was printed in error; the correct value reported by Goodwin et al. (1992) is listed here.

where the summation is over the n data points and the subscripts *exp* and *calc* refer to experimental and calculated values. The bias is a measure of any systematic deviation of the correlation with the data. The standard deviation

$$S.D. = \left\{\frac{1}{n-1} \sum_{i=1}^{n} \left(100(x_{i,\text{calc}} - x_{i,\text{exp}})/x_{i,\text{exp}} - bias\right)^2\right\}^{1/2} \quad (2b)$$

is a measure of the scatter of the data about the bias. The biases and standard deviations of the individual data sets used in the fit are given in Table 2; also listed are the total number of experimental points published and those actually used in the fit under the column labeled "no. of points total/used".

The saturated liquid density is represented in terms of the commonly used function

$$\rho_l = \rho_c(1 + d_1\tau^\beta + d_2\tau^{2/3} + d_3\tau + d_4\tau^{4/3}), \quad (3)$$

where β, an empirical exponent is 0.355, τ is as defined above, and ρ_c is the critical density. The coefficients of Eq. (3) are given in Table 4. This equation is valid from the triple point temperature of 166 K to the critical point. Although there is a fair amount of scatter in the data, the equation fits the data well as shown in Fig. 6. The bias is very small, 0.001%; the standard deviation of the fit is 0.07%. Again, the statistics for the individual data sets are given in Table 2.

The saturated vapor densities were fit to the form:

$$\rho_v = \frac{P_\sigma}{RT}\left\{1 + y\frac{P_\sigma T_c}{P_c T}(Z_c-1)\right\}^{-1}, \quad (4)$$

TABLE 2. Summary of saturation and ideal gas heat capacity data for R123

Source	No. of points Total/used	Temperature range (K)	Dev. from anc. eq. (%) bias	S.D.
Vapor pressure				
calc. from C_σ[1]	9/0	170–250	n.a.	n.a.
Fukushima (1990)	65/0	314–456	n.a.	n.a.
Fukushima (1991)	2/0	425–442	n.a.	n.a.
Goodwin et al. (1992)[2]	69/69	256–454	0.00	0.017
Goodwin et al. (1992)[3]	34/0	300–374	n.a.	n.a.
Kubota et al. (1989)	37/0	273–454	n.a.	n.a.
Weber (1990)	43/0	338–453	n.a.	n.a.
Weber (1992a)	14/0	272–308	n.a.	n.a.
Yamashita et al. (1989)	39/0	273–453	n.a.	n.a.
Saturated liquid density				
Fukushima (1990)	2/0	425–442	n.a.	n.a.
Fukushima et al. (1990)	15/0	392–456	n.a.	n.a.
Fukushima (1991)	10/10	281–352	0.02	0.10
Maezawa et al. (1990)	23/0	280–400	n.a.	n.a.
Magee & Howley (1993)[4]	8/8	174–328	−0.02	0.08
Morrison & Ward (1992)	16/8	280–373	0.06	0.13
Oguchi & Takaishi (1989)	10/10	254–343	−0.25	0.06
Schmidt (1989)	3/3	274–293	−0.08	0.06
Tanikawa et al. (1990)	13/0	401–455	n.a.	n.a.
Weber & Levelt Sengers (1990)	17/16	299–456	−0.01	0.19
Saturated vapor density				
Fukushima et al. (1990)	14/0	438–456	n.a.	n.a.
Tanikawa et al. (1990)	10/0	439–457	n.a.	n.a.
Weber & Levelt Sengers (1990)	7/7	433–453	0.35	0.45
calculated from virials of Weber (1990)[5]	7/7	340–400	0.02	0.07
calculated from virials of Goodwin (1991)[5]	7/7	260–320	0.01	0.01
Ideal gas heat capacity				
Goodwin & Moldover (1991)	6/6	260–335	0.00	0.08
Luft (1954)	7/3	200–800	0.01	0.01

[1]Vapor pressures calculated from C_σ data (see text).
[2]Vapor pressures measured with the compartive ebulliometer and the Burnett systems.
[3]Vapor pressures measured with the sapphire cell ebulliometer system.
[4]Isochoric PVT data extrapolated to saturation.
[5]Calculated by intersection of virial surface with vapor pressure equation.
n.a. – not applicable (data not used in correlation)
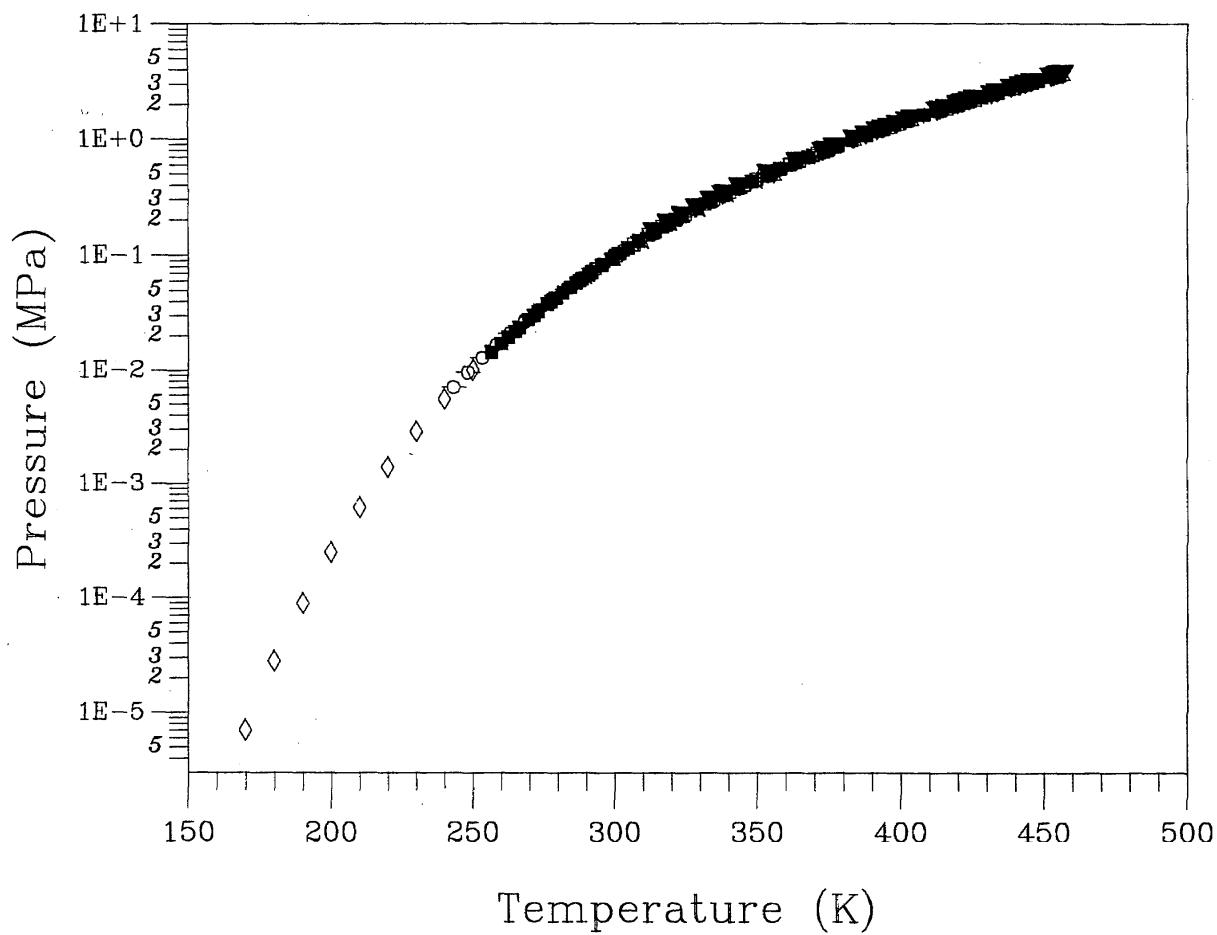
FIG. 1. Summary of experimental data for vapor pressure: data of Fukushima ($\triangle$), Goodwin *et al.* comparative ebulliometer and static vapor pressure ($\blacksquare$), Goodwin *et al.* sapphire ebulliometer ($\sqcup$), Kubota *et al.* ($\times$), Maezawa *et al.* ($\star$), Oguchi *et al.*, ($\ominus$), Weber, 1990 ($\triangle$), Weber, 1992 ($\triangledown$), Yamashita *et al.* (+), and data derived from the C_σ of Magee ($\diamond$). Filled symbols indicate data used in fitting.
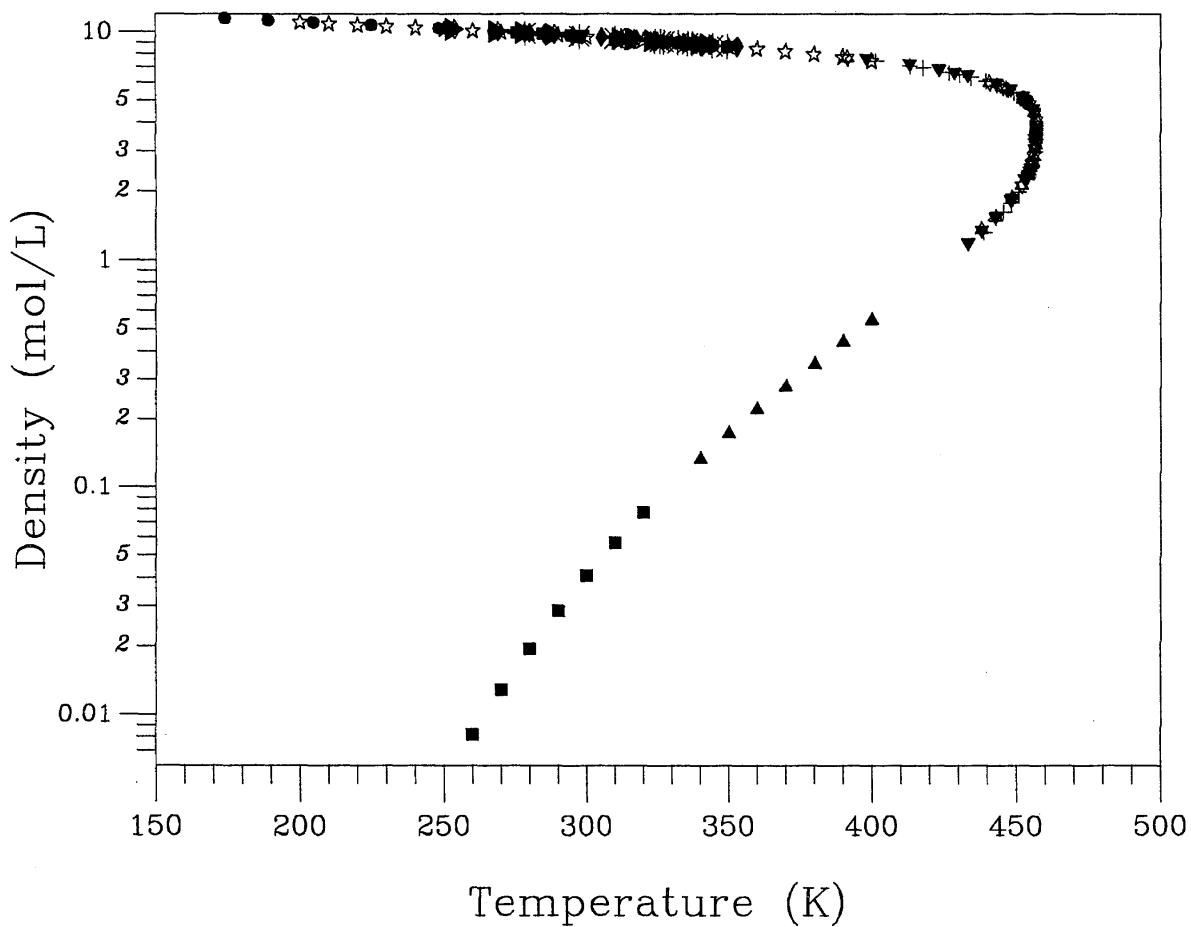
FIG. 2. Summary of data for saturated liquid and vapor densities. Data of Fukushima *et al.* (☆), Magee and Howley (●), Maezawa *et al.* (★), Morrison and Ward (◆) and (◇), Oguchi and Takaishi (✳), Schmidt (✦), Tanikawa (+), Weber and Levelt Sengers (▽), values computed from the virial coefficients of Goodwin and Moldover (■), and from Weber virials (▲). Filled symbols indicate data used in fitting.

where P_σ is the saturation pressure, R is the gas constant, and Z_c is the critical compressibility factor:

$$Z_c = \frac{P_c}{RT_c\rho_c} \; . \tag{5}$$

The factor y is defined as

$$y = 1 + (1 - T_r)^\beta \; (g_1 + g_2T_r + g_3T_r^2 + g_4T_r^3) \; , \tag{6}$$

where $T_r = T/T_c$ is the reduced temperature. There are only limited direct measurements of the saturated vapor density for R123 and no direct measurements at all below 433 K, and, thus, values calculated by the intersection of the virial surfaces of Weber (1990) and of Goodwin and Moldover (1991) with the vapor pressure ancillary equation were used at lower temperatures. A comparison of the ancillary equation with the measured and calculated points is shown in Fig. 7. The overall bias and standard deviation of the fit are 0.02% and 0.18%. These statistics are higher than the fit of the vapor pressure and saturated liquid density due, in part, to the difficulty of measuring saturated vapor density. Fortunately, saturated vapor density is not critical to the development of the MBWR equation of state, and it was given a low weight in the fit of the equation of state. Although far from perfect, Eq. (4) was superior to several other correlating functions investigated, primarily because of its behavior at the extremes of temperature: it gives the correct behavior in the critical region and approaches the ideal gas limit at low temperatures.

3.2. Ideal gas heat capacity

The ideal gas is used as a reference state for the equation of state. The ideal gas heat capacity was fitted to a simple polynomial in reduced temperature:

$$C_P^\circ = R(c_0 + c_1T_r + c_2T_r^2 + c_3T_r^3) \; . \tag{7}$$

The fit is based primarily on the values of Goodwin and Moldover (1991) computed from their speed of sound data. In addition, Luft's (1954) values at 200, 400, and 500 K were also included in the fit at a low weight to extend the temperature range of the fit. The bias of Eq. (7) is 0.00% and the standard deviation is 0.06%.

4. MBWR Equation of State

The modified Benedict-Webb-Rubin (MBWR) equation of state as described by Jacobsen and Stewart (1973) has been used to represent the thermodynamic properties of R123. The MBWR equation is applicable over wide ranges of temperature and pressure and has wide acceptance in representing fluid properties, including hydrocarbons (Younglove and Ely, 1987), cryogenic fluids (Younglove, 1982), and refrigerants (Huber and McLinden, 1992). The MBWR equation is capable of high accuracy and is flexible enough to fit the liquid,

TABLE 3. Summary of *PVT*, specific heat, and sound speed data for R123

Source	No. of points Total/used	T (K)	Range of data P (MPa)	ρ (mol/L)	Deviation from MBWR (%) bias	S.D.
Pressure-Volume-Temperature						
Fukushima (1990)	58/0	359–484	0.47–5.2	0.18–6.7	n.a.	
Maezawa (1989)	10/10	280–340	1.0–2.0	8.8–9.9	0.174	0.077
Magee (1993)	87/0	194–343	0.6–35	9.3–11.2	n.a.	
Magee & Howley (1993)	104/104	176–380	0.8–35	9.0–11.5	0.015	0.019
Morrison & Ward (1993)	69/65	280–364	0.4–3.8	8.3–9.9	0.048	0.041
Oguchi *et al.* (1991)	35/33	352–493	0.8–16	1.8–8.6	−0.051	0.107
Piao *et al.* (1991)	134/0	311–523	1.2–12	0.6–9.4	n.a.	
Weber (1989)	75/75	358–453	0.16–2.8	0.05–1.2	0.038	0.044
Isochoric heat capacity						
Magee (1993)—C_v	79/79	196–341	3.1–33	9.4–11	−0.73	0.65
Magee (1993)—C_σ	90/90	167–304	0.0–1.1	9.5–12	−0.09	0.32
Isobaric heat capacity						
Nakagawa (1991)	145/0	276–440	0.5–3.2	6.1–10	−1.37	0.30
Speed of sound						
Goodwin & Moldover (1991)	42/42	260–335	0.002–0.077	0.001–0.028	−0.001	0.004
Takagi (1991)	201/46	283–373	0.1–13.2	8.4–10	0.11	1.10
Second virial coefficient						
Goodwin & Moldover (1991)	12/12	260–453	n.a.	n.a.	0.57[1],	1.0[2]

[1]Bias in (L/mol)×1000
[2]Absolute average deviation in (L/mol)×1000
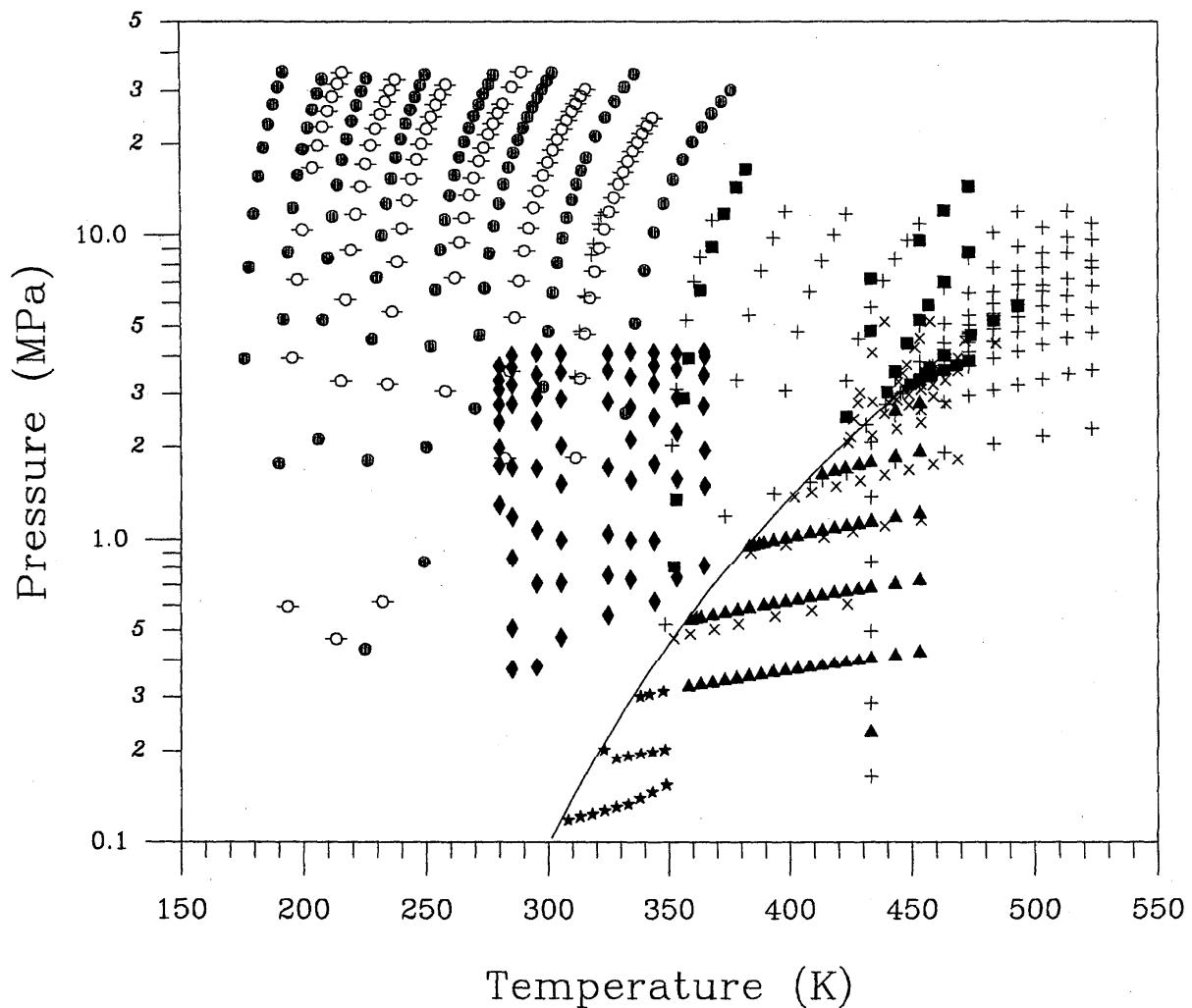
FIG. 3. Summary of experimental *PVT* data: data of Fukushima *et al*. (×), Maezawa (★), Magee and Howley (●), Magee (-O-), Morrison and Ward (♦), Oguchi *et al*. (■), Piao (+), and Weber (▲). The filled symbols, ★ ● ♦ ■ ▲ refer to data used in the MBWR fit. The solid line is the two-phase boundary.
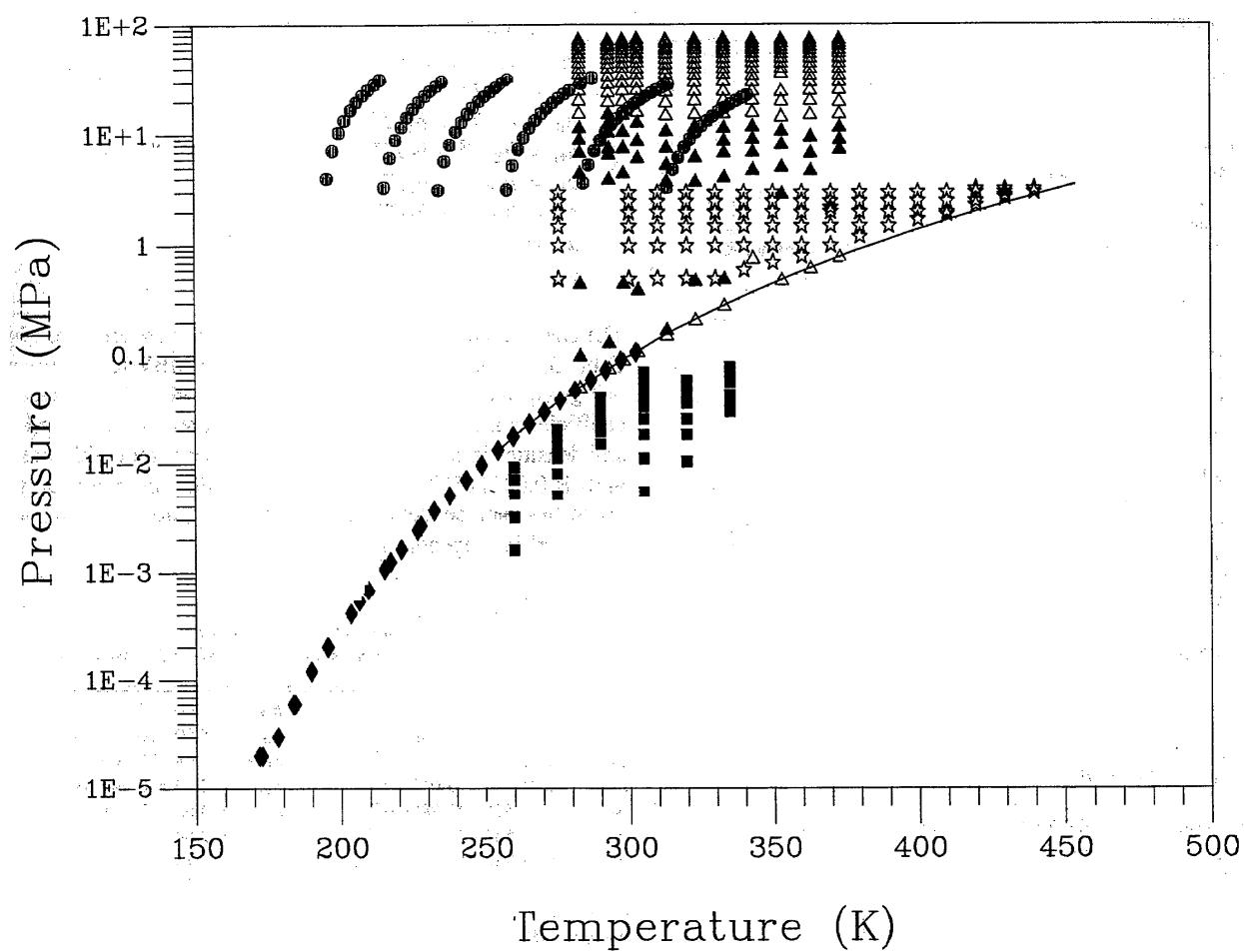
FIG. 4. Summary of experimental specific heat and sound speed data. The C_v and C_σ data of Magee (●) and (◆), the C_p data of Nakagawa et al. (☆), and the sound speed data of Goodwin and Moldover (■), and of Takagi et al. (▲) and (△). The filled symbols indicate data used in the fit of the MBWR equation. The solid line is the two-phase boundary.

TABLE 4. Coefficients and related constants for the ancillary equations and C

Critical parameters

T_c	456.831 K (ITS-90)
P_c	3.6618 MPa or 36.618 bar
ρ_c	3.596 417 mol/L

Relative molecular mass

M	152.930 g/mol

Gas constant

R	8.314 510 J/(mol·K) or 0.083 145 10 L·bar/(mol·K)

Vapor pressure, Eq. 1 (all coefficients dimensionless)

α_1	−7.447 552 68
α_2	2.222 058 28
α_2	−1.900 077 22
α_4	−3.194 718 27
α_5	−1.299 823 16

Saturated liquid density, Eq. 3 (all coefficients dimensionless)

β	0.355
d_1	2.032 125 41
d_2	0.615 138 615
d_3	−0.780 309 375
d_4	0.953 698 023

Saturated vapor density, Eq. 4–6 (all coefficients dimensionless)

β	0.355
g_1	19.364 572 3
g_2	−61.801 376 8
g_3	68.045 857 3
g_4	−26.476 017 6

Ideal gas heat capacity, Eq. 7 (all coefficients dimensionless)

c_0	2.046 009
c_1	22.231 991
c_2	−11.658 491
c_3	2.691 665

vapor, and supercritical regions of a fluid as well as the saturation line. We selected the MBWR equation because of our familiarity with it and, just as importantly, its proven performance. This second point cannot be neglected, because, although there is an extensive data set for R123, there are also gaps in the data. With the MBWR equation, we felt confident that the thermodynamic surface would reasonably interpolate and extrapolate across regions where data were scarce or nonexistent.

The MBWR equation represents the pressure P as a function of the absolute temperature T and the molar density ρ:

$$P = \sum_{n=1}^{9} a_n \rho^n + \exp(-\delta^2)\sum_{n=10}^{15} a_n \rho^{2n-17} , \tag{8}$$

where $\delta = \rho/\rho_c$, ρ_c is the critical density, and the temperature dependence of the coefficients is given by

$$a_1 = RT$$
$$a_2 = b_1T + b_2T^{1/2} + b_3 + b_4/T + b_5/T^2$$
$$a_3 = b_6T + b_7 + b_8T + b_9/T^2$$

$$a_4 = b_{10}T + b_{11} + b_{12}/T$$
$$a_5 = b_{13}$$
$$a_6 = b_{14}/T + b_{15}/T^2$$
$$a_7 = b_{16}/T$$
$$a_8 = b_{17}/T + b_{18}T^2$$
$$a_9 = b_{19}/T^2$$
$$a_{10} = b_{20}/T^2 + b_{21}/T^3$$
$$a_{11} = b_{22}/T^2 + b_{23}/T^4$$
$$a_{12} = b_{24}/T^2 + b_{25}/T^3$$
$$a_{13} = b_{26}/T^2 + b_{27}/T^4$$
$$a_{14} = b_{28}/T^2 + b_{29}/T^3$$
$$a_{15} = b_{30}/T^2 + b_{31}/T^3 + b_{32}/T^4 . \tag{9}$$

The coefficients to the MBWR equation of state are given in Table 5. To maintain consistency with the MBWR equations our group has developed in the past for other fluids, these coefficients are based on pressures in bar, temperatures in K, and densities in mol/L; the gas constant consistent with these units is 0.08314510 L·bar/(mol·K). All other thermodynamic properties can be determined by the equation of state, as described in Appendix A.

TABLE 5. Coefficients for the MBWR equation of state. The units are temperature in kelvins, pressure in bar, and density in mol/L.

b_1	= − 6.57 453 133 659·10⁻³	b_{17}	= − 1.06 148 632 128·10⁻¹
b_2	= 2.93 479 845 842	b_{18}	= 5.00 026 133 667·10¹
b_3	= − 9.89 140 469 845·10¹	b_{19}	= − 2.04 326 706 346
b_4	= 2.01 029 776 013·10⁴	b_{20}	= − 2.49 438 345 685·10⁶
b_5	= − 3.83 566 527 886·10⁶	b_{21}	= − 4.63 962 781 113·10⁸
b_6	= 2.27 587 641 969·10⁻³	b_{22}	= − 2.84 903 429 588·10⁵
b_7	= − 9.08 726 819 450	b_{23}	= 9.74 392 239 902·10⁹
b_8	= 4.34 181 417 995·10³	b_{24}	= − 6.37 314 379 308·10³
b_9	= 3.54 116 464 954·10⁶	b_{25}	= 3.14 121 189 813·10⁵
b_{10}	= − 6.35 394 849 670·10⁻⁴	b_{26}	= − 1.45 747 968 225·10²
b_{11}	= 3.20 786 715 274	b_{27}	= − 8.43 830 261 449·10⁶
b_{12}	= − 1.31 276 484 299·10³	b_{28}	= − 2.41 138 441 593
b_{13}	= − 1.16 360 713 718·10⁻¹	b_{29}	= 1.08 508 031 257·10³
b_{14}	= − 1.13 354 409 016·10¹	b_{30}	= − 1.06 653 193 965·10⁻²
b_{15}	= − 5.37 543 457 327·10³	b_{31}	= − 1.21 343 571 084·10¹
b_{16}	= 2.58 112 416 120	b_{32}	= − 2.57 510 383 240·10²

4.1. Development of the Equation of State

The coefficients of the MBWR equation are found by linear least squares fitting. Several thermodynamic properties such as PVT, heat capacity, and sound speed data are fitted simultaneously. As mentioned before, the saturation boundary is also included in the fit by means of ancillary equations.

Since sound speed is nonlinear, it is included in the fit in a two-step process. In the first iteration, values of the isothermal derivative $(\partial P/\partial \rho)_T$ are evaluated and then included as input data in the fit in the second iteration. This process is then repeated until the change in the values of the derivative are minimal. Thus, the nonlinear behavior of sound speed is avoided.

The final values of the coefficients for the MBWR equation, or "the fit," are arrived at after many trials. A consid-
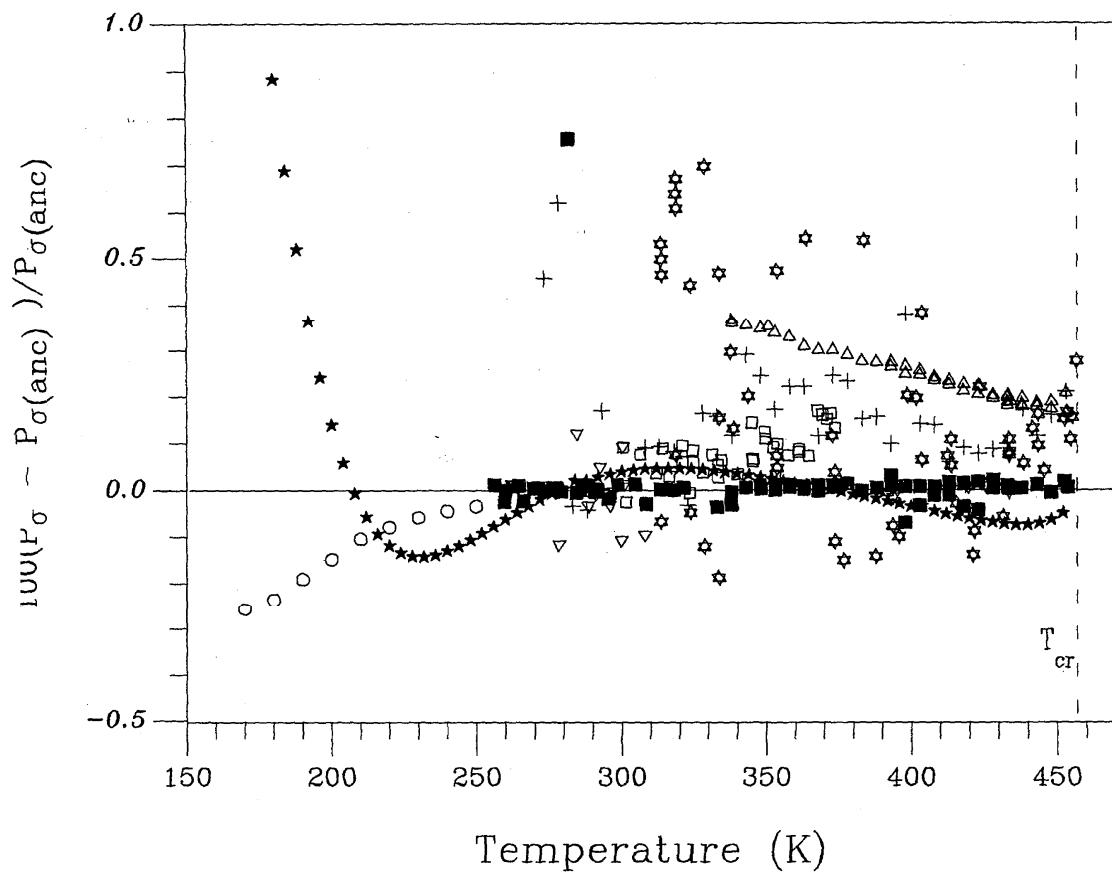
FIG. 5. Deviations of vapor pressures from the ancillary equation for vapor pressure (Eq. 1). Data of Fukushima (✿), Goodwin *et al.* comparitive ebulliometer and static vapor pressure (■), Goodwin *et al.* sapphire ebulliometer (□), Weber, 1990 (△), Weber, 1992 (▽), Yamishita *et al.* (+), values computed from the C_σ of Magee (○), values computed from the MBWR eqn. (★). The location of the critical point is indicated by T_{cr}.
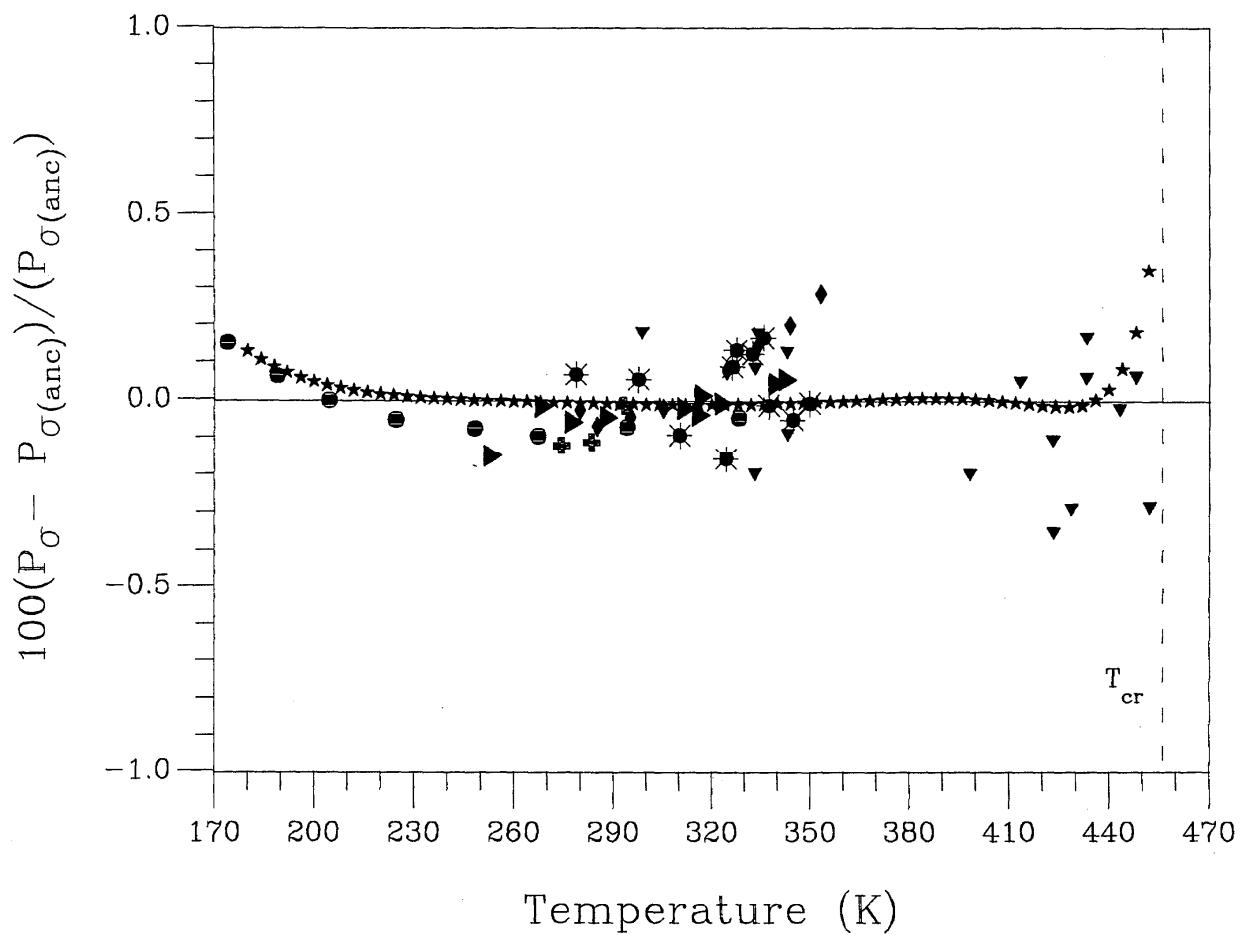
FIG. 6. Deviations of saturated liquid densities from the ancillary equation (Eq. 3). Data of Fukushima *et al.* (✳), Morrison and Ward (◆), Oguchi and Takaishi (▲), Schmidt (✚), Weber and Levelt Sengers (▼), data extrapolated from the *PVT*) data of Magee and Howley (●), and MBWR values (★). The location of the critical point is indicated by T_{cr}.

erable amount of attention is given to the weighting of the various sets of data and their effect on the fit of other sets of data. During fitting, deviations of the computed values of density, heat capacity, sound speed, etc. from the experimental values of the various sets of data are analyzed and are used to help in the decision making for the next step in the fitting process.

The weights are computed using routines developed by Hust and McCarty (1967) and are based on the reported values of the uncertainty of pressure, temperature, sound speed, etc. In addition, the weights are adjusted by biasing this computation. At the outset of the fitting a bias value of weights are assigned to each type of data, such as PVT or C_v data. As the fitting proceeds, these bias values are adjusted.

Certain data points are excluded from the fitting. The first consideration is whether they lie within the two-phase boundary. This set of points may change as the derived PVT surface changes with the iteration of the fit. Other data points are excluded if their deviation from the surface is so large as to be judged obviously erroneous.

4.1.1. Saturation Boundary

The vapor pressures computed using the MBWR equation of state together with the Maxwell criteria closely follow both the experimental data and the ancillary function as shown in Fig. 5. There is a small systematic deviation at temperatures below about 200 K with a maximum deviation of 0.6%. The overall standard deviation of the MBWR equation with the ancillary function, Eq. (1), is 0.04%.

The saturated liquid densities calculated with the MBWR equation also fit the data very well as shown in Fig. 6. The equation of state actually fits the experimental data at temperatures below 200 K better than the ancillary function. The overall standard deviation of the MBWR equation with the ancillary function, Eq. (3), is 0.07%.

The fit of the saturated vapor densities is not as good, with a standard deviation with the ancillary function, Eqs. (4–6), of 0.18% and a deviation of 0.6% near the critical point; see Fig. 7. But, as noted above, the saturated vapor densities are given very low weight in the fit. Given the difficulty of measuring saturated vapor densities, the fit of the vapor-phase PVT data, described below, is a much better indicator of the quality of the fit in this region.

4.1.2. Single-phase PVT Data and Second Virial Coefficients

The most important data employed in the fit of the equation of state were the pressure-volume-temperature (PVT) data. The available PVT data are listed in Table 3 along with deviations with the equation of state. Comparisons of experimental and calculated densities are plotted as a function of pressure in Fig. 8 for data used in the fit. The fit is excellent. The compressed liquid PVT data of Magee and Howley (1993) have a standard deviation of 0.02%. The vapor phase data of Weber (1990) and Maezawa (1990) show slightly higher deviations. The maximum deviation of 0.57% is seen with the near-critical region data of Oguchi et al. (1991). Fig. 9 shows a similar comparison for data sets not used in the fit. As

expected, these sets show greater deviations, but most of the points are within ±1.0%, and only a few near-critical points of Piao et al. (1991) and Fukushima (1990) show deviations greater than 2.0%.

Comparisons of the PVT data with the equation of state are shown in greater detail in Fig. 10. The left side of this figure shows a series of deviation plots versus pressure for a number of temperature ranges for those data measured along isotherms. The right side of the figure shows a similar set of deviation plots for a number of density ranges for data measured along isochores (lines of constant volume). No systematic deviations are seen with the isothermal data; these data are all in the relatively low pressure vapor region. The isochoric data show considerably more scatter at densities below 5 mol/L. The scatter in the range 2–5 mol/L is greatest at pressures of 3–5 MPa, in other words, in the immediate vicinity of the critical point; this result is not at all unexpected. The lower density (and pressure) data of Fukushima et al. (1990) show considerable scatter and are inconsistent with the overlapping (isochoric) data of Weber (1990); we chose the data of Weber for the fit.

The second virial coefficients of Goodwin and Moldover (1991) were also included in the fit of the equation of state. Virial coefficients are, in some sense, nearly equivalent to low-density vapor-phase PVT data for fitting purposes. The values of Goodwin and Moldover were derived from their speed of sound measurements and were represented with an absolute average deviation of 0.001 L/mol; this data set was particularly valuable because it extends down to a temperature of 260 K, approximately 50 K lower than the vapor PVT data.

4.1.3. Heat Capacity and Speed of Sound Data

The heat capacity and speed of sound are computed using derivatives of the equation of state, and, thus, are powerful consistency checks. The isochoric single phase C_v and two-phase C_σ heat capacities of Magee (1993) were included in the fit. The deviations of the calculated values with experimental points are shown in Fig. 11. The standard deviation is 0.65% for the C_v points and 0.32% for the C_σ points. A systematic offset, indicated by a bias of −0.73%, is seen for the C_v points. These deviations are somewhat greater than the ±0.5% uncertainty of the measurements. The isobaric C_p data of Nakagawa et al. (1991) were not included in the fit but were reproduced well with a bias of −1.4% and a standard deviation of 0.30%.

A comparison of calculated and experimental speed-of-sound results is shown in Fig. 12. The vapor phase data of Goodwin and Moldover (1991) are fitted extremely well (bias of −0.001% and standard deviation of 0.004%). This result is not altogether surprising: these data are at very low pressures where the fluid is nearly an ideal gas; furthermore, they were the primary data used in determining the ideal gas heat capacity. The compressed liquid speed-of-sound data of Takagi (1991) extend to pressures of 75 MPa. We had no other data above pressures of about 35 MPa and, thus, gave zero weight to the higher pressure points of Takagi (experience has shown that attempting to extend the range of the fit into a region where only speed of sound or heat capacity data are available
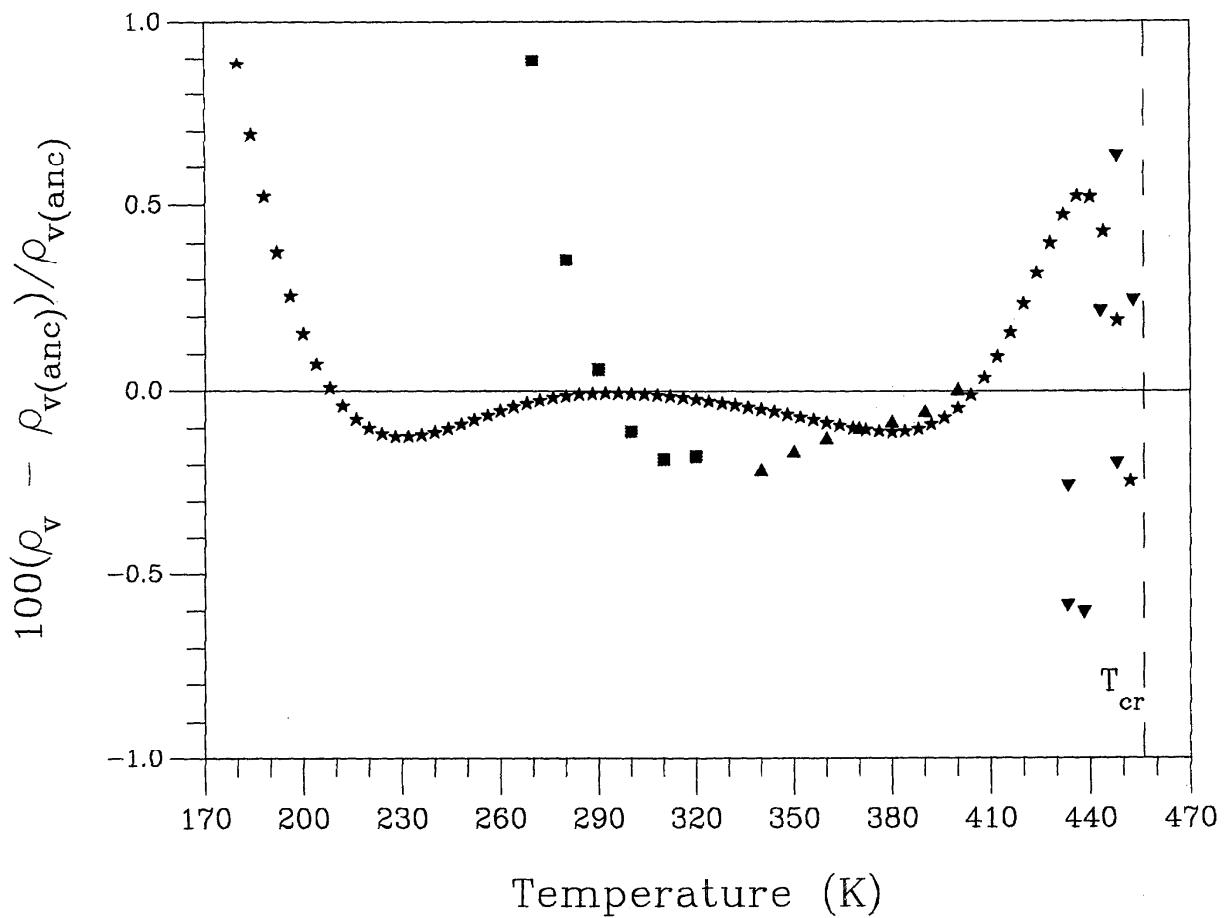
FIG. 7. Deviations of saturated vapor densities from the vapor densities computed using the ancillary equation (Eq. 4). Values computed from virial coefficients of Goodwin & Moldover (■), extrapolated values from the *PVT* data of Weber (▲), data of Weber & Levelt Sengers (▼), MBWR values (★). The critical point is indicated by T_{cr}.
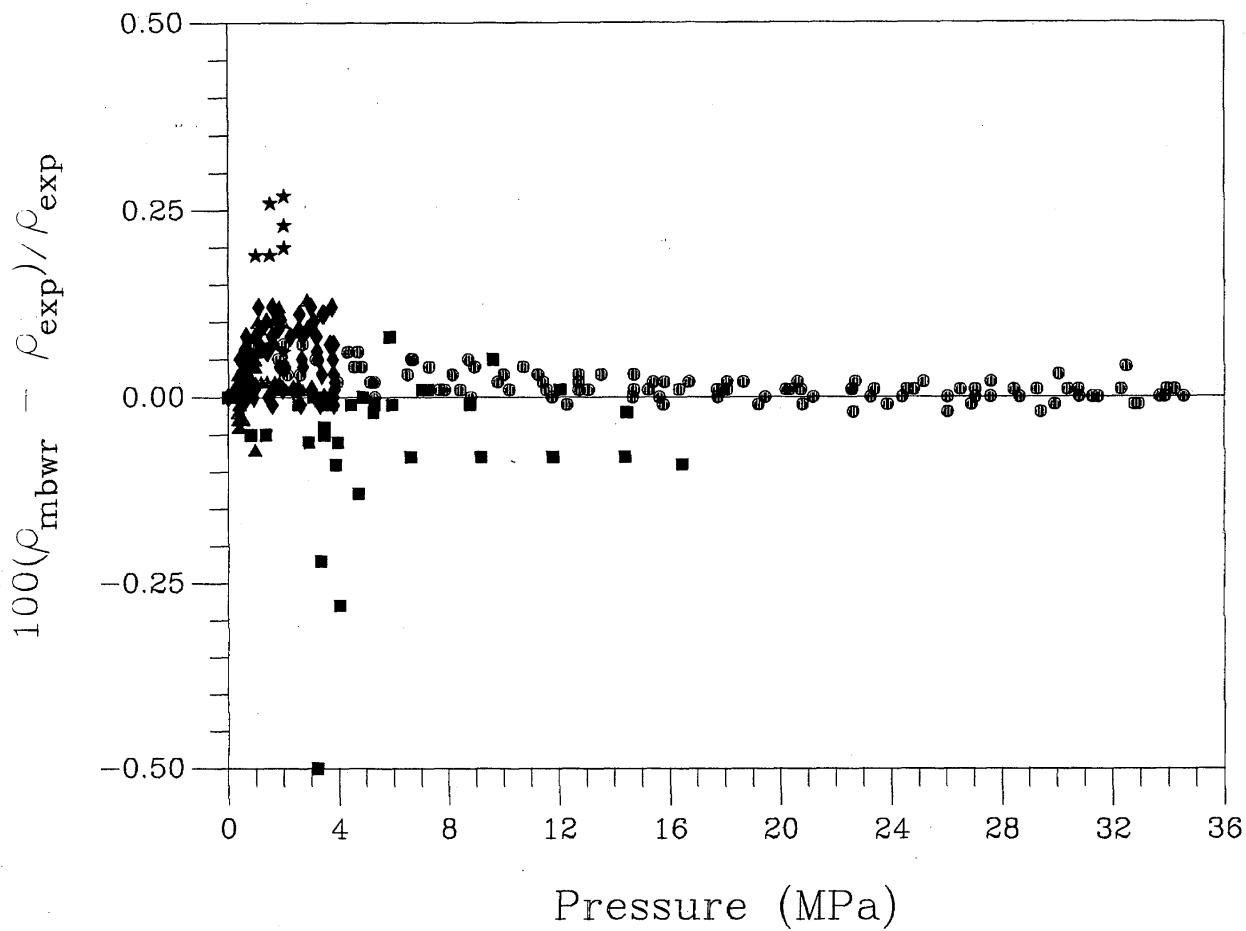
FIG. 8. Deviations of densities computed using the MBWR equation from the experimental data used in the fit of the MBWR eqn.: Maezawa *et al*. (★), Magee and Howley (●), Morrison & Ward (◆), Oguchi *et al*. (■), and Weber (▲).

can adversely affect the fit in other regions). The liquid speed-of-sound data show a strong systematic deviation with temperature with a bias of −0.1% and a standard deviation of −1.1%; attempts to improve the fit of these data by increasing their weight adversely affected the fit of other properties.

4.1.4. Pressure-Temperature Behavior of Heat Capacity and Speed of Sound

The comparisons of properties calculated from the MBWR equation of state with experimental data indicates a very good fit overall. An additional and severe test of the quality of the thermodynamic surface is provided by examining the behavior of the surface over very wide ranges of temperature and pressure. For this purpose, plots of the derived properties (properties computed using first and second derivatives of the equation of state) are most valuable.

Figs. 13–15 show the behavior of the isochoric and isobaric heat capacities and the speed of sound plotted along lines of constant pressure up to 40 MPa at temperatures from 166 to 600 K, i.e., from the triple point to more than 70 K above the highest experimental temperature. These plots display correct qualitative behavior (based on experience with a wide variety of other fluids) over the entire range with two minor exceptions. The isobaric heat capacity and the speed of sound show an unexpected ''crossing'' of the isobars at a temperature of about 180 K in the liquid phase; there is also an unexpected inflection in the isochoric heat capacity in this same region. Secondly, the speed of sound does not go to zero at the critical point as it should; this defect is common with analytical equations of state. These plots reveal that heat capacities and the speed of sound are not accurately represented in the liquid phase below about 200 K and in the immediate vicinity of the critical point.

5. Summary and Conclusions

New PVT, heat capacity, and speed-of-sound data measured at NIST and elsewhere have been used along with previously published PVT and saturation data to represent the thermodynamic properties of R123 in terms of a modified Benedict-Webb-Rubin (MBWR) equation of state with 32 adjustable coefficients. The data cover the general temperature range of 170–525 K with pressures to 35 MPa. The overall representation of the data is excellent with a bias and standard deviation for data used in the fit of 0.04% and 0.07%, respectively, for PVT, −0.73% and 0.65% for isochoric heat capacity, 0.00% and 0.06% for vapor pressure, and −0.01% and 0.04% for saturated liquid density. Examination of the behavior of the thermodynamic surface reveals that heat capacities and the sound speeds in the liquid phase are not accurately represented below about 180 K. Uncertainties are also larger in the critical region, which is bounded by densities of 2 and 5 mol/L, and with an upper temperature of 460 K and an upper pressure of 5 MPa. But, apart from these exceptions, the MBWR equation of state accurately represents the entire thermodynamic surface from the triple point (166 K) to 500 K for pressures to 40 MPa and densities to 11.6 mol/L (1774 kg/m^3); the equation of state also displays reasonable behavior upon extrapolation to 600 K.

This formulation has been selected as an international standard based on an evaluation of the available equations of state for R123 by a group working under the auspices of the International Energy Agency. It covers the entire range of interest for all refrigeration applications of this fluid and exceeds the accuracy requirements for most engineering calculations.
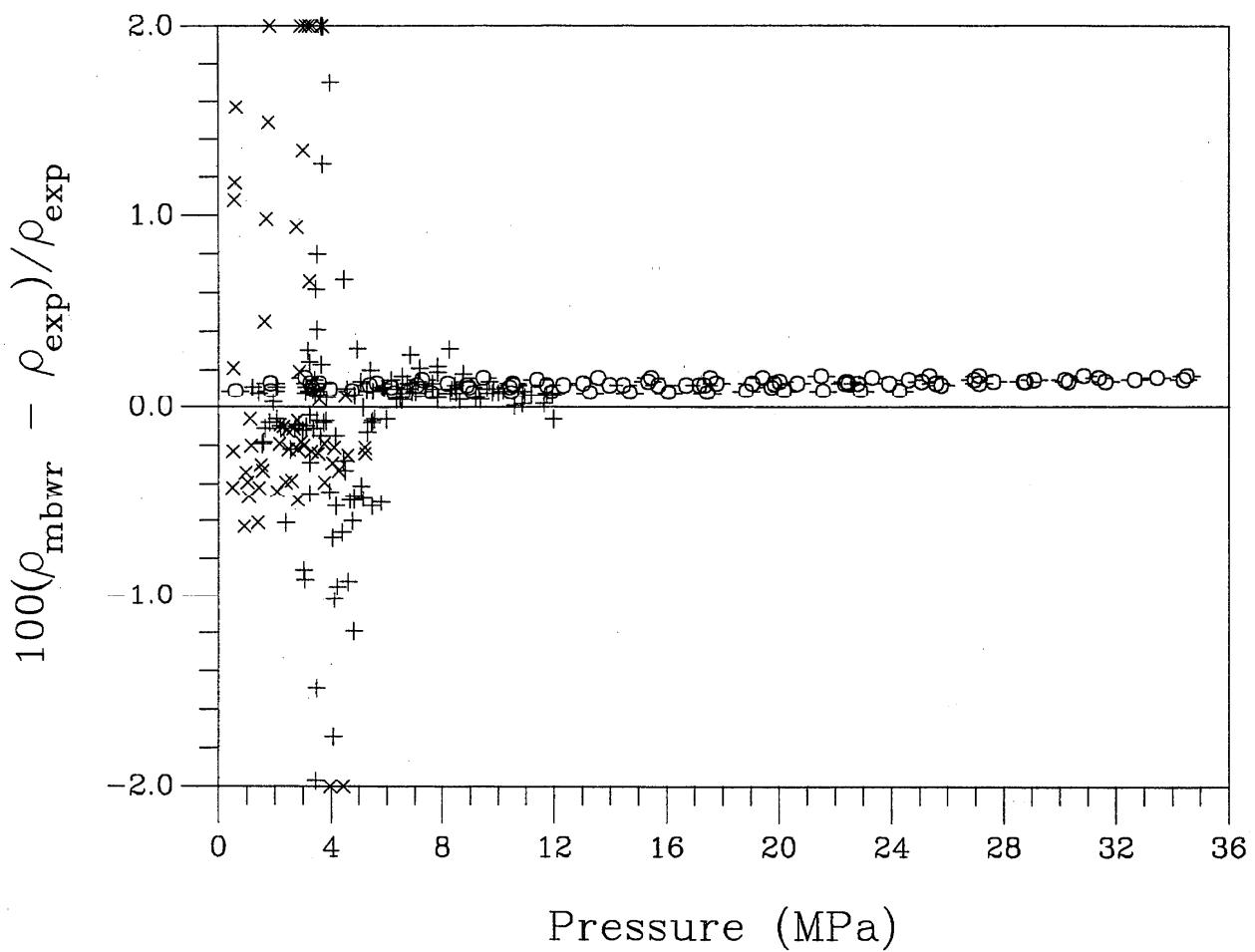
FIG. 9. Deviations of densities computed using the MBWR equation from the experimental densities of Fukushima *et al*. (×), Magee (O), and Piao (+).
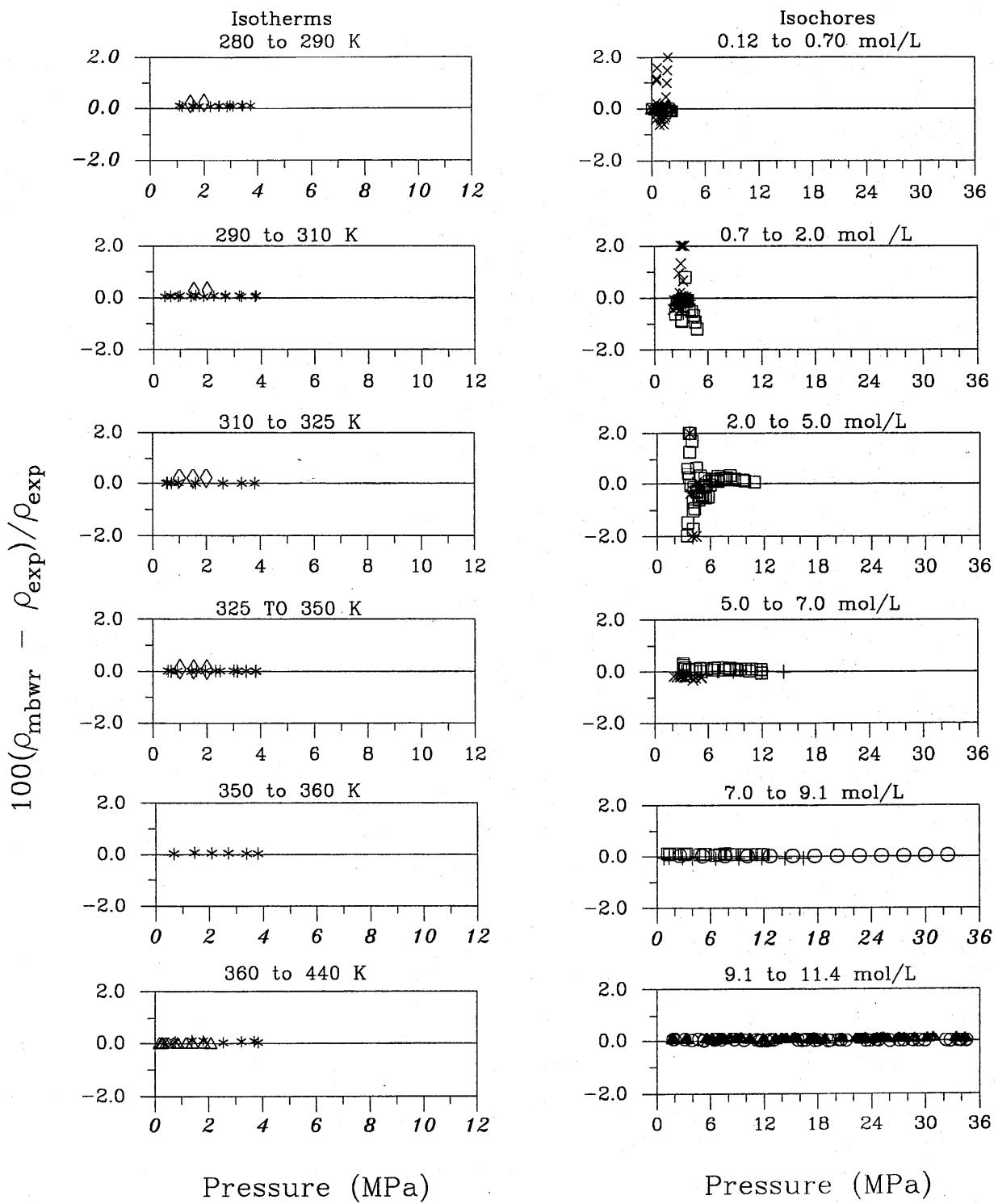
FIG. 10. Deviations of densities computed using the MBWR equation from the experimental densities of Fukushima *et al*. (x), Maezawa *et al*. (◊), Magee (△), Magee and Howley (○), Morrison and Ward (*), Oguchi *et al*. (+), Piao (□), and Weber (▲).
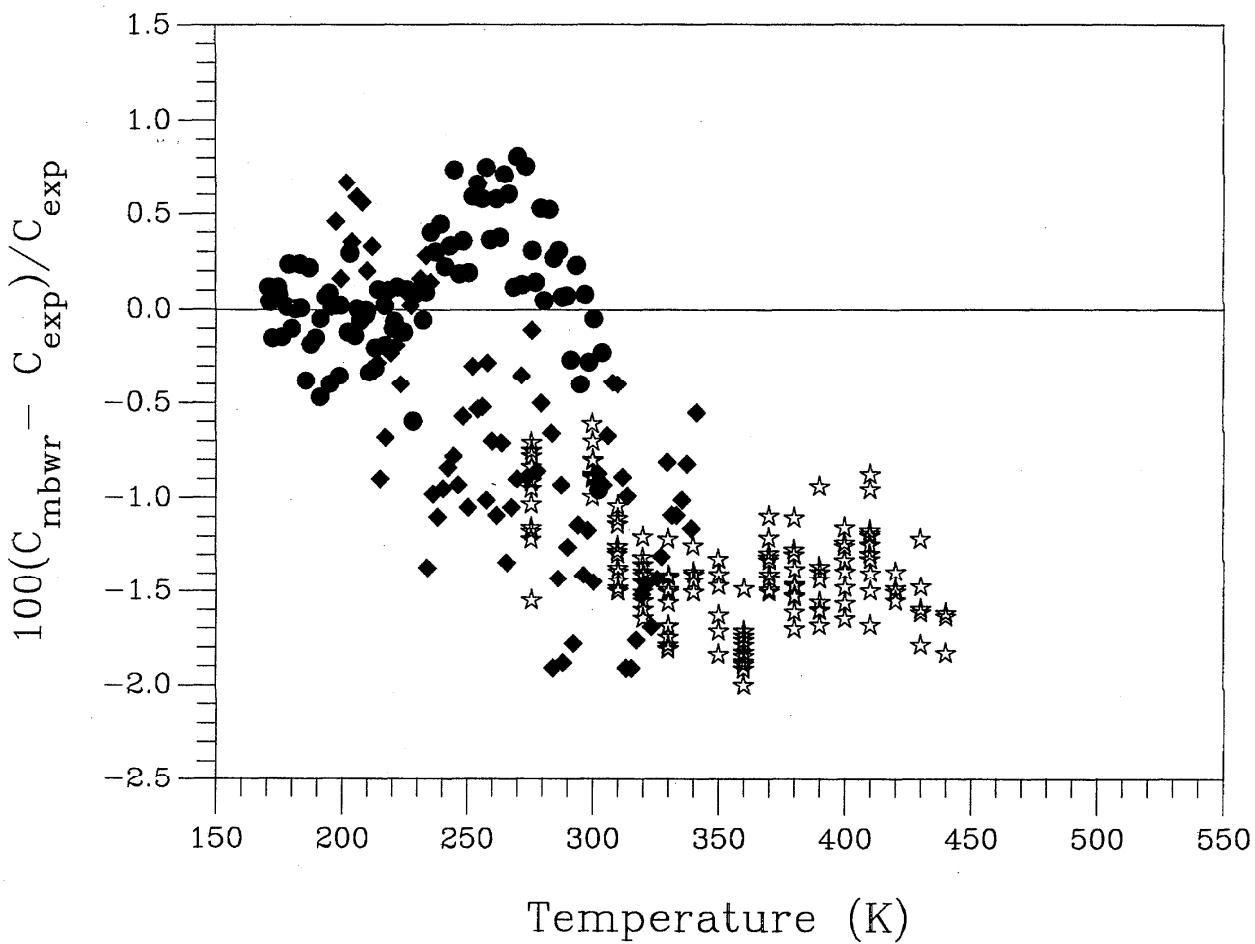
FIG. 11. Deviation of heat capacity computed using the MBWR equation from experimental values: Nakagawa C_p (☆), Magee C_v (◆), and Magee C_σ (●).
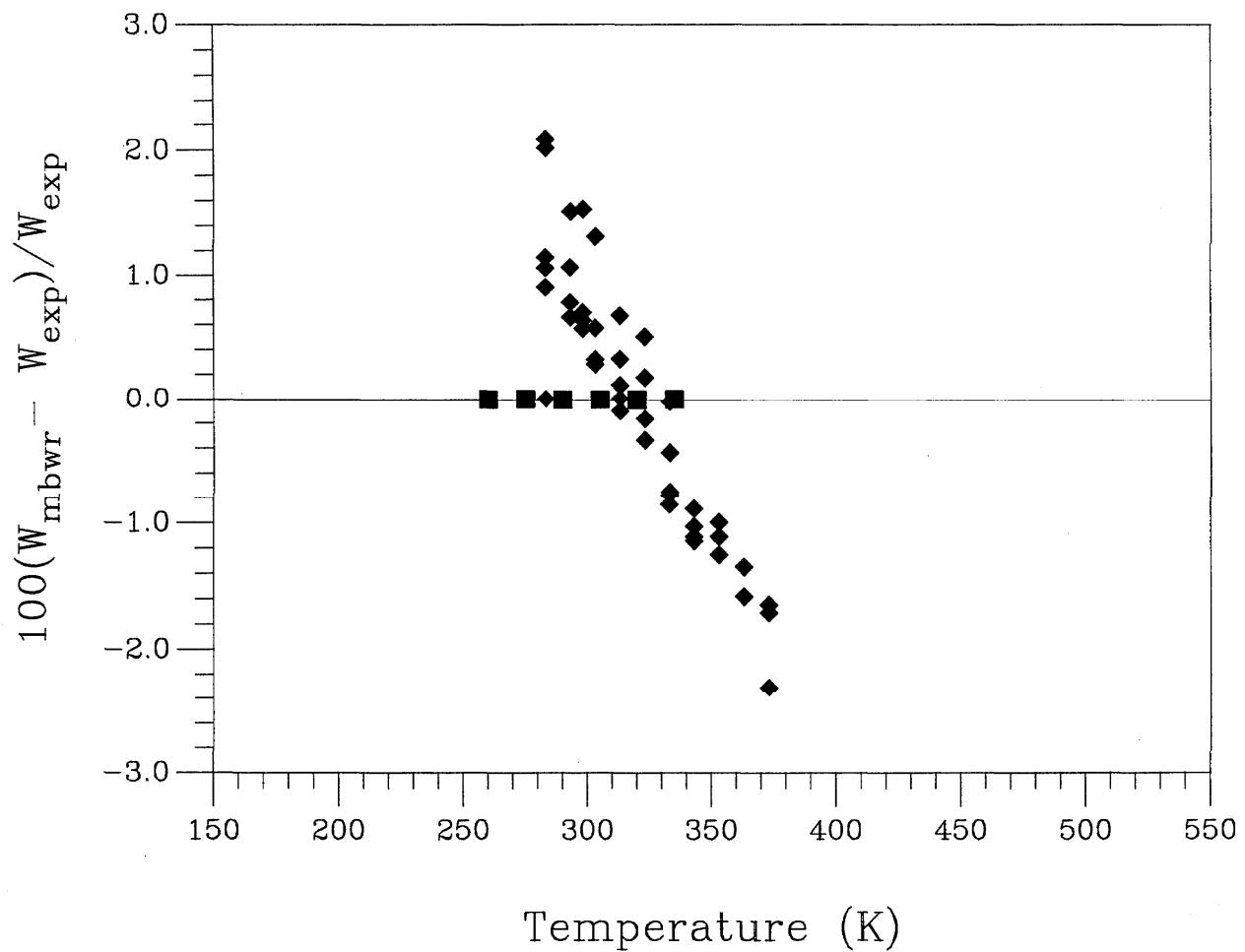
FIG. 12. Deviations of sound speeds computed from the MBWR equation from experimental values: data of Goodwin & Moldover (■), and Takagi (♦).
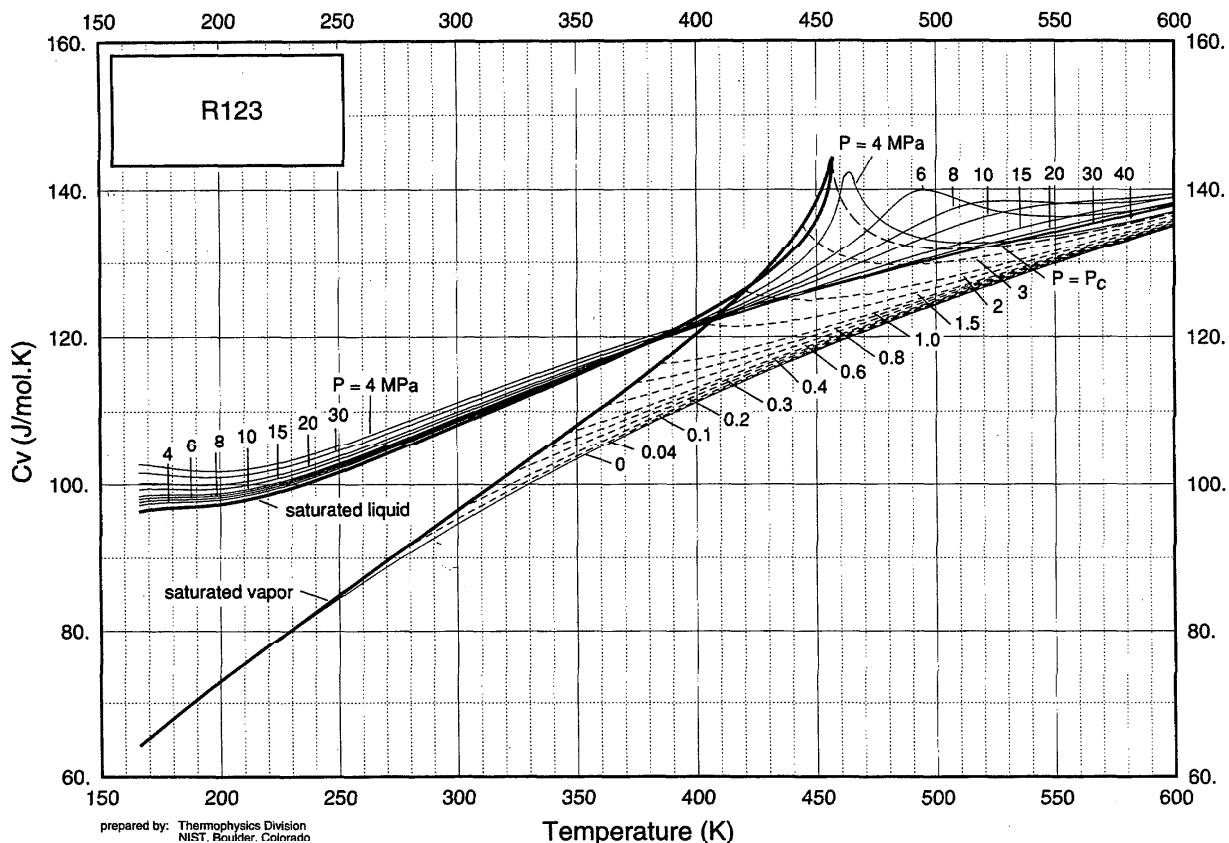
FIG. 13. Heat capacity at constant volume computed using the MBWR equation of state on isobars to 40 MPa. The gas phase isobars are shown as dashed lines. The saturated liquid and vapor phase boundaries are shown as heavier solid lines.
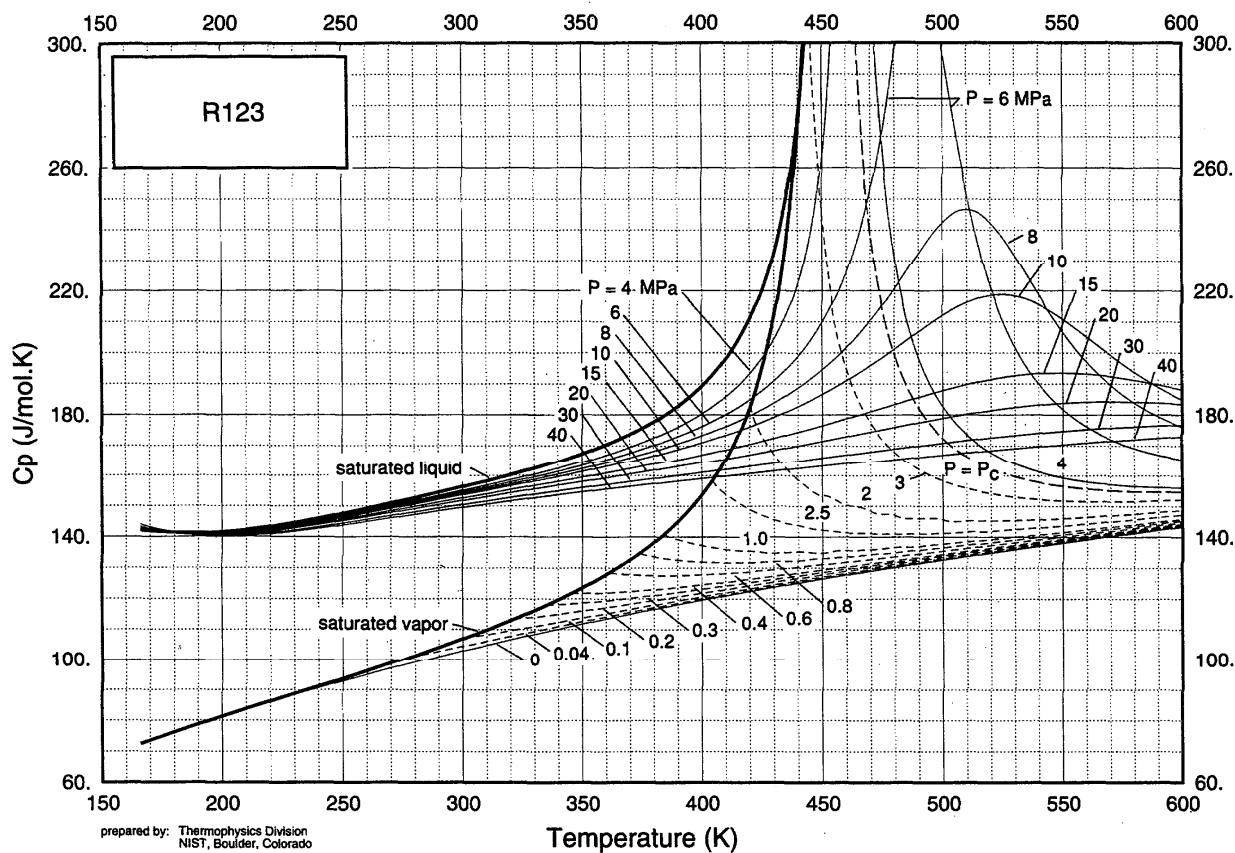
FIG. 14. Heat capacity at constant pressure computed using the MBWR equation of state on isobars to 40 MPa. The gas phase isobars are shown as dashed lines. The saturated liquid and vapor phase boundaries are shown as heavier solid lines.
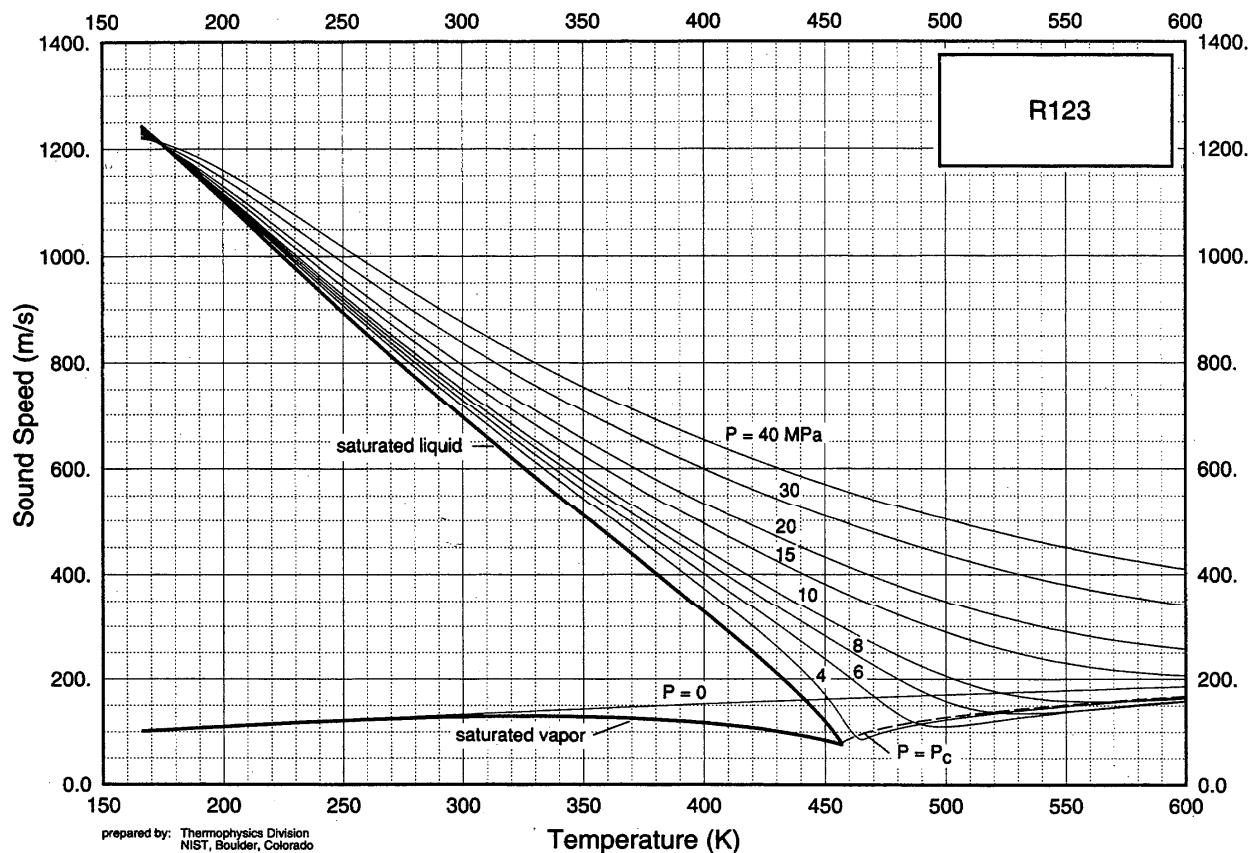
FIG. 15. Speed of sound computed using the MBWR equation of state on isobars to 40 MPa. The saturated liquid and vapor boundaries are shown as heavier solid lines.

6. Acknowledgements

7. References

Elhassan, A.E., Craven, R.J.B., and deReuck, K.M. (1993). Comparisons of equations of state with experimental data for R134a and R123. IUPAC Thermodynamic Tables Project Centre, Imperial College, London, report to IEA Annex 18, April, 1993.

Fukushima, M. (1990). Measurements of the PVT properties of HCFC123 and HFC134a. Trans. Japanese Assoc. of Refrigeration 7(3), 243.

Fukushima, M. (1991). Saturated liquid densities of HCFC123, HFC134a, CFC11 and CFC12. Trans. Japanese Assoc. of Refrigeration 8(1), 65.

Fukushima, M., Watanabe, N. and Kamimura, T. (1990). Measurements of the vapor-liquid coexistence curves and the critical parameters of HCFC-123 and HFC-134a. Trans. Japanese Assoc. of Refrigeration 7(2), 85.

Goodwin, A.R.H. and Moldover, M.R. (1991). Thermophysical properties of gaseous refrigerants from speed of sound measurements. III. Results for 1,1-dichloro-2,2,2-trifluoroethane (CHCl$_2$-CF$_3$) and 1,2-dichloro-1,2,2-trifluoroethane (CHClF-CClF$_2$). J. Chem. Phys. 95, 5236.

Goodwin, A.R.H., Defibaugh, D.R., Morrison, G., and Weber, L.A. (1992). The vapor pressure of 1,1-dichloro-2,2,2-trifluoroethane (R123). Int. J. Thermophysics, 13, 999.

Huber, M.L. (1994). Structural optimization of vapor pressure correlations using simulated annealing and threshold accepting: Application to R134a. Computers and Chemical Engineering 18, 929.

Huber, M.L. and McLinden, M.O. (1992). Thermodynamic properties of R134a (1,1,1,2-tetrafluoroethane). International Refrigeration Conference, West Lafayette, IN, Vol. II 453.

Hust, J.G. and McCarty R.D. (1967). Curve-fitting techniques and applications to thermodynamics. Cryogenics, 7, 200.

Jacobsen, R.T and Stewart, R.B. (1973). Thermodynamic properties of nitrogen including liquid and vapor phases from 63 K to 2000 K with pressures to 10,000 bar. J. Phys. Chem. Ref. Data 2, 757.

Japanese Association of Refrigeration (1990). Thermophysical Properties of Environmentally Acceptable Fluorocarbons — HFC-134a and HCFC-123.

Kubota, H., Yamashita, T., Tanaka, Y., and Makita, T. (1989). Vapor pressures of new fluorcarbons. Int. J. Thermophysics, 10, 629.

Luft, N. (1954). Assignment of torsional frequencies in some halogenated ethanes. J. Chem. Phys. 22, 155.

Maezawa, Y., Sato, H. and Watanabe, K. (1990). Saturated liquid densities of HCFC 123 and HFC 134a. J. Chem. Eng. Data 35, 225–228.

Magee, J.W. (1993). private communication, National Institute of Standards and Technology, Boulder, CO.

Magee, J.W. and Howley, J. (1993). private communication, National Institute of Standards and Technology, Boulder, CO.

McLinden, M.O., Gallagher, J.S., Weber, L.A., Morrison, G., Ward, D., Goodwin, A.R.H., Moldover, M.R., Schmidt, J.W., Chae, H.B., Bruno, T.J., Ely, J.F. and Huber, M.L. (1989). Measurement and formulation of the thermodynamic properties of refrigerants 134a (1,1,1,2-tetrafluoroethane) and 123 (1,1-dichloro-2,2,2-trifluoroethane). ASHRAE Trans. 95 (part 2), 263.

Morrison, G. and Ward, D.K. (1991). Thermodynamic properties of two alternative refrigerants: 1,1-dichloro-2,2,2-trifluoroethane (R123) and 1,1,1,2-tetrafluoroethane (R134a). Fluid Phase Equilibria 62, 65.

Nakagawa, N., Sato, H. and Watanabe, K. (1991). Isobaric heat capacity data for liquid HCFC-123 (CHCl$_2$CF$_3$, 2,2-dichloro-1,1,1-trifluoroethane). J. Chem. Eng. Data 36, 156.

Oguchi, K. and Takaishi, Y. (1989). Measurement of saturated liquid density of HCFC-123. The Tenth Japan Symposium on Thermophysical Properties, 55.

Oguchi, K., Yamagishi, M., and Murano, A. (1991). Experimental study of PVT properties of HCFC-123 (CHCl$_2$CF$_3$). Conference preprint for the 11th. Symposium on Thermophysical Properties, Boulder, Colorado.

Penoncello, S.G., Jacobsen R.T., Williams, R.C., and Lemmon, E.W. (1993). Comparison of equations of state for HCFC-123 for the International Energy Agency — Annex 18, Thermophysical properties of the environmentally acceptable refrigerants. CATS Report 93–3. Center for Applied Thermodynamic Studies, University of Idaho, Moscow, Idaho, USA.

Piao, C.C., Sato, H. and Watanabe, K. (1991). PVT and vapor pressure measurements on 1,1-dichloro-2,2,2-trifluoroethane (HCFC-123). J. Chem. Eng. Data 36, 398.

Piao, C.C., Sato, H. and Watanabe, K. (1992). An equation of state for a new working fluid HCFC-123. Fluid Phase Equilibria 80, 87.

Schmidt, J. (1989). National Institute of Standards and Technology Gaithersburg, MD, private communication.

Sukornic, B. (1989). Potentially acceptable substitutes for the chlorofluorocarbons: Properties and performance features of HFC-134a, HCFC-123, and HCFC-141b. Int. J. Thermophysics 10, 553.

Takagi, T. (1991). Ultrasonic speed for liquid trichlorofluoromethane and 1,1-dichloro-2,2,2-trifluoroethane at temperatures from 283 to 373 K and pressures up to 75 MPa. J. Chem. Eng. Data 36, 394.

Tanikawa, S., Kabata, Y., Sato, H., and Watanabe, K. (1990). Measurements of the critical parameters and the vapor-liquid coexistence curve in the critical region of HCFC 123. J. Chem. Eng. Data 35, 381.

Tillner-Roth, R. and Baehr, H.D. (1994). An international standard formulation of the thermodynamic properties of 1,1,1,2-tetrafluoroethane (HFC-134a) covering temperatures from 170 K to 455 K at pressures up to 70 MPa. J. Phys. Chem. Ref. Data 23, 657.

Weber, L.A. (1992a). Ebulliometric measurement of the vapor pressures of R123 and R141b. Fluid Phase Equilibria 80, 141.

Weber, L.A. and Levelt Sengers, J.M.H. (1990). Critical parameters and saturation densities of 1,1-dichloro-2,2,2-trifluoroethane. Fluid Phase Equilibria 55, 241.

Weber, L.A. (1992b). Criteria for establishing accurate vapor pressure curves. International Refrigeration Conference. W. Lafayette, IN, Vol. II, 463.

Weber, L.A. (1990). Vapor pressure and gas-phase PVT data for 1,1-dichloro-2,2,2-trifluoroethane. J. Chem. Eng. Data 35, 237.

Yamashita, T., Kubota, H., Tanaka, Y., Makita, T., and Kashiwagi, H. (1989). Physical properties of new halogenated hydrocarbons. The Tenth Japan Symposium on Thermophysical Properties.

Younglove, B.A. (1982). Thermophysical properties of fluids. I. Argon, ethylene, parahydrogen, nitrogen, nitrogen trifluoride, and oxygen. J. Phys. Chem. Ref. Data 11 (suppl. No. 1).

Younglove, B.A. and Ely, J.F. (1987). Thermophysical properties of fluids. II. Methane, ethane, propane, isobutane and normal butane. J. Phys. Chem. Ref. Data 16, 577.

Appendix A
Derived Properties

All other thermodynamic properties can be calculated from a pressure-volume-temperature equation of state by the appropriate manipulations. The starting point is the Helmholtz free energy A which is related to pressure by

$$P = -\left(\frac{\partial A}{\partial V}\right)_T. \tag{A1}$$

Thus, the Helmholtz energy can be evaluated from the pressure-explicit MBWR equation of state by an integration over volume:

$$A(T,\rho) = -\int P_{\text{MBWR}}\, dV. \tag{A2}$$

This expression has two problems, however. First, the integration limits are not yet defined; as will be seen shortly, setting one of the limits to $V = \infty$ (or $\rho \to 0$) will result in considerable simplifications. But this choice of an integration limit results in the second problem: the integral diverges. The introduction of the ideal gas as a reference state solves both of these problems. All gases approach ideal behavior in the limit of $\rho = 0$. The difference between the actual pressure and the pressure of an ideal gas at the same temperature and density does not diverge as $\rho \to 0$. The pressure of an ideal gas is

$$P^\circ = RT\rho, \tag{A3}$$

where the superscript $^\circ$ denotes the ideal gas state. Integrating the pressure difference gives the residual Helmholtz free energy (the difference between the molar Helmholtz free energy and the free energy of the ideal gas state):

$$A^r = A - A^\circ = \int_V^\infty (P - RT\rho)\, dV. \tag{A4}$$

The entropy is given by the temperature derivative of A at constant density and, again, it is convenient to compute a residual quantity:

$$S^r = S - S^\circ = -\left(\frac{\partial(A - A^\circ)}{\partial T}\right)_V. \tag{A5}$$

The residual internal energy E^r, enthalpy H^r, and Gibbs free energy G^r follow directly from their definitions:

$$E \equiv A + TS$$
$$E - E^\circ = (A - A^\circ) + T(S - S^\circ) \tag{A6}$$

$$H \equiv E + P/\rho$$
$$H - H^\circ = (A - A^\circ) + T(S - S^\circ) + (P/\rho - RT) \tag{A7}$$

$$G \equiv A + P/\rho$$
$$G^r = G - G^\circ = (A - A^\circ) + (P/\rho - RT). \tag{A8}$$

In Eq. (A8) G^r is a function of T and ρ; it is often more convenient, however, to define the ideal gas reference state in terms of a (as yet undefined) reference pressure rather than density. The difference between the G° at the reference pressure P^* and the actual pressure P is

$$G^\circ(T,P) - G^\circ(T,P^*) = RT \ln\left(\frac{RT\rho}{P^*}\right). \tag{A9}$$

Combining Eqs. (A8) and (A9) yields

$$G(T,\rho) - G^\circ(T,P^*) =$$
$$G(T,\rho) - G^\circ(T,\rho) + RT \ln\left(\frac{RT\rho}{P^*}\right). \tag{A10}$$

The Gibbs free energy is most often used as a difference in phase equilibrium calculations where the pressure and temperature of two phases are equal; in this case

$$\{G(T,\rho^{(1)}) - G^\circ(T,P^*)\} - \{G(T,\rho^{(2)}) - G^\circ(T,P^*)\} =$$
$$(G - G^\circ)^{(1)} - (G - G^\circ)^{(2)} +$$
$$RT\ln\left(\frac{RT\rho^{(1)}}{P^*}\right) - RT\ln\left(\frac{RT\rho^{(2)}}{P^*}\right), \tag{A11}$$

and

$$G(T,\rho^{(1)}) - G(T,\rho^{(2)}) =$$
$$(G - G^\circ)^{(1)} - (G - G^\circ)^{(2)} + RT \ln\left(\frac{\rho^{(1)}}{\rho^{(2)}}\right), \tag{A12}$$

where the superscripts (1) and (2) refer to the two phases and the reference pressure P^* cancels.

The heat capacity at constant volume is

$$C_v \equiv \left(\frac{\partial E}{\partial T}\right)_V = T\left(\frac{\partial S}{\partial T}\right)_V. \tag{A13}$$

Again, the difference from the ideal gas value is evaluated

$$C_v - C_v^\circ = \left(\frac{\partial(E - E^\circ)}{\partial T}\right)_V \tag{A14}$$

or, upon substituting from above

$$C_v - C_v^\circ = -T\left(\frac{\partial^2(A - A^\circ)}{\partial T^2}\right)_V. \tag{A15}$$

The isobaric (constant pressure) heat capacity is evaluated most easily in terms of C_v:

$$C_p = C_v + \frac{T}{\rho^2}\left(\frac{\partial P}{\partial T}\right)_V^2 \Big/ \left(\frac{\partial P}{\partial \rho}\right)_T. \tag{A16}$$

Finally, the speed of sound is given by

$$W = \left[\frac{1}{M}\frac{C_p}{C_v}\left(\frac{\partial P}{\partial \rho}\right)_T\right]^{(1/2)}. \tag{A17}$$

where M is the relative molecular mass; it is needed to convert units when molar density is used.

The above expressions are all in terms of residual quantities, but engineering calculations require absolute quantities which may be obtained by breaking the calculation into several parts. For example, to compute molar enthalpy at some temperature T and density ρ from the residual enthalpy, add and subtract terms:

$$H(T,\rho) - H(T_{ref}, \rho_{ref}) = [H(T,\rho) - H^{\circ}(T)]$$
$$+ [H^{\circ}(T) - H^{\circ}(T_{ref})]$$
$$+ [H^{\circ}(T_{ref}) - H(T_{ref},\rho_{ref})] . \qquad (A18)$$

This expression reduces to the simple identity $H(T, \rho) = H(T, \rho)$, and it might first appear that nothing has been accomplished. But, by clever choice of the terms added and subtracted, we have obtained an expression which can be evaluated. The left side of the equation is the difference between the enthalpy at the desired temperature and density and that at some (arbitrary) reference temperature and density; this is precisely the quantity tabulated in handbooks. (One of the more common reference states, that adopted by the International Institute of Refrigeration, sets the enthalpy to 200 kJ/kg at a temperature of 0 °C and a density corresponding to that of the saturated liquid at that temperature.) The first pair of terms on the right hand side of Eq. (A18) are those in Eq. (A7). The second line is easily evaluated in terms of the ancillary function for the ideal gas heat capacity:

$$H^{\circ}(T) - H^{\circ}(T_{ref}) = \int_{T_{ref}}^{T} C_p^{\circ} dT . \qquad (A19)$$

The final line of Eq. (A18) is simply the negative of Eq. (A7) evaluated at T_{ref} and ρ_{ref}. Internal energy can be evaluated in a similar fashion, noting that

$$E^{\circ}(T) - E^{\circ}(T_{ref}) = \int_{T_{ref}}^{T} (C_p^{\circ} - R)dT . \qquad (A20)$$

The evaluation of entropy involves additional terms since the entropy of the ideal gas, S°, depends on density:

$$S(T,\rho) - S(T_{ref},\rho_{ref}) = [S(T,\rho) - S^{\circ}(T,\rho)]$$
$$+ [S^{\circ}(T,\rho) - S^{\circ}(T,\rho_{ref})]$$
$$+ [S^{\circ}(T,\rho_{ref}) - S^{\circ}(T_{ref},\rho_{ref})]$$
$$+ [S^{\circ}(T_{ref},\rho_{ref}) - S(T_{ref},\rho_{ref})] . \qquad (A21)$$

As with enthalpy, the left side of the equation is the quantity desired. The first pair of terms on the right hand side, as well as that in the final line, are given by Eq. (A5). The second line is equal to the integral of the volume derivative of S°:

$$S^{\circ}(T,\rho) - S^{\circ}(T,\rho_{ref}) = \int_{V_{ref}}^{V} \left(\frac{\partial S^{\circ}}{\partial V}\right)_T dV , \qquad (A22)$$

where $V = 1/\rho$ and $V_{ref} = 1/\rho_{ref}$, and the derivative in the integral can be more easily evaluated by making use of a Maxwell relation:

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V . \qquad (A23)$$

For the ideal gas, this derivative is simply

$$\left(\frac{\partial P^{\circ}}{\partial T}\right)_V = \frac{R}{V} . \qquad (A24)$$

The second line of Eq. (A21), thus, becomes

$$S^{\circ}(T,\rho) - S^{\circ}(T,\rho_{ref}) = \int_{V_{ref}}^{V} \frac{R}{V} dV$$

$$= R \ln\left(\frac{V}{V_{ref}}\right)$$

$$= R \ln\left(\frac{\rho_{ref}}{\rho}\right) . \qquad (A25)$$

The third line is given by an integral of the ideal gas isochoric heat capacity:

$$S^{\circ}(T,\rho_{ref}) - S^{\circ}(T_{ref},\rho_{ref}) = \int_{T_{ref}}^{T} \frac{C_v^{\circ}}{T} dT,$$

$$= \int_{T_{ref}}^{T} \frac{C_p^{\circ}}{T} dT - R \ln\frac{T}{T_{ref}} . \qquad (A26)$$

The calculation of vapor pressure requires an iteration to find the liquid and vapor densities, $\rho^{(l)}$ and $\rho^{(V)}$, which satisfy:

$$G(T,\rho^{(l)}) = G(T,\rho^{(V)}) , \qquad (A27)$$

and

$$P(T,\rho^{(l)}) = P(T,\rho^{(V)}) \qquad (A28)$$

where the P in Eq. (A28) is the vapor pressure.

From Eqs. (A1)-(A28), we arrive at a core set of functions necessary to calculate all of the thermodynamic quantities used in engineering calculations:

$$P(T,\rho), \qquad \left(\frac{\partial P}{\partial T}\right)_v , \qquad \left(\frac{\partial P}{\partial \rho}\right)_T ,$$

$$A - A^{\circ}, \qquad \left(\frac{\partial (A - A^{\circ})}{\partial T}\right)_v , \qquad \left(\frac{\partial^2 (A - A^{\circ})}{\partial T^2}\right)_v ,$$

$$C_p^{\circ} , \qquad \int_{T_{ref}}^{T} C_p^{\circ} dT , \qquad \int_{T_{ref}}^{T} \frac{C_p^{\circ}}{T} dT .$$

These functions are tabulated in Appendix B in terms of the coefficients of the modified Benedict-Webb-Rubin equation of state and the ancillary equation for ideal gas heat capacity.

Appendix B
Thermodynamic functions derived from MBWR equations

This appendix presents the functions needed to calculate thermodynamic properties from the pressure-explicit MBWR equation of state.

The MBWR equation represents the pressure P as a function of the absolute temperature T and the molar density ρ

$$P = \sum_{n=1}^{9} a_n \rho^n + \exp(-\delta^2) \sum_{n=10}^{15} a_n \rho^{2n-17}, \qquad (B1)$$

where $\delta = \rho/\rho_c$, ρ_c is the critical density, and the temperature dependence of the coefficients is given by

$$
\begin{aligned}
a_1 &= RT \\
a_2 &= b_1 T + b_2 T^{1/2} + b_3 + b_4/T + b_5/T^2 \\
a_3 &= b_6 T + b_7 + b_8/T + b_9/T^2 \\
a_4 &= b_{10} T + b_{11} + b_{12}/T \\
a_5 &= b_{13} \\
a_6 &= b_{14}/T + b_{15}/T^2 \\
a_7 &= b_{16}/T \qquad\qquad\qquad\qquad (B2) \\
a_8 &= b_{17}/T + b_{18}/T^2 \\
a_9 &= b_{19}/T^2 \\
a_{10} &= b_{20}/T^2 + b_{21}/T^3 \\
a_{11} &= b_{22}/T^2 + b_{23}/T^4 \\
a_{12} &= b_{24}/T^2 + b_{25}/T^3 \\
a_{13} &= b_{26}/T^2 + b_{27}/T^4 \\
a_{14} &= b_{28}/T^2 + b_{29}/T^3 \\
a_{15} &= b_{30}/T^2 + b_{31}/T^3 + b_{32}/T^4 .
\end{aligned}
$$

The partial derivative of pressure with respect to temperature is given by

$$\left(\frac{\partial P}{\partial T}\right)_V = \sum_{n=1}^{9}\left(\frac{\partial a_n}{\partial T}\right)_V \rho^n + \exp(-\delta^2)\sum_{n=10}^{15}\left(\frac{\partial a_n}{\partial T}\right)_V \rho^{2n-17}. \quad (B3)$$

The partial derivatives of the coefficients are

$$
\begin{aligned}
\left(\frac{\partial a_1}{\partial T}\right)_V &= R \\
\left(\frac{\partial a_2}{\partial T}\right)_V &= b_1 + \frac{b_2}{2T^{1/2}} - \frac{b_4}{T^2} - 2\frac{b_5}{T^3} \\
\left(\frac{\partial a_3}{\partial T}\right)_V &= b_6 - \frac{b_8}{T^2} - 2\frac{b_9}{T^3} \\
\left(\frac{\partial a_4}{\partial T}\right)_V &= b_{10} - \frac{b_{12}}{T^2} \\
\left(\frac{\partial a_5}{\partial T}\right)_V &= 0 \\
\left(\frac{\partial a_6}{\partial T}\right)_V &= -\frac{b_{14}}{T^2} - 2\frac{b_{15}}{T^3} \\
\left(\frac{\partial a_7}{\partial T}\right)_V &= -\frac{b_{16}}{T^2} \\
\left(\frac{\partial a_8}{\partial T}\right)_V &= -\frac{b_{17}}{T^2} - 2\frac{b_{18}}{T^3} \qquad\qquad (B4) \\
\left(\frac{\partial a_9}{\partial T}\right)_V &= -2\frac{b_{19}}{T^3}
\end{aligned}
$$

$$
\begin{aligned}
\left(\frac{\partial a_{10}}{\partial T}\right)_V &= -2\frac{b_{20}}{T^3} - 3\frac{b_{21}}{T^4} \\
\left(\frac{\partial a_{11}}{\partial T}\right)_V &= -2\frac{b_{22}}{T^3} - 4\frac{b_{23}}{T^5} \\
\left(\frac{\partial a_{12}}{\partial T}\right)_V &= -2\frac{b_{24}}{T^3} - 3\frac{b_{25}}{T^4} \\
\left(\frac{\partial a_{13}}{\partial T}\right)_V &= -2\frac{b_{26}}{T^3} - 4\frac{b_{27}}{T^5} \\
\left(\frac{\partial a_{14}}{\partial T}\right)_V &= -2\frac{b_{28}}{T^3} - 3\frac{b_{29}}{T^4} \\
\left(\frac{\partial a_{15}}{\partial T}\right)_V &= -2\frac{b_{30}}{T^3} - 3\frac{b_{31}}{T^4} - 4\frac{b_{32}}{T^5} .
\end{aligned}
$$

The partial derivative of pressure with respect to molar density is given by

$$\left(\frac{\partial P}{\partial \rho}\right)_T = \sum_{n=1}^{9} n a_n \rho^{n-1}$$
$$+ \exp(-\delta^2)\sum_{n=10}^{15}\{2n-17-2\delta^2\}a_n\rho^{2n-18}. \qquad (B5)$$

The residual Helmholtz free energy, given in terms of the MBWR coefficients is

$$A^r = \sum_{n=2}^{9}\frac{a_n}{n-1}\rho^{n-1}$$
$$- \frac{1}{2}a_{10}\rho_c^2\{\exp(-\delta^2)-1\}$$
$$- \frac{1}{2}a_{11}\rho_c^4\{\exp(-\delta^2)[\delta^2 + 1] - 1\}$$
$$- \frac{1}{2}a_{12}\rho_c^6\{\exp(-\delta^2)[\delta^4 + 2\delta^2 + 2] - 2\} \qquad (B6)$$
$$- \frac{1}{2}a_{13}\rho_c^8\{\exp(-\delta^2)[\delta^6 + 3\delta^4 + 6\delta^2 + 6] - 6\}$$
$$- \frac{1}{2}a_{14}\rho_c^{10}\{\exp(-\delta^2)[\delta^8 + 4\delta^6 + 12\delta^4 + 24\delta^2 + 24] - 24\}$$
$$- \frac{1}{2}a_{15}\rho_c^{12}\{\exp(-\delta^2)[\delta^{10} + 5\delta^8 + 20\delta^6 + 60\delta^4 + 120\delta^2 + 120] - 120\},$$

where δ is ρ/ρ_c and the a_i are defined in Eq. B2.

The derivative of A^r with respect to temperature is

$$\left(\frac{\partial A^r}{\partial T}\right)_V = \sum_{n=2}^{9}\left(\frac{\partial a_n}{\partial T}\right)_V \frac{\rho^{n-1}}{n-1}$$
$$- \frac{1}{2}\left(\frac{\partial a_{10}}{\partial T}\right)_V \rho_c^2\{\exp(-\delta^2)-1\}$$
$$- \frac{1}{2}\left(\frac{\partial a_{11}}{\partial T}\right)_V \rho_c^4\{\exp(-\delta^2)[\delta^2 + 1]-1\}$$
$$- \frac{1}{2}\left(\frac{\partial a_{12}}{\partial T}\right)_V \rho_c^6\{\exp(-\delta^2)[\delta^4 + 2\delta^2 + 2]-2\} \qquad (B7)$$
$$- \frac{1}{2}\left(\frac{\partial a_{13}}{\partial T}\right)_V \rho_c^8\{\exp(-\delta^2)[\delta^6 + 3\delta^4 + 6\delta^2 + 6]-6\}$$
$$- \frac{1}{2}\left(\frac{\partial a_{14}}{\partial T}\right)_V \rho_c^{10}\{\exp(-\delta^2)[\delta^8 + 4\delta^6 + 12\delta^4 + 24\delta^2 + 24]-24\}$$

$$-\frac{1}{2}\left(\frac{\partial a_{15}}{\partial T}\right)_V \rho_c^{12}\{\exp(-\delta^2)[\delta^{10} + 5\delta^8 + 20\delta^6 + 60\delta^4 + 120\delta^2 + 120] - 120\}$$

where δ is ρ/ρ_c and the partial derivatives of a_i are defined in Eq. (B4.)

The second derivative of A^r with respect to temperature is

$$\left(\frac{\partial^2 A^r}{\partial T^2}\right)_V = \sum_{n=2}^{9}\left(\frac{\partial^2 a_n}{\partial T^2}\right)_V \frac{\rho^{n-1}}{n-1}$$

$$-\frac{1}{2}\left(\frac{\partial^2 a_{10}}{\partial T^2}\right)_V \rho_c^2\{\exp(-\delta^2)-1\}$$

$$-\frac{1}{2}\left(\frac{\partial^2 a_{11}}{\partial T^2}\right)_V \rho_c^4\{\exp(-\delta^2)[\delta^2 + 1]-1\}$$

$$-\frac{1}{2}\left(\frac{\partial^2 a_{12}}{\partial T^2}\right)_V \rho_c^6\{\exp(-\delta^2)[\delta^4 + 2\delta^2 + 2]-2\} \qquad \text{(B8)}$$

$$-\frac{1}{2}\left(\frac{\partial^2 a_{13}}{\partial T^2}\right)_V \rho_c^8\{\exp(-\delta^2)[\delta^6 + 3\delta^4 + 6\delta^2 + 6]-6\}$$

$$-\frac{1}{2}\left(\frac{\partial^2 a_{14}}{\partial T^2}\right)_V \rho_c^{10}\{\exp(-\delta^2)[\delta^8 + 4\delta^6 + 12\delta^4 + 24\delta^2 + 24]-24\}$$

$$-\frac{1}{2}\left(\frac{\partial^2 a_{15}}{\partial T^2}\right)_V \rho_c^{12}\{\exp(-\delta^2)[\delta^{10} + 5\delta^8 + 20\delta^6 + 60\delta^4 + 120\delta^2 + 120]-120\}$$

where δ is ρ/ρ_c and the partial derivatives of a_i are given below.

The second partial derivatives of the coefficients with respect to temperature are

$$\left(\frac{\partial^2 a_1}{\partial T^2}\right)_V = 0$$

$$\left(\frac{\partial^2 a_2}{\partial T^2}\right)_V = -\frac{b_2}{4T^{3/2}} + 2\frac{b_4}{T^3} + 6\frac{b_5}{T^4}$$

$$\left(\frac{\partial^2 a_3}{\partial T^2}\right)_V = 2\frac{b_8}{T^3} + 6\frac{b_9}{T^4}$$

$$\left(\frac{\partial^2 a_4}{\partial T^2}\right)_V = 2\frac{b_{12}}{T^3}$$

$$\left(\frac{\partial^2 a_5}{\partial T^2}\right)_V = 0$$

$$\left(\frac{\partial^2 a_6}{\partial T^2}\right)_V = 2\frac{b_{14}}{T^3} + 6\frac{b_{15}}{T^4}$$

$$\left(\frac{\partial^2 a_7}{\partial T^2}\right)_V = 2\frac{b_{16}}{T^3}$$

$$\left(\frac{\partial^2 a_8}{\partial T^2}\right)_V = 2\frac{b_{17}}{T^3} + 6\frac{b_{18}}{T^4}$$

$$\left(\frac{\partial^2 a_9}{\partial T^2}\right)_V = 6\frac{b_{19}}{T^4} \qquad \text{(B9)}$$

$$\left(\frac{\partial^2 a_{10}}{\partial T^2}\right)_V = 6\frac{b_{20}}{T^4} + 12\frac{b_{21}}{T^5}$$

$$\left(\frac{\partial^2 a_{11}}{\partial T^2}\right)_V = 6\frac{b_{22}}{T^4} + 20\frac{b_{23}}{T^6}$$

$$\left(\frac{\partial^2 a_{12}}{\partial T^2}\right)_V = 6\frac{b_{24}}{T^4} + 12\frac{b_{25}}{T^5}$$

$$\left(\frac{\partial^2 a_{13}}{\partial T^2}\right)_V = 6\frac{b_{26}}{T^4} + 20\frac{b_{27}}{T^6}$$

$$\left(\frac{\partial^2 a_{14}}{\partial T^2}\right)_V = 6\frac{b_{28}}{T^4} + 12\frac{b_{29}}{T^5}$$

$$\left(\frac{\partial^2 a_{15}}{\partial T^2}\right)_V = 6\frac{b_{30}}{T^4} + 12\frac{b_{31}}{T^5} + 20\frac{b_{32}}{T^6}.$$

The ideal gas heat capacity is a polynomial in reduced temperature T/T_c:

$$C_p^0 = R(c_0 + c_1 T_r + c_2 T_r^2 + c_3 T_r^3). \qquad \text{(B10)}$$

The integral of C with respect to temperature is

$$\int_{T_{ref}}^{T} C_p^0 \, dT = R\{c_0(T-T_{ref}) + \frac{c_1}{2T_c}(T^2 - T_{ref}^2) + \frac{c_2}{3T_c^2}(T^3 - T_{ref}^3) + \frac{c_3}{4T_c^3}(T^4 - T_{ref}^4)\}, \qquad \text{(B11)}$$

and the integral of C_p^0/T with respect to temperature is

$$\int_{T_{ref}}^{T} \frac{C_p^0}{T} \, dT = R\{c_0 \ln(T/T_{ref}) + \frac{c_1}{T_c}(T - T_{ref}) + \frac{c_2}{2T_c^2}(T^2 - T_{ref}^2) + \frac{c_3}{3T_c^3}(T^3 - T_{ref}^3)\}. \qquad \text{(B12)}$$

Appendix C
Calculated properties for R123

This appendix presents tables for the properties of R123 and also a diagram of the thermodynamic surface on pressure-enthalpy coordinates. Following usual engineering practice, temperatures are in °C and all properties are on a mass basis. The reference states for enthalpy and entropy follow the convention of the International Institute of Refrigeration, namely $h = 200.0$ kJ/kg for the saturated liquid at 0 °C and $s = 1.00$ kJ/(kg·K), also for the saturated liquid at 0 °C.

TABLE C.1. Properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) along the saturation boundary

	Temperature (°C)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
liquid	−107.15	0.00000	1770.9	98.81	0.5311	0.630	0.929	1243.8
vapor			0.0005	322.50	1.8786	0.419	0.474	101.0
liquid	−106.00	0.00000	1768.3	99.88	0.5375	0.630	0.928	1239.3
vapor			0.0005	323.04	1.8726	0.421	0.476	101.3
liquid	−104.00	0.00001	1763.7	101.73	0.5485	0.631	0.928	1231.3
vapor			0.0007	324.00	1.8626	0.425	0.479	101.8
liquid	−102.00	0.00001	1759.1	103.59	0.5594	0.632	0.927	1223.3
vapor			0.0009	324.96	1.8529	0.428	0.483	102.4
liquid	−100.00	0.00001	1754.5	105.44	0.5702	0.632	0.926	1215.3
vapor			0.0012	325.93	1.8436	0.432	0.486	102.9
liquid	−98.00	0.00002	1750.0	107.29	0.5808	0.632	0.925	1207.2
vapor			0.0016	326.90	1.8347	0.435	0.490	103.5
liquid	−96.00	0.00002	1745.4	109.14	0.5913	0.633	0.925	1199.1
vapor			0.0020	327.89	1.8261	0.439	0.493	104.0
liquid	−94.00	0.00003	1740.9	110.99	0.6017	0.633	0.924	1191.0
vapor			0.0026	328.88	1.8179	0.442	0.497	104.6
liquid	−92.00	0.00003	1736.4	112.84	0.6120	0.633	0.924	1182.8
vapor			0.0033	329.87	1.8101	0.446	0.500	105.1
liquid	−90.00	0.00004	1731.9	114.68	0.6221	0.633	0.923	1174.6
vapor			0.0041	330.87	1.8025	0.449	0.503	105.6
liquid	−88.00	0.00005	1727.5	116.53	0.6321	0.634	0.923	1166.3
vapor			0.0052	331.88	1.7953	0.452	0.507	106.2
liquid	−86.00	0.00007	1723.0	118.38	0.6421	0.634	0.923	1158.1
vapor			0.0064	332.90	1.7883	0.456	0.510	106.7
liquid	−84.00	0.00008	1718.5	120.22	0.6519	0.634	0.923	1149.8
vapor			0.0079	333.92	1.7816	0.459	0.514	107.2
liquid	−82.00	0.00010	1714.1	122.07	0.6616	0.634	0.923	1141.4
vapor			0.0098	334.95	1.7753	0.462	0.517	107.8
liquid	−80.00	0.00013	1709.6	123.92	0.6712	0.635	0.924	1133.1
vapor			0.0120	335.98	1.7691	0.466	0.520	108.3
liquid	−78.00	0.00015	1705.2	125.76	0.6807	0.635	0.924	1124.7
vapor			0.0145	337.03	1.7633	0.469	0.524	108.8
liquid	−76.00	0.00019	1700.7	127.61	0.6901	0.635	0.924	1116.3
vapor			0.0176	338.07	1.7576	0.472	0.527	109.3
liquid	−74.00	0.00023	1696.3	129.46	0.6995	0.636	0.925	1107.9
vapor			0.0212	339.13	1.7523	0.476	0.530	109.8

TABLE C.1. Properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) along the saturation boundary — Continued

	Temperature (°C)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
liquid	−72.00	0.00028	1691.8	131.31	0.7087	0.636	0.926	1099.5
vapor			0.0255	340.19	1.7471	0.479	0.533	110.3
liquid	−70.00	0.00034	1687.4	133.17	0.7179	0.637	0.927	1091.1
vapor			0.0304	341.25	1.7422	0.482	0.537	110.8
liquid	−68.00	0.00040	1682.9	135.02	0.7270	0.638	0.927	1082.6
vapor			0.0362	342.32	1.7374	0.485	0.540	111.3
liquid	−66.00	0.00048	1678.5	136.88	0.7360	0.638	0.928	1074.2
vapor			0.0429	343.40	1.7329	0.489	0.543	111.8
liquid	−64.00	0.00058	1674.0	138.73	0.7449	0.639	0.930	1065.7
vapor			0.0507	344.48	1.7286	0.492	0.546	112.3
liquid	−62.00	0.00068	1669.5	140.59	0.7537	0.640	0.931	1057.2
vapor			0.0596	345.57	1.7245	0.495	0.550	112.8
liquid	−60.00	0.00081	1665.1	142.46	0.7625	0.641	0.932	1048.7
vapor			0.0698	346.66	1.7206	0.498	0.553	113.3
liquid	−58.00	0.00095	1660.6	144.32	0.7712	0.642	0.933	1040.3
vapor			0.0814	347.76	1.7168	0.501	0.556	113.8
liquid	−56.00	0.00112	1656.1	146.19	0.7799	0.643	0.935	1031.8
vapor			0.0947	348.87	1.7132	0.505	0.559	114.2
liquid	−54.00	0.00131	1651.6	148.06	0.7884	0.644	0.936	1023.3
vapor			0.1098	349.98	1.7098	0.508	0.563	114.7
liquid	−52.00	0.00152	1647.1	149.94	0.7970	0.645	0.938	1014.9
vapor			0.1268	351.09	1.7065	0.511	0.566	115.2
liquid	−50.00	0.00177	1642.6	151.81	0.8054	0.646	0.939	1006.4
vapor			0.1461	352.21	1.7035	0.514	0.569	115.6
liquid	−48.00	0.00205	1638.1	153.69	0.8138	0.647	0.941	998.0
vapor			0.1677	353.34	1.7005	0.517	0.572	116.1
liquid	−46.00	0.00236	1633.6	155.58	0.8221	0.649	0.943	989.5
vapor			0.1920	354.47	1.6977	0.520	0.575	116.6
liquid	−44.00	0.00272	1629.0	157.46	0.8304	0.650	0.944	981.1
vapor			0.2191	355.60	1.6950	0.523	0.579	117.0
liquid	−42.00	0.00312	1624.5	159.35	0.8386	0.651	0.946	972.7
vapor			0.2494	356.74	1.6925	0.526	0.582	117.5
liquid	−40.00	0.00358	1619.9	161.25	0.8468	0.653	0.948	964.3
vapor			0.2831	357.88	1.6901	0.529	0.585	117.9
liquid	−38.00	0.00408	1615.4	163.15	0.8549	0.654	0.950	955.9
vapor			0.3205	359.03	1.6879	0.533	0.588	118.3
liquid	−36.00	0.00465	1610.8	165.05	0.8629	0.655	0.952	947.6
vapor			0.3620	360.18	1.6857	0.536	0.591	118.8
liquid	−34.00	0.00527	1606.2	166.96	0.8709	0.657	0.954	939.2
vapor			0.4077	361.33	1.6837	0.539	0.595	119.2
liquid	−32.00	0.00597	1601.6	168.87	0.8789	0.658	0.956	930.9
vapor			0.4581	362.49	1.6818	0.542	0.598	119.6
liquid	−30.00	0.00675	1597.0	170.78	0.8868	0.660	0.958	922.6
vapor			0.5136	363.65	1.6800	0.545	0.601	120.0

TABLE C.1.   Properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) along the saturation boundary — Continued

	Temperature (°C)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
liquid	−28.00	0.00761	1592.4	172.70	0.8946	0.661	0.960	914.3
vapor			0.5745	364.82	1.6783	0.548	0.604	120.4
liquid	−26.00	0.00855	1587.7	174.62	0.9024	0.663	0.962	906.0
vapor			0.6411	365.99	1.6767	0.551	0.608	120.8
liquid	−24.00	0.00959	1583.1	176.55	0.9102	0.664	0.964	897.8
vapor			0.7140	367.16	1.6753	0.554	0.611	121.2
liquid	−22.00	0.01074	1578.4	178.48	0.9179	0.666	0.966	889.5
vapor			0.7934	368.34	1.6739	0.557	0.614	121.6
liquid	−20.00	0.01200	1573.8	180.41	0.9256	0.667	0.968	881.3
vapor			0.8800	369.52	1.6726	0.560	0.617	122.0
liquid	−18.00	0.01337	1569.1	182.35	0.9332	0.669	0.970	873.2
vapor			0.9740	370.70	1.6714	0.563	0.621	122.4
liquid	−16.00	0.01488	1564.4	184.29	0.9408	0.671	0.972	865.0
vapor			1.0760	371.88	1.6703	0.566	0.624	122.8
liquid	−14.00	0.01652	1559.6	186.24	0.9483	0.672	0.975	856.9
vapor			1.1865	373.07	1.6693	0.569	0.627	123.1
liquid	−12.00	0.01831	1554.9	188.19	0.9558	0.674	0.977	848.8
vapor			1.3059	374.26	1.6683	0.572	0.631	123.5
liquid	−10.00	0.02025	1550.1	190.15	0.9633	0.676	0.979	840.7
vapor			1.4349	375.45	1.6675	0.575	0.634	123.8
liquid	−8.00	0.02235	1545.4	192.11	0.9707	0.677	0.981	832.6
vapor			1.5739	376.64	1.6667	0.578	0.637	124.2
liquid	−6.00	0.02464	1540.6	194.08	0.9781	0.679	0.983	824.6
vapor			1.7235	377.84	1.6660	0.581	0.641	124.5
liquid	−4.00	0.02711	1535.8	196.05	0.9854	0.681	0.986	816.6
vapor			1.8843	379.04	1.6653	0.584	0.644	124.8
liquid	−2.00	0.02977	1530.9	198.02	0.9927	0.682	0.988	808.6
vapor			2.0568	380.24	1.6647	0.587	0.647	125.1
liquid	0.00	0.03265	1526.1	200.00	1.0000	0.684	0.990	800.7
vapor			2.2417	381.44	1.6642	0.590	0.651	125.4
liquid	2.00	0.03574	1521.2	201.98	1.0072	0.686	0.993	792.7
vapor			2.4396	382.64	1.6638	0.593	0.654	125.7
liquid	4.00	0.03907	1516.4	203.97	1.0144	0.687	0.995	784.8
vapor			2.6511	383.84	1.6634	0.596	0.658	126.0
liquid	6.00	0.04264	1511.5	205.97	1.0216	0.689	0.997	777.0
vapor			2.8769	385.05	1.6631	0.599	0.661	126.3
liquid	8.00	0.04647	1506.5	207.96	1.0287	0.691	0.999	769.1
vapor			3.1177	386.25	1.6628	0.602	0.665	126.6
liquid	10.00	0.05057	1501.6	209.97	1.0358	0.692	1.002	761.3
vapor			3.3741	387.46	1.6626	0.605	0.668	126.8
liquid	12.00	0.05495	1496.6	211.97	1.0428	0.694	1.004	753.5
vapor			3.6469	388.67	1.6625	0.608	0.672	127.1
liquid	14.00	0.05963	1491.7	213.99	1.0499	0.696	1.006	745.7
vapor			3.9368	389.87	1.6624	0.612	0.675	127.3

TABLE C.1. Properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) along the saturation boundary — Continued

	Temperature (°C)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
liquid	16.00	0.06463	1486.7	216.00	1.0569	0.698	1.009	738.0
vapor			4.2446	391.08	1.6623	0.615	0.679	127.6
liquid	18.00	0.06995	1481.6	218.02	1.0638	0.699	1.011	730.3
vapor			4.5710	392.29	1.6623	0.618	0.682	127.8
liquid	20.00	0.07561	1476.6	220.05	1.0707	0.701	1.014	722.6
vapor			4.9168	393.50	1.6624	0.621	0.686	128.0
liquid	22.00	0.08163	1471.5	222.08	1.0776	0.703	1.016	714.9
vapor			5.2828	394.70	1.6625	0.624	0.690	128.2
liquid	24.00	0.08802	1466.4	224.12	1.0845	0.705	1.018	707.2
vapor			5.6699	395.91	1.6626	0.627	0.693	128.4
liquid	26.00	0.09480	1461.3	226.16	1.0913	0.706	1.021	699.6
vapor			6.0788	397.12	1.6628	0.630	0.697	128.6
liquid	27.82	0.10132	1456.6	228.03	1.0975	0.708	1.023	692.7
vapor			6.4713	398.22	1.6630	0.632	0.701	128.7
liquid	28.00	0.10198	1456.2	228.21	1.0981	0.708	1.023	692.0
vapor			6.5104	398.32	1.6630	0.633	0.701	128.7
liquid	30.00	0.10958	1451.0	230.26	1.1049	0.710	1.026	684.4
vapor			6.9658	399.53	1.6633	0.636	0.705	128.9
liquid	32.00	0.11762	1445.8	232.31	1.1116	0.711	1.028	676.9
vapor			7.4456	400.73	1.6636	0.639	0.709	129.0
liquid	34.00	0.12611	1440.6	234.38	1.1184	0.713	1.031	669.3
vapor			7.9509	401.94	1.6639	0.642	0.712	129.1
liquid	36.00	0.13507	1435.3	236.44	1.1250	0.715	1.033	661.8
vapor			8.4827	403.14	1.6642	0.645	0.716	129.3
liquid	38.00	0.14452	1430.1	238.52	1.1317	0.717	1.036	654.3
vapor			9.0419	404.34	1.6646	0.648	0.720	129.4
liquid	40.00	0.15447	1424.8	240.59	1.1383	0.718	1.038	646.8
vapor			9.6294	405.54	1.6651	0.651	0.724	129.5
liquid	42.00	0.16495	1419.4	242.67	1.1449	0.720	1.041	639.3
vapor			10.247	406.73	1.6655	0.654	0.728	129.5
liquid	44.00	0.17597	1414.1	244.76	1.1515	0.722	1.044	631.9
vapor			10.894	407.93	1.6660	0.657	0.732	129.6
liquid	46.00	0.18755	1408.7	246.86	1.1581	0.724	1.046	624.5
vapor			11.573	409.12	1.6665	0.660	0.736	129.7
liquid	48.00	0.19971	1403.3	248.95	1.1646	0.726	1.049	617.0
vapor			12.285	410.31	1.6670	0.663	0.741	129.7
liquid	50.00	0.21246	1397.8	251.06	1.1711	0.727	1.052	609.6
vapor			13.031	411.50	1.6676	0.666	0.745	129.7
liquid	52.00	0.22584	1392.3	253.17	1.1776	0.729	1.055	602.3
vapor			13.812	412.69	1.6682	0.669	0.749	129.7
liquid	54.00	0.23985	1386.8	255.28	1.1840	0.731	1.058	594.9
vapor			14.629	413.87	1.6688	0.672	0.753	129.7
liquid	56.00	0.25451	1381.2	257.41	1.1905	0.733	1.060	587.5
vapor			15.484	415.05	1.6694	0.675	0.758	129.7

TABLE C.1. Properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) along the saturation boundary — Continued

	Temperature (°C)	Pressure (MPa)	Density (kg/m^3)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
liquid	58.00	0.26985	1375.6	259.53	1.1969	0.734	1.063	580.2
vapor			16.377	416.23	1.6701	0.678	0.762	129.7
liquid	60.00	0.28589	1370.0	261.67	1.2033	0.736	1.066	572.9
vapor			17.311	417.40	1.6707	0.681	0.767	129.6
liquid	62.00	0.30264	1364.3	263.81	1.2096	0.738	1.069	565.5
vapor			18.286	418.57	1.6714	0.684	0.771	129.6
liquid	64.00	0.32013	1358.6	265.95	1.2160	0.740	1.072	558.2
vapor			19.304	419.73	1.6721	0.687	0.776	129.5
liquid	66.00	0.33838	1352.8	268.10	1.2223	0.742	1.076	550.9
vapor			20.367	420.90	1.6728	0.690	0.781	129.4
liquid	68.00	0.35740	1347.0	270.26	1.2286	0.743	1.079	543.6
vapor			21.476	422.05	1.6735	0.693	0.785	129.3
liquid	70.00	0.37722	1341.2	272.43	1.2349	0.745	1.082	536.4
vapor			22.632	423.21	1.6743	0.696	0.790	129.2
liquid	72.00	0.39787	1335.3	274.60	1.2411	0.747	1.085	529.1
vapor			23.838	424.35	1.6750	0.699	0.795	129.0
liquid	74.00	0.41936	1329.3	276.77	1.2474	0.749	1.089	521.8
vapor			25.094	425.50	1.6758	0.702	0.800	128.9
liquid	76.00	0.44171	1323.3	278.96	1.2536	0.751	1.092	514.6
vapor			26.404	426.63	1.6766	0.706	0.806	128.7
liquid	78.00	0.46494	1317.3	281.15	1.2598	0.752	1.096	507.3
vapor			27.768	427.77	1.6774	0.709	0.811	128.5
liquid	80.00	0.48909	1311.2	283.35	1.2660	0.754	1.100	500.0
vapor			29.188	428.89	1.6781	0.712	0.816	128.3
liquid	82.00	0.51416	1305.1	285.55	1.2722	0.756	1.103	492.8
vapor			30.667	430.01	1.6789	0.715	0.822	128.1
liquid	84.00	0.54019	1298.9	287.77	1.2784	0.758	1.107	485.5
vapor			32.207	431.13	1.6797	0.718	0.827	127.8
liquid	86.00	0.56720	1292.6	289.99	1.2845	0.760	1.111	478.3
vapor			33.809	432.24	1.6806	0.721	0.833	127.6
liquid	88.00	0.59520	1286.3	292.22	1.2906	0.762	1.115	471.0
vapor			35.477	433.34	1.6814	0.724	0.839	127.3
liquid	90.00	0.62423	1279.9	294.45	1.2967	0.764	1.120	463.8
vapor			37.212	434.43	1.6822	0.727	0.845	127.0
liquid	92.00	0.65430	1273.4	296.70	1.3028	0.765	1.124	456.5
vapor			39.018	435.51	1.6830	0.730	0.851	126.6
liquid	94.00	0.68544	1266.9	298.95	1.3089	0.767	1.129	449.3
vapor			40.896	436.59	1.6838	0.733	0.858	126.3
liquid	96.00	0.71768	1260.3	301.22	1.3150	0.769	1.133	442.0
vapor			42.850	437.66	1.6846	0.737	0.864	125.9
liquid	98.00	0.75103	1253.7	303.49	1.3211	0.771	1.138	434.7
vapor			44.882	438.72	1.6854	0.740	0.871	125.5
liquid	100.00	0.78553	1246.9	305.77	1.3271	0.773	1.143	427.5
vapor			46.996	439.77	1.6862	0.743	0.878	125.1

TABLE C.1. Properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) along the saturation boundary — Continued

	Temperature (°C)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
liquid	102.00	0.82119	1240.1	308.06	1.3332	0.775	1.149	420.2
vapor			49.195	440.82	1.6870	0.746	0.885	124.7
liquid	104.00	0.85805	1233.2	310.36	1.3392	0.777	1.154	412.9
vapor			51.482	441.85	1.6878	0.749	0.893	124.3
liquid	106.00	0.89613	1226.2	312.67	1.3452	0.779	1.160	405.6
vapor			53.862	442.87	1.6886	0.752	0.900	123.8
liquid	108.00	0.93545	1219.1	314.99	1.3512	0.781	1.166	398.3
vapor			56.338	443.88	1.6894	0.756	0.908	123.3
liquid	110.00	0.97603	1211.9	317.32	1.3572	0.783	1.172	391.0
vapor			58.914	444.88	1.6902	0.759	0.917	122.8
liquid	112.00	1.01792	1204.6	319.66	1.3633	0.785	1.178	383.6
vapor			61.595	445.86	1.6909	0.762	0.925	122.2
liquid	114.00	1.06113	1197.3	322.01	1.3693	0.787	1.185	376.3
vapor			64.386	446.84	1.6917	0.766	0.935	121.6
liquid	116.00	1.10569	1189.7	324.38	1.3753	0.789	1.192	368.9
vapor			67.292	447.80	1.6924	0.769	0.944	121.0
liquid	118.00	1.15162	1182.1	326.76	1.3813	0.791	1.199	361.5
vapor			70.318	448.74	1.6931	0.772	0.954	120.4
liquid	120.00	1.19896	1174.4	329.15	1.3872	0.794	1.207	354.1
vapor			73.471	449.68	1.6938	0.775	0.964	119.8
liquid	122.00	1.24774	1166.5	331.55	1.3932	0.796	1.215	346.7
vapor			76.756	450.59	1.6945	0.779	0.975	119.1
liquid	124.00	1.29798	1158.5	333.97	1.3992	0.798	1.224	339.2
vapor			80.182	451.49	1.6951	0.782	0.987	118.4
liquid	126.00	1.34971	1150.3	336.40	1.4052	0.800	1.233	331.8
vapor			83.755	452.37	1.6958	0.786	0.999	117.6
liquid	128.00	1.40297	1142.0	338.85	1.4112	0.802	1.243	324.3
vapor			87.484	453.23	1.6964	0.789	1.012	116.9
liquid	130.00	1.45778	1133.5	341.32	1.4173	0.805	1.254	316.7
vapor			91.379	454.08	1.6969	0.793	1.026	116.0
liquid	132.00	1.51417	1124.9	343.80	1.4233	0.807	1.265	309.2
vapor			95.448	454.90	1.6975	0.796	1.040	115.2
liquid	134.00	1.57218	1116.1	346.30	1.4293	0.810	1.277	301.6
vapor			99.703	455.70	1.6980	0.800	1.056	114.3
liquid	136.00	1.63184	1107.0	348.82	1.4353	0.812	1.289	293.9
vapor			104.16	456.47	1.6984	0.804	1.073	113.4
liquid	138.00	1.69319	1097.8	351.36	1.4414	0.814	1.303	286.3
vapor			108.82	457.22	1.6989	0.807	1.091	112.5
liquid	140.00	1.75626	1088.3	353.92	1.4475	0.817	1.318	278.6
vapor			113.71	457.94	1.6992	0.811	1.111	111.5
liquid	142.00	1.82108	1078.6	356.51	1.4536	0.820	1.334	270.8
vapor			118.84	458.63	1.6996	0.815	1.132	110.5
liquid	144.00	1.88769	1068.6	359.12	1.4597	0.822	1.351	263.0
vapor			124.24	459.29	1.6998	0.819	1.155	109.4

TABLE C.1. Properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) along the saturation boundary — Continued

	Temperature (°C)	Pressure (MPa)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
liquid	146.00	1.95614	1058.3	361.75	1.4658	0.825	1.370	255.2
vapor			129.92	459.92	1.7001	0.823	1.181	108.3
liquid	148.00	2.02645	1047.7	364.41	1.4720	0.828	1.391	247.3
vapor			135.91	460.51	1.7002	0.827	1.209	107.2
liquid	150.00	2.09868	1036.8	367.11	1.4782	0.831	1.415	239.3
vapor			142.23	461.06	1.7003	0.831	1.240	106.0
liquid	152.00	2.17287	1025.5	369.83	1.4845	0.834	1.441	231.2
vapor			148.92	461.56	1.7002	0.835	1.276	104.8
liquid	154.00	2.24905	1013.8	372.59	1.4908	0.837	1.470	223.1
vapor			156.02	462.01	1.7001	0.840	1.315	103.5
liquid	156.00	2.32729	1001.6	375.39	1.4972	0.840	1.502	214.9
vapor			163.57	462.41	1.6999	0.844	1.360	102.1
liquid	158.00	2.40763	988.9	378.24	1.5036	0.843	1.540	206.6
vapor			171.62	462.75	1.6996	0.849	1.412	100.7
liquid	160.00	2.49012	975.7	381.13	1.5101	0.847	1.584	198.2
vapor			180.24	463.02	1.6991	0.853	1.473	99.3
liquid	162.00	2.57483	961.8	384.08	1.5167	0.851	1.635	189.7
vapor			189.51	463.21	1.6985	0.858	1.544	97.8
liquid	164.00	2.66182	947.1	387.09	1.5234	0.854	1.695	181.0
vapor			199.53	463.31	1.6977	0.864	1.630	96.2
liquid	166.00	2.75115	931.5	390.17	1.5302	0.859	1.769	172.2
vapor			210.42	463.30	1.6967	0.869	1.734	94.6
liquid	168.00	2.84291	914.9	393.34	1.5371	0.863	1.861	163.2
vapor			222.35	463.17	1.6954	0.875	1.865	92.9
liquid	170.00	2.93717	896.9	396.61	1.5443	0.868	1.979	154.0
vapor			235.54	462.89	1.6939	0.881	2.033	91.1
liquid	172.00	3.03405	877.4	400.01	1.5517	0.873	2.137	144.5
vapor			250.32	462.43	1.6919	0.887	2.259	89.2
liquid	174.00	3.13366	855.7	403.58	1.5595	0.879	2.360	134.7
vapor			267.17	461.72	1.6895	0.894	2.578	87.2
liquid	176.00	3.23614	831.2	407.38	1.5677	0.885	2.700	124.5
vapor			286.86	460.68	1.6863	0.901	3.065	85.2
liquid	178.00	3.34168	802.2	411.51	1.5766	0.893	3.288	113.7
vapor			310.78	459.16	1.6822	0.910	3.898	83.0
liquid	180.00	3.45057	765.9	416.23	1.5867	0.902	4.549	102.3
vapor			341.95	456.82	1.6763	0.919	5.661	80.6
liquid	182.00	3.56326	712.6	422.28	1.5997	0.915	9.130	89.8
vapor			389.79	452.67	1.6664	0.931	11.857	78.1
critical point	183.68	3.66180	550.0	437.39	1.6290	∞	∞	0.0

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TABLE C.2. Single-phase properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane)

	Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
				Pressure = 0.010 MPa			
	−100.00	1754.5	105.44	0.5702	0.632	0.926	1215.3
	−90.00	1732.0	114.69	0.6221	0.633	0.923	1174.6
	−80.00	1709.6	123.92	0.6712	0.635	0.924	1133.1
	−70.00	1687.4	133.17	0.7179	0.637	0.927	1091.1
	−60.00	1665.1	142.46	0.7625	0.641	0.932	1048.8
	−50.00	1642.6	151.82	0.8054	0.646	0.939	1006.4
	−40.00	1620.0	161.25	0.8468	0.653	0.948	964.3
	−30.00	1597.0	170.78	0.8868	0.660	0.958	922.6
sat liquid	−23.27	1581.4	177.25	0.9130	0.665	0.965	894.8
sat vapor	−23.27	0.742	367.59	1.6748	0.555	0.612	121.4
	−20.00	0.732	369.60	1.6827	0.560	0.616	122.2
	−10.00	0.704	375.83	1.7069	0.573	0.629	124.5
	0.00	0.677	382.19	1.7306	0.586	0.642	126.8
	10.00	0.653	388.67	1.7539	0.599	0.655	129.1
	20.00	0.630	395.28	1.7768	0.611	0.667	131.3
	30.00	0.609	402.01	1.7994	0.624	0.679	133.4
	40.00	0.589	408.87	1.8217	0.636	0.691	135.6
	50.00	0.571	415.83	1.8436	0.647	0.703	137.7
	60.00	0.554	422.92	1.8651	0.659	0.714	139.7
	70.00	0.537	430.11	1.8864	0.670	0.725	141.7
	80.00	0.522	437.41	1.9074	0.681	0.736	143.7
	90.00	0.508	444.82	1.9281	0.691	0.746	145.7
	100.00	0.494	452.33	1.9485	0.701	0.756	147.6
	110.00	0.481	459.95	1.9686	0.711	0.766	149.5
	120.00	0.469	467.66	1.9885	0.721	0.776	151.4
	130.00	0.457	475.47	2.0081	0.731	0.786	153.3
	140.00	0.446	483.37	2.0275	0.740	0.795	155.1
	150.00	0.435	491.36	2.0466	0.749	0.804	156.9
	160.00	0.425	499.45	2.0655	0.758	0.813	158.7
	170.00	0.415	507.62	2.0841	0.767	0.821	160.5
	180.00	0.406	515.87	2.1025	0.775	0.830	162.2
	190.00	0.397	524.21	2.1207	0.783	0.838	164.0
	200.00	0.389	532.63	2.1387	0.792	0.846	165.7
	210.00	0.381	541.13	2.1565	0.799	0.854	167.4
	220.00	0.373	549.71	2.1741	0.807	0.862	169.1
	230.00	0.366	558.37	2.1915	0.815	0.869	170.7
	240.00	0.359	567.10	2.2086	0.822	0.877	172.4
	250.00	0.352	575.91	2.2256	0.830	0.884	174.0
				Pressure = 0.020 MPa			
	−100.00	1754.5	105.45	0.5702	0.632	0.926	1215.3
	−90.00	1732.0	114.69	0.6221	0.633	0.923	1174.6
	−80.00	1709.6	123.93	0.6712	0.635	0.924	1133.1
	−70.00	1687.4	133.17	0.7179	0.637	0.927	1091.1
	−60.00	1665.1	142.47	0.7625	0.641	0.932	1048.8
	−50.00	1642.6	151.82	0.8054	0.646	0.939	1006.5
	−40.00	1620.0	161.26	0.8468	0.653	0.948	964.4
	−30.00	1597.0	170.78	0.8868	0.660	0.958	922.6
	−20.00	1573.8	180.41	0.9256	0.667	0.968	881.4
sat liquid	−10.25	1550.7	189.91	0.9624	0.675	0.979	841.7

TABLE C.2.   Single-phase properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) — Continued

	Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
			Pressure = 0.020 MPa — Continued				
sat vapor	−10.25	1.419	375.30	1.6676	0.575	0.634	123.8
	−10.00	1.417	375.46	1.6682	0.575	0.634	123.8
	0.00	1.363	381.86	1.6920	0.588	0.646	126.2
	10.00	1.313	388.38	1.7155	0.601	0.658	128.5
	20.00	1.266	395.02	1.7385	0.613	0.670	130.8
	30.00	1.223	401.78	1.7612	0.625	0.682	133.0
	40.00	1.183	408.65	1.7835	0.637	0.693	135.2
	50.00	1.146	415.64	1.8054	0.648	0.704	137.3
	60.00	1.110	422.73	1.8271	0.659	0.715	139.4
	70.00	1.077	429.94	1.8484	0.670	0.726	141.4
	80.00	1.046	437.26	1.8694	0.681	0.737	143.4
	90.00	1.017	444.68	1.8901	0.692	0.747	145.4
	100.00	0.990	452.20	1.9105	0.702	0.757	147.4
	110.00	0.963	459.82	1.9307	0.712	0.767	149.3
	120.00	0.939	467.54	1.9506	0.722	0.777	151.2
	130.00	0.915	475.36	1.9702	0.731	0.786	153.1
	140.00	0.893	483.26	1.9896	0.740	0.795	154.9
	150.00	0.871	491.26	2.0087	0.749	0.804	156.8
	160.00	0.851	499.35	2.0276	0.758	0.813	158.6
	170.00	0.832	507.53	2.0463	0.767	0.822	160.3
	180.00	0.813	515.79	2.0647	0.775	0.830	162.1
	190.00	0.796	524.13	2.0829	0.784	0.838	163.9
	200.00	0.779	532.55	2.1009	0.792	0.846	165.6
	210.00	0.763	541.06	2.1187	0.800	0.854	167.3
	220.00	0.747	549.64	2.1363	0.807	0.862	169.0
	230.00	0.732	558.30	2.1537	0.815	0.870	170.6
	240.00	0.718	567.04	2.1709	0.822	0.877	172.3
	250.00	0.704	575.84	2.1879	0.830	0.884	173.9
			Pressure = 0.040 MPa				
	−100.00	1754.6	105.46	0.5702	0.632	0.926	1215.3
	−90.00	1732.0	114.70	0.6221	0.633	0.923	1174.6
	−80.00	1709.7	123.93	0.6712	0.635	0.924	1133.1
	−70.00	1687.4	133.18	0.7178	0.637	0.927	1091.1
	−60.00	1665.1	142.47	0.7625	0.641	0.932	1048.8
	−50.00	1642.7	151.83	0.8054	0.646	0.939	1006.5
	−40.00	1620.0	161.26	0.8467	0.653	0.948	964.4
	−30.00	1597.1	170.79	0.8867	0.660	0.958	922.7
	−20.00	1573.8	180.42	0.9256	0.667	0.968	881.4
	−10.00	1550.2	190.16	0.9633	0.676	0.979	840.8
	0.00	1526.1	200.00	1.0000	0.684	0.990	800.7
sat liquid	4.54	1515.1	204.51	1.0163	0.688	0.995	782.7
sat vapor	4.54	2.710	384.17	1.6633	0.597	0.659	126.1
	10.00	2.654	387.78	1.6762	0.604	0.665	127.4
	20.00	2.556	394.48	1.6995	0.616	0.675	129.8
	30.00	2.467	401.29	1.7223	0.627	0.686	132.1
	40.00	2.384	408.21	1.7448	0.639	0.697	134.4
	50.00	2.306	415.23	1.7668	0.650	0.708	136.6
	60.00	2.234	422.36	1.7886	0.661	0.719	138.7
	70.00	2.166	429.60	1.8100	0.672	0.729	140.8
	80.00	2.103	436.94	1.8311	0.682	0.739	142.9
	90.00	2.043	444.39	1.8519	0.693	0.749	144.9

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TABLE C.2. Single-phase properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) — Continued

Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
Pressure = 0.040 MPa — Continued						
100.00	1.987	451.93	1.8723	0.703	0.759	146.9
110.00	1.934	459.57	1.8925	0.713	0.769	148.9
120.00	1.883	467.30	1.9125	0.722	0.778	150.8
130.00	1.836	475.13	1.9321	0.732	0.788	152.7
140.00	1.790	483.05	1.9515	0.741	0.797	154.6
150.00	1.747	491.06	1.9707	0.750	0.806	156.4
160.00	1.706	499.16	1.9896	0.759	0.814	158.3
170.00	1.667	507.35	2.0083	0.767	0.823	160.1
180.00	1.630	515.62	2.0268	0.776	0.831	161.8
190.00	1.594	523.97	2.0450	0.784	0.839	163.6
200.00	1.560	532.40	2.0630	0.792	0.847	165.3
210.00	1.527	540.91	2.0808	0.800	0.855	167.1
220.00	1.496	549.50	2.0984	0.808	0.863	168.8
230.00	1.466	558.17	2.1158	0.815	0.870	170.4
240.00	1.437	566.91	2.1330	0.823	0.878	172.1
250.00	1.410	575.72	2.1500	0.830	0.885	173.8
Pressure = 0.060 MPa						
−100.00	1754.6	105.46	0.5701	0.632	0.926	1215.3
−90.00	1732.0	114.71	0.6221	0.633	0.923	1174.6
−80.00	1709.7	123.94	0.6711	0.635	0.924	1133.1
−70.00	1687.4	133.19	0.7178	0.637	0.927	1091.1
−60.00	1665.1	142.48	0.7625	0.641	0.932	1048.9
−50.00	1642.7	151.84	0.8054	0.646	0.939	1006.6
−40.00	1620.0	161.27	0.8467	0.653	0.948	964.5
−30.00	1597.1	170.80	0.8867	0.660	0.958	922.7
−20.00	1573.8	180.43	0.9255	0.667	0.968	881.5
−10.00	1550.2	190.16	0.9633	0.676	0.979	840.8
0.00	1526.2	200.01	1.0000	0.684	0.990	800.8
10.00	1501.6	209.97	1.0358	0.692	1.002	761.3
14.15	1491.3	214.14	1.0504	0.696	1.007	745.1
14.15	3.960	389.96	1.6624	0.612	0.676	127.4
20.00	3.872	393.93	1.6761	0.618	0.681	128.8
30.00	3.731	400.80	1.6991	0.630	0.691	131.2
40.00	3.602	407.76	1.7217	0.641	0.701	133.5
50.00	3.482	414.82	1.7439	0.652	0.712	135.8
60.00	3.371	421.99	1.7657	0.662	0.722	138.0
70.00	3.267	429.26	1.7872	0.673	0.732	140.2
80.00	3.169	436.63	1.8084	0.683	0.742	142.3
90.00	3.078	444.09	1.8292	0.694	0.751	144.4
100.00	2.992	451.65	1.8498	0.703	0.761	146.4
110.00	2.911	459.31	1.8700	0.713	0.771	148.4
120.00	2.834	467.06	1.8900	0.723	0.780	150.4
130.00	2.761	474.91	1.9097	0.732	0.789	152.3
140.00	2.693	482.84	1.9291	0.741	0.798	154.2
150.00	2.628	490.86	1.9483	0.750	0.807	156.1
160.00	2.565	498.97	1.9673	0.759	0.815	158.0
170.00	2.506	507.17	1.9860	0.768	0.824	159.8
180.00	2.450	515.45	2.0044	0.776	0.832	161.6
190.00	2.395	523.81	2.0227	0.784	0.840	163.4
200.00	2.344	532.25	2.0407	0.792	0.848	165.1

TABLE C.2.   Single-phase properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) — Continued

Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
			Pressure = 0.060 MPa — Continued			
210.00	2.295	540.76	2.0585	0.800	0.856	166.8
220.00	2.248	549.36	2.0761	0.808	0.863	168.6
230.00	2.202	558.03	2.0935	0.815	0.871	170.3
240.00	2.158	566.78	2.1108	0.823	0.878	171.9
250.00	2.117	575.59	2.1278	0.830	0.885	173.6
			Pressure = 0.100 MPa			
−100.00	1754.6	105.48	0.5701	0.632	0.926	1215.2
−90.00	1732.1	114.73	0.6220	0.633	0.923	1174.6
−80.00	1709.7	123.96	0.6711	0.635	0.924	1133.2
−70.00	1687.5	133.21	0.7178	0.637	0.927	1091.2
−60.00	1665.2	142.50	0.7624	0.641	0.932	1048.9
−50.00	1642.7	151.85	0.8053	0.646	0.939	1006.6
−40.00	1620.1	161.29	0.8467	0.653	0.948	964.6
−30.00	1597.2	170.82	0.8867	0.660	0.958	922.9
−20.00	1573.9	180.45	0.9255	0.668	0.968	881.6
−10.00	1550.3	190.18	0.9632	0.676	0.979	841.0
0.00	1526.3	200.02	0.9999	0.684	0.990	801.0
10.00	1501.7	209.98	1.0357	0.692	1.002	761.5
20.00	1476.7	220.06	1.0707	0.701	1.014	722.7
sat liquid 27.46	1457.6	227.65	1.0963	0.708	1.023	694.1
sat vapor 27.46	6.392	398.00	1.6629	0.632	0.700	128.7
30.00	6.329	399.78	1.6688	0.634	0.702	129.3
40.00	6.097	406.84	1.6918	0.645	0.711	131.9
50.00	5.884	413.99	1.7142	0.655	0.719	134.3
60.00	5.687	421.23	1.7363	0.665	0.728	136.7
70.00	5.504	428.56	1.7580	0.676	0.738	138.9
80.00	5.334	435.98	1.7793	0.686	0.747	141.2
90.00	5.175	443.49	1.8003	0.695	0.756	143.3
100.00	5.027	451.10	1.8209	0.705	0.765	145.5
110.00	4.887	458.80	1.8413	0.715	0.774	147.5
120.00	4.755	466.58	1.8613	0.724	0.783	149.6
130.00	4.631	474.45	1.8811	0.733	0.792	151.6
140.00	4.513	482.42	1.9006	0.742	0.800	153.5
150.00	4.401	490.46	1.9199	0.751	0.809	155.4
160.00	4.296	498.59	1.9389	0.760	0.817	157.3
170.00	4.195	506.81	1.9576	0.768	0.826	159.2
180.00	4.099	515.10	1.9761	0.777	0.834	161.0
190.00	4.007	523.48	1.9944	0.785	0.842	162.9
200.00	3.920	531.94	2.0125	0.793	0.849	164.6
210.00	3.836	540.47	2.0303	0.800	0.857	166.4
220.00	3.757	549.08	2.0479	0.808	0.865	168.2
230.00	3.680	557.76	2.0654	0.816	0.872	169.9
240.00	3.607	566.51	2.0826	0.823	0.879	171.6
250.00	3.536	575.34	2.0996	0.830	0.886	173.3
			Pressure = 0.101 325 MPa			
−100.00	1754.6	105.48	0.5701	0.632	0.926	1215.2
−90.00	1732.1	114.73	0.6220	0.633	0.923	1174.6
−80.00	1709.7	123.96	0.6711	0.635	0.924	1133.2
−70.00	1687.5	133.21	0.7178	0.637	0.927	1091.2
−60.00	1665.2	142.50	0.7624	0.641	0.932	1048.9

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TABLE C.2. Single-phase properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) — Continued

Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
Pressure = 0.101 325 MPa — Continued						
−50.00	1642.7	151.85	0.8053	0.646	0.939	1006.7
−40.00	1620.1	161.29	0.8467	0.653	0.948	964.6
−30.00	1597.2	170.82	0.8867	0.660	0.958	922.9
−20.00	1573.9	180.45	0.9255	0.668	0.968	881.6
−10.00	1550.3	190.18	0.9632	0.676	0.979	841.0
0.00	1526.3	200.03	0.9999	0.684	0.990	801.0
10.00	1501.7	209.98	1.0357	0.692	1.002	761.6
20.00	1476.7	220.06	1.0707	0.701	1.014	722.7
sat liquid 27.82	1456.6	228.03	1.0975	0.708	1.023	692.7
sat vapor 27.82	6.471	398.22	1.6630	0.632	0.701	128.7
30.00	6.417	399.74	1.6680	0.635	0.702	129.3
40.00	6.181	406.81	1.6910	0.645	0.711	131.8
50.00	5.964	413.96	1.7135	0.655	0.720	134.3
60.00	5.764	421.20	1.7355	0.665	0.729	136.6
70.00	5.579	428.54	1.7572	0.676	0.738	138.9
80.00	5.407	435.96	1.7785	0.686	0.747	141.1
90.00	5.245	443.47	1.7995	0.696	0.756	143.3
100.00	5.094	451.08	1.8202	0.705	0.765	145.4
110.00	4.952	458.78	1.8405	0.715	0.774	147.5
120.00	4.819	466.56	1.8606	0.724	0.783	149.5
130.00	4.693	474.44	1.8804	0.733	0.792	151.5
140.00	4.574	482.40	1.8999	0.742	0.801	153.5
150.00	4.460	490.45	1.9191	0.751	0.809	155.4
160.00	4.353	498.58	1.9381	0.760	0.817	157.3
170.00	4.251	506.80	1.9569	0.768	0.826	159.2
180.00	4.154	515.09	1.9754	0.777	0.834	161.0
190.00	4.061	523.47	1.9937	0.785	0.842	162.8
200.00	3.973	531.93	2.0117	0.793	0.849	164.6
210.00	3.888	540.46	2.0296	0.800	0.857	166.4
220.00	3.807	549.07	2.0472	0.808	0.865	168.1
230.00	3.729	557.75	2.0646	0.816	0.872	169.9
240.00	3.655	566.51	2.0819	0.823	0.879	171.6
250.00	3.584	575.34	2.0989	0.830	0.886	173.2
Pressure = 0.200 MPa						
−100.00	1754.7	105.53	0.5700	0.632	0.926	1215.2
−90.00	1732.2	114.77	0.6220	0.634	0.923	1174.6
−80.00	1709.9	124.00	0.6710	0.635	0.924	1133.3
−70.00	1687.6	133.25	0.7177	0.637	0.926	1091.3
−60.00	1665.3	142.54	0.7624	0.641	0.932	1049.1
−50.00	1642.9	151.90	0.8052	0.646	0.939	1006.9
−40.00	1620.2	161.33	0.8466	0.653	0.948	964.8
−30.00	1597.3	170.86	0.8866	0.660	0.958	923.2
−20.00	1574.1	180.48	0.9254	0.668	0.968	882.0
−10.00	1550.5	190.22	0.9631	0.676	0.979	841.4
0.00	1526.5	200.06	0.9998	0.684	0.990	801.4
10.00	1502.0	210.02	1.0356	0.693	1.001	762.0
20.00	1476.9	220.09	1.0706	0.701	1.013	723.2
30.00	1451.3	230.29	1.1048	0.710	1.026	685.0
40.00	1424.9	240.61	1.1383	0.719	1.038	647.1
sat liquid 48.05	1403.1	249.00	1.1647	0.726	1.049	616.9

TABLE C.2.   Single-phase properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) — Continued

	Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
				Pressure = 0.200 MPa — Continued			
sat vapor	48.05	12.302	410.34	1.6670	0.663	0.741	129.7
	50.00	12.207	411.79	1.6715	0.665	0.742	130.3
	60.00	11.747	419.23	1.6942	0.673	0.747	133.0
	70.00	11.328	426.74	1.7164	0.682	0.754	135.7
	80.00	10.944	434.31	1.7382	0.692	0.761	138.2
	90.00	10.591	441.96	1.7595	0.701	0.768	140.6
	100.00	10.263	449.68	1.7805	0.710	0.776	143.0
	110.00	9.957	457.47	1.8011	0.719	0.784	145.2
	120.00	9.673	465.35	1.8214	0.727	0.791	147.4
	130.00	9.406	473.30	1.8414	0.736	0.799	149.6
	140.00	9.154	481.33	1.8611	0.745	0.807	151.7
	150.00	8.918	489.44	1.8804	0.753	0.815	153.8
	160.00	8.694	497.63	1.8996	0.762	0.823	155.8
	170.00	8.482	505.90	1.9184	0.770	0.830	157.8
	180.00	8.280	514.24	1.9371	0.778	0.838	159.7
	190.00	8.089	522.66	1.9554	0.786	0.846	161.6
	200.00	7.908	531.15	1.9736	0.794	0.853	163.5
	210.00	7.734	539.72	1.9915	0.802	0.860	165.3
	220.00	7.568	548.36	2.0092	0.809	0.868	167.1
	230.00	7.410	557.08	2.0267	0.816	0.875	168.9
	240.00	7.259	565.86	2.0440	0.824	0.882	170.7
	250.00	7.114	574.72	2.0611	0.831	0.889	172.4
				Pressure = 0.400 MPa			
	−100.00	1754.9	105.62	0.5699	0.633	0.926	1215.1
	−90.00	1732.4	114.86	0.6218	0.634	0.923	1174.7
	−80.00	1710.1	124.09	0.6709	0.635	0.923	1133.4
	−70.00	1687.9	133.34	0.7176	0.637	0.926	1091.6
	−60.00	1665.6	142.63	0.7622	0.641	0.932	1049.5
	−50.00	1643.2	151.98	0.8051	0.647	0.939	1007.3
	−40.00	1620.6	161.41	0.8464	0.653	0.948	965.4
	−30.00	1597.7	170.94	0.8864	0.660	0.957	923.8
	−20.00	1574.5	180.56	0.9252	0.668	0.968	882.7
	−10.00	1550.9	190.30	0.9629	0.676	0.979	842.2
	0.00	1526.9	200.14	0.9996	0.684	0.990	802.3
	10.00	1502.5	210.09	1.0354	0.693	1.001	763.0
	20.00	1477.5	220.16	1.0704	0.701	1.013	724.3
	30.00	1451.9	230.35	1.1045	0.710	1.025	686.2
	40.00	1425.6	240.66	1.1380	0.719	1.038	648.4
	50.00	1398.5	251.11	1.1708	0.727	1.051	611.0
	60.00	1370.5	261.69	1.2031	0.736	1.066	573.8
	70.00	1341.3	272.43	1.2348	0.745	1.082	536.6
sat liquid	72.20	1334.7	274.82	1.2418	0.747	1.086	528.4
sat vapor	72.20	23.962	424.47	1.6751	0.700	0.796	129.0
	80.00	23.185	430.68	1.6929	0.705	0.796	131.6
	90.00	22.285	438.64	1.7151	0.712	0.798	134.7
	100.00	21.474	446.64	1.7369	0.719	0.801	137.6
	110.00	20.736	454.67	1.7581	0.727	0.806	140.3
	120.00	20.061	462.75	1.7789	0.735	0.811	143.0
	130.00	19.437	470.89	1.7994	0.742	0.816	145.5
	140.00	18.860	479.08	1.8194	0.750	0.822	147.9
	150.00	18.326	487.33	1.8391	0.758	0.828	150.3
	160.00	17.822	495.64	1.8586	0.766	0.835	152.5

TABLE C.2.   Single-phase properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) — Continued

Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
			Pressure = 0.400 MPa — Continued			
170.00	17.352	504.02	1.8777	0.774	0.841	154.8
180.00	16.908	512.47	1.8965	0.781	0.848	156.9
190.00	16.491	520.98	1.9151	0.789	0.854	159.0
200.00	16.096	529.56	1.9334	0.796	0.861	161.1
210.00	15.721	538.20	1.9515	0.804	0.868	163.1
220.00	15.366	546.91	1.9694	0.811	0.874	165.0
230.00	15.026	555.69	1.9870	0.818	0.881	167.0
240.00	14.705	564.53	2.0044	0.825	0.888	168.9
250.00	14.397	573.44	2.0216	0.832	0.894	170.7
			Pressure = 0.600 MPa			
−100.00	1755.1	105.70	0.5697	0.633	0.926	1215.0
−90.00	1732.6	114.95	0.6217	0.634	0.923	1174.7
−80.00	1710.3	124.18	0.6707	0.635	0.923	1133.6
−70.00	1688.1	133.43	0.7174	0.638	0.926	1091.9
−60.00	1665.8	142.71	0.7620	0.642	0.932	1049.8
−50.00	1643.5	152.07	0.8049	0.647	0.939	1007.8
−40.00	1620.9	161.50	0.8463	0.653	0.948	965.9
−30.00	1598.0	171.02	0.8862	0.660	0.957	924.4
−20.00	1574.8	180.64	0.9250	0.668	0.968	883.4
−10.00	1551.3	190.37	0.9627	0.676	0.978	843.0
0.00	1527.4	200.21	0.9994	0.684	0.989	803.2
10.00	1503.0	210.16	1.0352	0.693	1.001	764.0
20.00	1478.0	220.23	1.0701	0.701	1.013	725.4
30.00	1452.5	230.41	1.1043	0.710	1.025	687.3
40.00	1426.3	240.72	1.1377	0.719	1.037	649.7
50.00	1399.3	251.16	1.1706	0.728	1.051	612.5
60.00	1371.3	261.74	1.2028	0.736	1.065	575.4
70.00	1342.3	272.46	1.2345	0.745	1.081	538.4
80.00	1311.9	283.36	1.2658	0.754	1.099	501.2
sat liquid 88.34	1285.2	292.59	1.2916	0.762	1.116	469.8
sat vapor 88.34	35.763	433.52	1.6815	0.725	0.840	127.2
90.00	35.482	434.92	1.6854	0.725	0.839	127.9
100.00	33.924	443.28	1.7081	0.731	0.835	131.5
110.00	32.553	451.62	1.7301	0.736	0.834	134.9
120.00	31.329	459.96	1.7516	0.743	0.834	138.1
130.00	30.225	468.31	1.7726	0.749	0.836	141.1
140.00	29.219	476.69	1.7931	0.756	0.840	143.9
150.00	28.300	485.11	1.8133	0.763	0.844	146.6
160.00	27.448	493.57	1.8330	0.770	0.848	149.2
170.00	26.661	502.08	1.8524	0.778	0.853	151.6
180.00	25.922	510.64	1.8715	0.785	0.859	154.0
190.00	25.236	519.25	1.8903	0.792	0.864	156.3
200.00	24.590	527.92	1.9089	0.799	0.870	158.6
210.00	23.981	536.65	1.9271	0.806	0.876	160.8
220.00	23.406	545.43	1.9451	0.813	0.882	162.9
230.00	22.865	554.28	1.9629	0.820	0.888	165.0
240.00	22.349	563.19	1.9804	0.827	0.894	167.0
250.00	21.862	572.15	1.9977	0.834	0.900	169.0

TABLE C.2.   Single-phase properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) — Continued

	Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
				Pressure = 1.000 MPa			
	−100.00	1755.5	105.88	0.5695	0.633	0.926	1214.9
	−90.00	1733.0	115.12	0.6214	0.635	0.923	1174.9
	−80.00	1710.8	124.35	0.6704	0.636	0.923	1133.9
	−70.00	1688.6	133.60	0.7171	0.638	0.926	1092.4
	−60.00	1666.4	142.89	0.7617	0.642	0.931	1050.6
	−50.00	1644.0	152.23	0.8046	0.647	0.939	1008.7
	−40.00	1621.5	161.66	0.8459	0.654	0.947	967.0
	−30.00	1598.7	171.18	0.8859	0.661	0.957	925.6
	−20.00	1575.6	180.80	0.9247	0.668	0.967	884.8
	−10.00	1552.1	190.53	0.9623	0.676	0.978	844.5
	0.00	1528.3	200.36	0.9990	0.685	0.989	804.9
	10.00	1504.0	210.30	1.0348	0.693	1.000	765.9
	20.00	1479.1	220.36	1.0697	0.702	1.012	727.5
	30.00	1453.7	230.54	1.1038	0.710	1.024	689.7
	40.00	1427.7	240.84	1.1372	0.719	1.036	652.4
	50.00	1400.8	251.27	1.1700	0.728	1.049	615.4
	60.00	1373.1	261.83	1.2022	0.737	1.063	578.6
	70.00	1344.3	272.54	1.2339	0.745	1.079	542.0
	80.00	1314.2	283.41	1.2651	0.754	1.096	505.2
	90.00	1282.4	294.47	1.2960	0.764	1.117	468.1
	100.00	1248.6	305.76	1.3266	0.773	1.141	430.3
	110.00	1212.2	317.31	1.3572	0.783	1.171	391.3
sat liquid	111.15	1207.7	318.66	1.3607	0.784	1.175	386.7
sat vapor	111.15	60.445	445.45	1.6906	0.761	0.922	122.4
	120.00	57.583	453.52	1.7114	0.763	0.905	126.7
	130.00	54.831	462.52	1.7340	0.766	0.894	131.0
	140.00	52.457	471.42	1.7558	0.770	0.887	134.9
	150.00	50.367	480.27	1.7770	0.775	0.884	138.5
	160.00	48.515	489.10	1.7976	0.781	0.882	141.8
	170.00	46.838	497.92	1.8177	0.786	0.883	144.9
	180.00	45.311	506.75	1.8374	0.792	0.884	147.9
	190.00	43.909	515.61	1.8568	0.799	0.887	150.7
	200.00	42.625	524.49	1.8757	0.805	0.890	153.4
	210.00	41.425	533.41	1.8944	0.811	0.894	156.0
	220.00	40.317	542.37	1.9127	0.818	0.898	158.5
	230.00	39.276	551.37	1.9308	0.824	0.902	160.9
	240.00	38.294	560.42	1.9486	0.830	0.907	163.2
	250.00	37.371	569.51	1.9662	0.837	0.912	165.4
				Pressure = 2.000 MPa			
	−100.00	1756.5	106.32	0.5687	0.635	0.926	1214.5
	−90.00	1734.1	115.57	0.6206	0.636	0.923	1175.1
	−80.00	1711.9	124.79	0.6697	0.637	0.923	1134.8
	−70.00	1689.8	134.03	0.7163	0.639	0.926	1093.8
	−60.00	1667.7	143.32	0.7609	0.643	0.931	1052.4
	−50.00	1645.5	152.66	0.8037	0.648	0.938	1011.0
	−40.00	1623.0	162.08	0.8450	0.654	0.946	969.7
	−30.00	1600.4	171.59	0.8850	0.661	0.956	928.7
	−20.00	1577.4	181.20	0.9237	0.669	0.966	888.3
	−10.00	1554.1	190.91	0.9613	0.677	0.977	848.5

TABLE C.2.   Single-phase properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) — Continued

Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
			Pressure = 2.000 MPa — Continued			
0.00	1530.5	200.73	0.9980	0.686	0.987	809.3
10.00	1506.4	210.66	1.0337	0.694	0.999	770.7
20.00	1481.8	220.70	1.0685	0.703	1.010	732.8
30.00	1456.7	230.86	1.1026	0.711	1.021	695.5
40.00	1431.0	241.14	1.1359	0.720	1.034	658.8
50.00	1404.6	251.53	1.1686	0.728	1.046	622.5
60.00	1377.3	262.06	1.2007	0.737	1.060	586.5
70.00	1349.1	272.73	1.2323	0.746	1.074	550.7
80.00	1319.7	283.55	1.2633	0.755	1.090	515.0
90.00	1288.9	294.55	1.2940	0.764	1.109	479.1
100.00	1256.4	305.74	1.3244	0.773	1.131	442.8
110.00	1221.5	317.17	1.3547	0.782	1.157	405.8
120.00	1183.7	328.90	1.3849	0.793	1.190	367.6
130.00	1141.6	341.02	1.4153	0.804	1.236	327.6
140.00	1093.2	353.69	1.4464	0.816	1.304	284.6
sat liquid 147.25	1051.7	363.42	1.4697	0.827	1.383	250.2
sat vapor 147.25	133.636	460.29	1.7001	0.825	1.198	107.6
150.00	129.994	463.53	1.7078	0.823	1.160	110.2
160.00	119.518	474.64	1.7338	0.818	1.072	118.0
170.00	111.704	485.11	1.7577	0.817	1.025	124.3
180.00	105.481	495.20	1.7802	0.818	0.996	129.7
190.00	100.305	505.07	1.8017	0.820	0.978	134.5
200.00	95.874	514.78	1.8225	0.823	0.966	138.8
210.00	92.014	524.40	1.8426	0.826	0.958	142.7
220.00	88.589	533.96	1.8622	0.831	0.954	146.4
230.00	85.518	543.48	1.8813	0.835	0.951	149.8
240.00	82.732	552.99	1.9000	0.840	0.950	153.0
250.00	80.186	562.49	1.9183	0.845	0.950	156.1
			Pressure = 4.000 MPa			
−100.00	1758.5	107.21	0.5673	0.637	0.926	1213.8
−90.00	1736.2	116.45	0.6191	0.638	0.923	1175.8
−80.00	1714.1	125.67	0.6682	0.639	0.922	1136.6
−70.00	1692.2	134.90	0.7148	0.641	0.925	1096.6
−60.00	1670.3	144.18	0.7593	0.645	0.930	1056.1
−50.00	1648.3	153.51	0.8021	0.650	0.937	1015.5
−40.00	1626.1	162.91	0.8433	0.656	0.945	975.0
−30.00	1603.7	172.41	0.8832	0.663	0.954	934.9
−20.00	1581.1	182.00	0.9219	0.671	0.964	895.2
−10.00	1558.1	191.69	0.9594	0.679	0.974	856.2
0.00	1534.8	201.49	0.9960	0.687	0.985	817.8
10.00	1511.2	211.39	1.0316	0.695	0.996	780.2
20.00	1487.1	221.40	1.0663	0.704	1.006	743.2
30.00	1462.6	231.52	1.1002	0.712	1.017	706.9
40.00	1437.5	241.75	1.1334	0.721	1.029	671.2
50.00	1411.8	252.09	1.1660	0.729	1.040	636.1
60.00	1385.4	262.56	1.1979	0.738	1.053	601.5
70.00	1358.3	273.15	1.2292	0.747	1.066	567.3
80.00	1330.2	283.88	1.2600	0.755	1.080	533.4
90.00	1301.0	294.76	1.2904	0.764	1.096	499.6

TABLE C.2. Single-phase properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) — Continued

Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
			Pressure = 4.000 MPa — Continued			
100.00	1270.4	305.81	1.3204	0.773	1.114	465.8
110.00	1238.2	317.05	1.3501	0.782	1.134	431.8
120.00	1203.9	328.51	1.3796	0.791	1.159	397.5
130.00	1167.0	340.25	1.4091	0.800	1.190	362.5
140.00	1126.4	352.33	1.4387	0.811	1.229	326.5
150.00	1080.9	364.88	1.4687	0.822	1.283	289.0
160.00	1027.8	378.08	1.4996	0.835	1.365	249.1
170.00	961.5	392.38	1.5322	0.851	1.513	205.0
180.00	864.9	409.11	1.5695	0.875	1.926	151.6
190.00	492.3	449.56	1.6575	0.937	7.969	81.4
200.00	304.4	482.11	1.7272	0.896	1.869	98.2
210.00	260.0	498.09	1.7607	0.880	1.421	109.6
220.00	234.3	511.37	1.7879	0.872	1.257	118.1
230.00	216.2	523.48	1.8122	0.869	1.172	125.1
240.00	202.4	534.92	1.8347	0.868	1.121	131.2
250.00	191.2	545.96	1.8560	0.868	1.088	136.5
			Pressure = 6.000 MPa			
−100.00	1760.4	108.09	0.5658	0.640	0.926	1213.2
−90.00	1738.2	117.33	0.6177	0.640	0.922	1176.5
−80.00	1716.4	126.55	0.6667	0.641	0.922	1138.4
−70.00	1694.6	135.78	0.7133	0.643	0.924	1099.4
−60.00	1672.9	145.04	0.7578	0.647	0.929	1059.8
−50.00	1651.0	154.36	0.8005	0.652	0.936	1020.0
−40.00	1629.1	163.75	0.8417	0.658	0.944	980.3
−30.00	1607.0	173.23	0.8815	0.665	0.953	941.0
−20.00	1584.6	182.81	0.9201	0.672	0.962	902.1
−10.00	1562.0	192.48	0.9575	0.680	0.972	863.8
0.00	1539.1	202.25	0.9940	0.689	0.982	826.2
10.00	1515.8	212.13	1.0295	0.697	0.993	789.4
20.00	1492.2	222.11	1.0641	0.705	1.003	753.2
30.00	1468.2	232.19	1.0980	0.714	1.014	717.9
40.00	1443.7	242.38	1.1310	0.722	1.024	683.2
50.00	1418.7	252.68	1.1634	0.731	1.035	649.2
60.00	1393.1	263.09	1.1951	0.739	1.047	615.8
70.00	1366.9	273.62	1.2263	0.747	1.059	582.9
80.00	1339.9	284.27	1.2569	0.756	1.072	550.4
90.00	1312.0	295.05	1.2870	0.764	1.085	518.3
100.00	1283.1	305.98	1.3167	0.772	1.101	486.5
110.00	1252.9	317.07	1.3460	0.781	1.118	454.8
120.00	1221.2	328.34	1.3750	0.790	1.137	423.2
130.00	1187.6	339.83	1.4039	0.798	1.160	391.5
140.00	1151.8	351.56	1.4326	0.808	1.187	359.6
150.00	1113.0	363.59	1.4614	0.817	1.221	327.4
160.00	1070.3	376.00	1.4904	0.827	1.263	294.8
170.00	1022.4	388.90	1.5198	0.839	1.320	261.4
180.00	967.1	402.47	1.5501	0.851	1.400	227.2
190.00	900.6	417.04	1.5819	0.865	1.523	192.0
200.00	815.8	433.21	1.6164	0.883	1.728	156.6
210.00	702.8	451.96	1.6556	0.902	2.028	126.0
220.00	573.2	473.03	1.6988	0.914	2.111	111.2
230.00	470.7	492.94	1.7388	0.911	1.844	110.9
240.00	404.7	509.94	1.7722	0.904	1.572	116.0
250.00	361.2	524.72	1.8008	0.897	1.399	122.2

TABLE C.2.   Single-phase properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) — Continued

Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
Pressure =10.000 MPa						
−100.00	1764.4	109.86	0.5629	0.645	0.926	1212.2
−90.00	1742.4	119.10	0.6148	0.645	0.922	1178.2
−80.00	1720.8	128.31	0.6638	0.645	0.921	1142.3
−70.00	1699.3	137.52	0.7103	0.647	0.923	1105.2
−60.00	1677.9	146.77	0.7547	0.650	0.927	1067.3
−50.00	1656.5	156.07	0.7973	0.655	0.933	1029.1
−40.00	1635.0	165.44	0.8384	0.661	0.941	990.9
−30.00	1613.3	174.89	0.8781	0.668	0.950	953.0
−20.00	1591.5	184.43	0.9166	0.675	0.959	915.5
−10.00	1569.5	194.07	0.9539	0.683	0.968	878.7
0.00	1547.2	203.80	0.9902	0.691	0.978	842.5
10.00	1524.7	213.63	1.0255	0.700	0.988	807.1
20.00	1501.9	223.56	1.0600	0.708	0.997	772.5
30.00	1478.8	233.58	1.0936	0.716	1.007	738.8
40.00	1455.4	243.70	1.1264	0.724	1.017	705.8
50.00	1431.6	253.92	1.1586	0.733	1.027	673.7
60.00	1407.4	264.24	1.1900	0.741	1.037	642.3
70.00	1382.7	274.66	1.2208	0.749	1.047	611.5
80.00	1357.5	285.19	1.2511	0.757	1.058	581.5
90.00	1331.7	295.82	1.2807	0.765	1.069	552.0
100.00	1305.2	306.57	1.3099	0.773	1.081	523.1
110.00	1278.0	317.44	1.3387	0.781	1.094	494.7
120.00	1249.9	328.45	1.3671	0.788	1.108	466.7
130.00	1220.8	339.60	1.3951	0.796	1.123	439.2
140.00	1190.4	350.91	1.4228	0.804	1.139	412.1
150.00	1158.8	362.39	1.4502	0.812	1.158	385.4
160.00	1125.5	374.07	1.4775	0.820	1.179	359.2
170.00	1090.3	385.97	1.5047	0.828	1.202	333.4
180.00	1053.0	398.13	1.5318	0.837	1.229	308.3
190.00	1013.2	410.56	1.5589	0.845	1.259	283.9
200.00	970.6	423.31	1.5862	0.854	1.292	260.5
210.00	924.9	436.40	1.6136	0.862	1.327	238.4
220.00	876.2	449.86	1.6411	0.871	1.363	218.2
230.00	824.7	463.66	1.6688	0.879	1.396	200.3
240.00	771.4	477.75	1.6965	0.886	1.420	185.3
250.00	717.8	492.02	1.7241	0.893	1.430	173.7
Pressure = 20.000 MPa						
−100.00	1774.1	114.30	0.5559	0.655	0.927	1211.2
−90.00	1752.6	123.53	0.6078	0.654	0.921	1183.5
−80.00	1731.5	132.73	0.6566	0.653	0.919	1152.9
−70.00	1710.7	141.92	0.7030	0.654	0.920	1120.3
−60.00	1690.1	151.13	0.7473	0.657	0.923	1086.4
−50.00	1669.6	160.39	0.7897	0.662	0.929	1051.8
−40.00	1649.0	169.71	0.8306	0.668	0.936	1017.0
−30.00	1628.4	179.10	0.8700	0.674	0.943	982.3
−20.00	1607.7	188.58	0.9082	0.682	0.952	947.9
−10.00	1587.0	198.14	0.9453	0.689	0.960	914.0
0.00	1566.1	207.79	0.9812	0.697	0.969	880.8
10.00	1545.1	217.52	1.0163	0.705	0.978	848.5
20.00	1524.0	227.34	1.0503	0.713	0.986	816.9
30.00	1502.8	237.25	1.0836	0.721	0.995	786.3
40.00	1481.4	247.24	1.1160	0.729	1.003	756.6

TABLE C.2. Single-phase properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) — Continued

Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
Pressure = 20.000 MPa — Continued

Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
50.00	1459.8	257.32	1.1477	0.737	1.012	727.7
60.00	1438.1	267.47	1.1786	0.745	1.020	699.8
70.00	1416.1	277.71	1.2089	0.753	1.028	672.8
80.00	1394.0	288.03	1.2385	0.760	1.036	646.6
90.00	1371.7	298.42	1.2676	0.767	1.044	621.2
100.00	1349.1	308.90	1.2960	0.775	1.052	596.6
110.00	1326.2	319.46	1.3239	0.782	1.060	572.8
120.00	1303.1	330.10	1.3514	0.789	1.068	549.7
130.00	1279.7	340.83	1.3783	0.796	1.077	527.3
140.00	1255.9	351.64	1.4048	0.802	1.086	505.7
150.00	1231.8	362.55	1.4309	0.809	1.095	484.7
160.00	1207.3	373.54	1.4566	0.815	1.104	464.4
170.00	1182.3	384.64	1.4819	0.822	1.114	444.9
180.00	1157.0	395.83	1.5068	0.828	1.124	426.0
190.00	1131.2	407.11	1.5315	0.834	1.134	408.0
200.00	1105.0	418.50	1.5558	0.840	1.144	390.7
210.00	1078.3	429.99	1.5798	0.846	1.154	374.3
220.00	1051.2	441.58	1.6036	0.852	1.163	358.8
230.00	1023.8	453.26	1.6270	0.857	1.173	344.2
240.00	996.2	465.03	1.6502	0.863	1.181	330.7
250.00	968.3	476.87	1.6731	0.868	1.188	318.2

Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
Pressure = 40.000 MPa

Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
−100.00	1793.1	123.16	0.5423	0.670	0.932	1213.5
−90.00	1772.2	132.42	0.5943	0.667	0.922	1197.7
−80.00	1752.0	141.62	0.6432	0.666	0.917	1176.6
−70.00	1732.3	150.78	0.6895	0.666	0.916	1152.0
−60.00	1712.8	159.95	0.7335	0.668	0.918	1125.0
−50.00	1693.6	169.15	0.7757	0.672	0.922	1096.6
−40.00	1674.5	178.41	0.8163	0.678	0.928	1067.2
−30.00	1655.5	187.72	0.8554	0.684	0.935	1037.5
−20.00	1636.6	197.11	0.8932	0.691	0.942	1007.9
−10.00	1617.7	206.57	0.9299	0.698	0.950	978.5
0.00	1598.9	216.10	0.9654	0.706	0.958	949.6
10.00	1580.1	225.72	1.0000	0.714	0.965	921.4
20.00	1561.3	235.41	1.0336	0.722	0.973	893.9
30.00	1542.5	245.17	1.0664	0.730	0.980	867.2
40.00	1523.8	255.01	1.0983	0.737	0.987	841.4
50.00	1505.1	264.91	1.1294	0.745	0.994	816.4
60.00	1486.4	274.88	1.1598	0.752	1.000	792.4
70.00	1467.8	284.92	1.1895	0.760	1.007	769.3
80.00	1449.2	295.02	1.2185	0.767	1.013	747.0
90.00	1430.5	305.18	1.2469	0.774	1.019	725.5
100.00	1412.0	315.39	1.2746	0.780	1.025	704.9
110.00	1393.4	325.67	1.3018	0.787	1.030	685.1
120.00	1374.9	336.00	1.3284	0.793	1.036	666.0
130.00	1356.3	346.39	1.3545	0.800	1.042	647.7
140.00	1337.8	356.83	1.3801	0.806	1.047	630.0
150.00	1319.3	367.33	1.4052	0.812	1.052	613.0
160.00	1300.9	377.88	1.4299	0.818	1.058	596.7
170.00	1282.4	388.48	1.4541	0.823	1.063	581.0
180.00	1264.0	399.14	1.4778	0.829	1.068	565.9
190.00	1245.6	409.84	1.5012	0.834	1.073	551.5

TABLE C.2. Single-phase properties of refrigerant 123 (2,2-dichloro-1,1,1-trifluoroethane) — Continued

Temperature (°C)	Density (kg/m³)	Enthalpy (kJ/kg)	Entropy (kJ/(kg·K))	C_v (kJ/(kg·K))	C_p (kJ/(kg·K))	Speed of Sound (m/s)
			Pressure = 40.000 MPa — Continued			
200.00	1227.2	420.60	1.5242	0.840	1.078	537.5
210.00	1208.8	431.41	1.5468	0.845	1.084	524.2
220.00	1190.5	442.27	1.5690	0.850	1.088	511.4
230.00	1172.2	453.18	1.5909	0.855	1.093	499.2
240.00	1153.9	464.14	1.6125	0.860	1.098	487.6
250.00	1135.8	475.14	1.6337	0.865	1.103	476.5

Refrigerant 123
(2,2-dichloro-1,1,1-trifluoroethane)
reference state:
h = 200.0 kJ/kg, s = 1.00 kJ/kg·K
for saturated liquid at 0 °C

Enthalpy (kJ/kg)

Pressure (MPa)
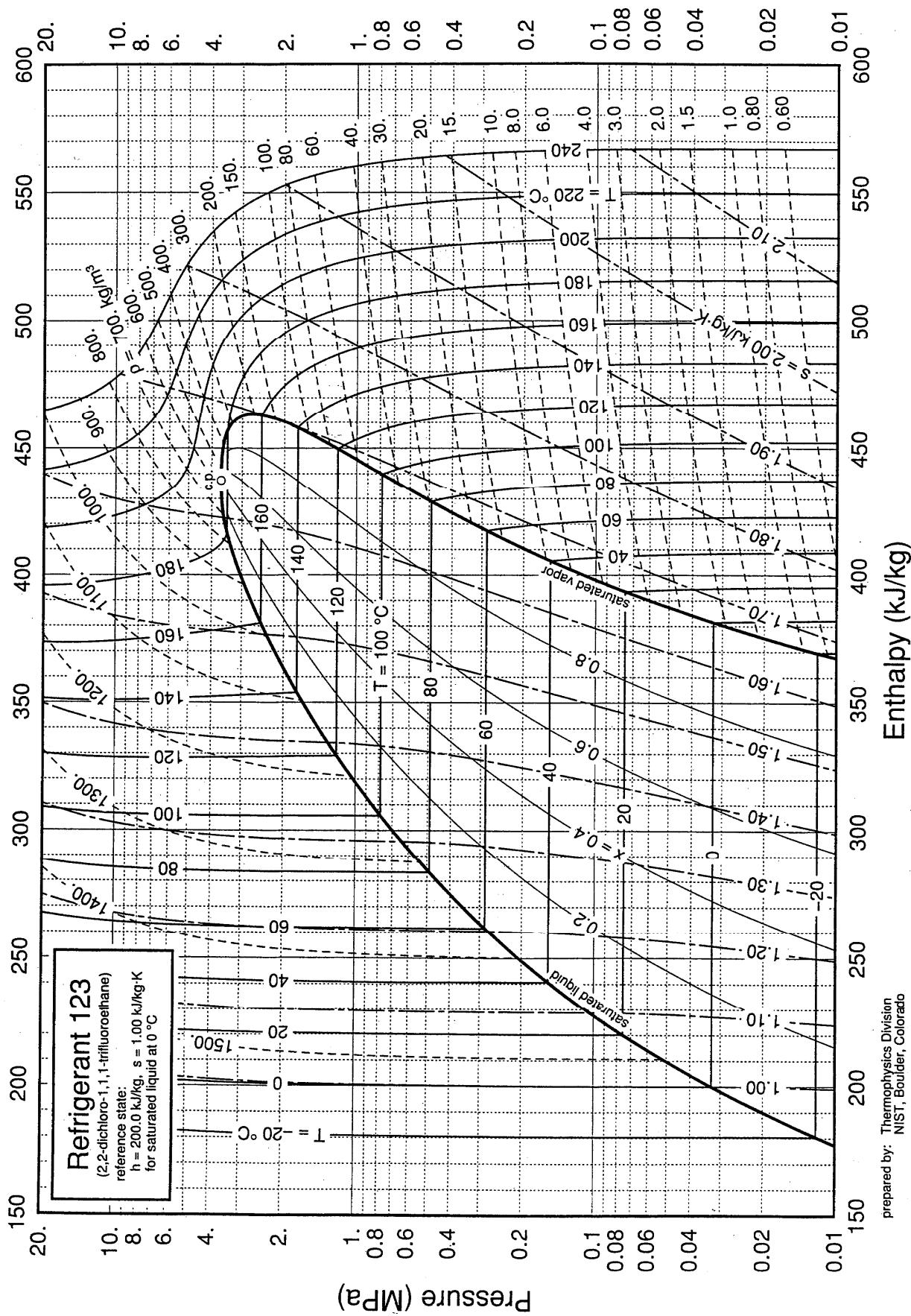
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