

PHYSICAL PROPERTIES OF FLUORINATED PROPANE AND BUTANE DERIVATIVES AS ALTERNATIVE REFRIGERANTS

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ABSTRACT

Physical property measurements are presented for 24 fluorinated propane and butane derivatives and one fluorinated ether. These measurements include melting point, boiling point, vapor pressure below the boiling point, heat of vaporization at the boiling point, critical properties (temperature and density), and liquid-phase heat capacities at 40°C (104°F). Measured vapor pressures are obtained up to the critical temperature for four of the compounds: R-227ea, R-245cb, R-236ea (all HFCs), and R-125a (an HFE). These measured data, combined with estimated vapor-phase densities, heat capacities, and vapor pressures, may be used to evaluate the chemicals as alternative refrigerants. Modified corresponding states methods, using R-134a (an HFC) as a reference fluid, are presented as a means of obtaining the needed estimated data, and the accuracy of these methods is judged by comparisons with measured data.

INTRODUCTION

Twenty-four fluorinated propane and butane derivatives and one fluorinated ether (see Table 1) have been investigated as second-generation alternatives for currently used chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). These investigations included both syntheses and physical property measurements. Synthetic routes were emphasized that used inexpensive, commercially available starting materials and basic synthetic procedures (chlorination, hydrogenation, and addition of hydrogen fluoride [Hudlicky 1976; Lovelace et al. 1958]) that are carried out industrially. However, further details regarding the synthetic procedures are left for a separate publication, and in this paper only the results of the physical property investigations are presented. The emphasis is on hydrogen-containing compounds that are expected to have finite atmospheric lifetimes that reduce their greenhouse warming potential. Sixteen of the chemicals investigated contain no chlorine

and therefore have zero ozone depletion potential. The remaining nine chlorine-containing chemicals were selected for investigation before the current calls for the complete phaseout of chlorine-containing refrigerants (U.S. 1990; UNEP 1990). Nevertheless, the low chlorine content of these chemicals, combined with a finite atmospheric lifetime, may in some cases yield an alternative with a sufficiently low ozone depletion potential. Therefore, it is possible that some of the chlorine-containing chemicals studied in this work may eventually prove to be valuable as we gain more knowledge about the ozone depletion problem.

The physical property investigations included measurement of the melting point, boiling point, vapor pressure below the boiling point, heat of vaporization at the boiling point, critical properties (temperature and density), liquid densities, and liquid-phase heat capacities at 40°C (104°F). Measured vapor pressures are reported from the boiling point, T_b , to the critical temperature, T_c , for four of the compounds: R-125a, an HFE ($T_b = -34.6^\circ\text{C}$ [-30.3°F] and $T_c = 80.7^\circ\text{C}$ [177.3°F]), and the HFCs R227ea ($T_b = -18.3^\circ\text{C}$ [-0.9°F] and $T_c = 102.8^\circ\text{C}$ [217°F]), R-245cb ($T_b = -18.3^\circ\text{C}$ [-0.9°F] and $T_c = 108.5^\circ\text{C}$ [227.3°F]), and R-236ea ($T_b = 6.5^\circ\text{C}$ [43.7°F] and $T_c = 141.1^\circ\text{C}$ [286.0°F]). The chemical formula equivalents for each compound are given in Table 1. The purpose of these measurements was to provide data for judging these compounds as alternative refrigerants. Portions of the data have already been used to estimate the performance of these chemicals as refrigerants by modeling the refrigeration operation (Sand and Fischer 1992).

The screening of the compounds as alternative refrigerants requires, in addition to the measured data, the vapor-phase heat capacities, vapor densities, and vapor pressures up to the critical point for all the compounds. For initial screening purposes, these may be estimated from the measured data obtained in this work, ideal gas heat capacities, and various equations of state. The ideal gas heat capacities may be estimated by a functional group method

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TABLE 1
The ASHRAE Code for Each Compound Along with Its Chemical Formula

Code	Formula	Code	Formula
HFE-125a	$\text{CF}_3\text{OCF}_2\text{H}$	HFC-338cca	$\text{HCF}_2\text{CF}_2\text{CF}_2\text{CF}_2\text{H}$
HFC-227ea	$\text{CF}_3\text{CHFCF}_3$	HFC-338ccb	$\text{CF}_3\text{CF}_2\text{CF}_2\text{CF}_2\text{H}$
HFC-227ca	$\text{CF}_3\text{CF}_2\text{CF}_2\text{H}$	HFC-347ccd	$\text{CF}_3\text{CF}_2\text{CF}_2\text{CH}_3$
HFC-236fa	$\text{CF}_3\text{CH}_2\text{CF}_3$	HCFC-226da	$\text{CF}_3\text{CHClCF}_3$
HFC-236ea	$\text{CF}_3\text{CHFCF}_2\text{H}$	HCFC-226ea	$\text{CF}_3\text{CHFCF}_2\text{Cl}$
HFC-236cb	$\text{CF}_3\text{CF}_2\text{CFH}_2$	HCFC-235ca	$\text{CF}_3\text{CF}_2\text{CH}_2\text{Cl}$
HFC-236ca	$\text{HCF}_2\text{CF}_2\text{CF}_2\text{H}$	HCFC-244ca	$\text{HCF}_2\text{CF}_2\text{CH}_2\text{Cl}$
HFC-245fa	$\text{CF}_3\text{CH}_2\text{CF}_2\text{H}$	HCFC-225da	$\text{CF}_3\text{CHClCF}_2\text{Cl}$
HFC-245ca	$\text{HCF}_2\text{CF}_2\text{CFH}_2$	HCFC-225ba	$\text{CF}_3\text{CFClCFHCl}$
HFC-245cb	$\text{CF}_3\text{CF}_2\text{CH}_3$	HCFC-234da	$\text{CF}_3\text{CHClCFHCl}$
HFC-254cb	$\text{HCF}_2\text{CF}_2\text{CH}_3$	HCFC-243da	$\text{CF}_3\text{CHClCH}_2\text{Cl}$
HFC-329ccb	$\text{CF}_3\text{CF}_2\text{CF}_2\text{CF}_2\text{H}$	C-326d	cyclic-(CF_2) ₃ CHCl
HFC-338eea	$\text{CF}_3\text{CFHCFHCF}_3$		

and the extensive data base of Benson et al. (1969). In order to demonstrate the accuracy that one can expect from estimates for the saturated vapor density and the vapor pressure between the boiling point and the critical point, these were estimated by a modified corresponding states technique (Reid et al. 1984) and compared with measured values for R-12 (a CFC), R-227ea, R-245cb, R-236ea, and R-125a. The measured liquid-phase heat capacity at 40°C (104°F) is useful for judging the accuracy of caloric data (liquid and vapor heat capacities) estimated from equations of state and the ideal gas heat capacity.

EXPERIMENTAL METHODS

The compounds were synthesized to 99.5% purity. The vapor pressure was measured across about a 30°C (54°F) temperature range from temperatures below the boiling point up to the boiling point with a mercury isoteniscope to within ± 0.5 kPa (± 0.1 psia). From these measurements, the boiling point was obtained to within $\pm 0.2^\circ\text{C}$ ($\pm 0.4^\circ\text{F}$) and heat of vaporization at the boiling point to within ± 0.1 kJ/mole (± 0.1 Btu/lb). The vapor pressure above the boiling point was measured to about ± 3 kPa (± 0.4 psia) using a precision pressure sensor with a vacuum on its reference side. The pressure sensor is connected to a stainless steel sample cell immersed in a bath with the temperature controlled to within $\pm 0.1^\circ\text{C}$ (0.2°F). The total volume of the pressure sensor and cell combination is 50 mL (3 in.³). Thus to measure pressures near the critical point at least 20 g (0.7 oz) of sample is required. Since the pressure sensor is external to the temperature bath, both the sensor and its connection to the sample cell are heated to a temperature well above the critical temperature of the sample. The electronic readout automatically compensates for the temperature effect on the pressure sensor.

The melting point was determined to within $\pm 0.2^\circ\text{C}$ ($\pm 0.4^\circ\text{F}$) as the thermocouple temperature at which a solidified ring of the compound disappeared from the surface of a sample tube. The critical temperature was measured by slowly raising the temperature of the sample in a sealed tube until the meniscus disappears.

The liquid density in the liquid-vapor coexistence region was determined by enclosing a sample in a 1.5-mL (0.09-in.³) tube (about 12 cm [4.7 in.] long) and measuring the displacement of the meniscus to within 0.05 mm (0.002 in.) from the bottom of the tube with a cathetometer. The mass of the sample was determined gravimetrically, and the cathetometer readings are converted to the volumes of the saturated liquid and vapor phases by a calibration procedure with weighed amounts of water in the tube. The sample temperature was controlled to within $\pm 0.1^\circ\text{C}$ ($\pm 0.2^\circ\text{F}$) and was measured to the same accuracy. The experiment is performed for several samples of differing mass. In order to show that the average density (or diameter), $\bar{\rho} = (\rho_l + \rho_g)/2$ (ρ_l and ρ_g being the liquid and vapor densities), is most accurately obtained by this technique, the sample mass-to-volume ratio is expressed in terms of $\bar{\rho}$ by

$$\frac{m}{V} = \bar{\rho} + \frac{V_l - V_g}{V} \Delta\rho, \quad (1)$$

where $\Delta\rho$ is given by

$$\Delta\rho = \frac{\rho_l - \rho_g}{2}. \quad (2)$$

V is the sample volume, and V_l and V_g are the liquid and vapor volumes, respectively. The $\Delta\rho$ is obtained to within 2% by comparing samples with widely differing weights, i.e.,

$$\Delta\rho = \frac{\left[\frac{m}{V}\right]_2 - \left[\frac{m}{V}\right]_1}{\left[\frac{V_l - V_g}{V}\right]_2 - \left[\frac{V_l - V_g}{V}\right]_1} \quad (3)$$

where the subscripts 1 and 2 indicate that the data are obtained from measurements on two separate samples. The diameter, $\bar{\rho}$, is then accurately obtained (to within 0.5%) from measurements on samples where V_l and V_g are comparable in value. For such cases, the second term in Equation 1 is small and the measured $\bar{\rho}$ is sensitive only to m and V , both of which are precisely measured. Normally measurements are obtained to within 20% of the critical point, and the critical density is calculated to within about 2% accuracy by extrapolating the diameters to the critical temperature. The liquid densities are obtained to within 2% from $\bar{\rho}$ and $\Delta\rho$ with the relation

$$\rho_l = \bar{\rho} + \Delta\rho. \quad (4)$$

The vapor densities can also be obtained from measured $\bar{\rho}$ and $\Delta\rho$ as $\rho_g = \bar{\rho} - \Delta\rho$. However, our experiments were not precise enough to obtain accurate saturated vapor densities. Therefore, no measured vapor densities are reported, although the reader may calculate them from the measured diameters and liquid densities that are presented in Table A-1 of the appendix (Table A-1a is in SI units and Table A-1b is in I-P units).

The liquid-phase heat capacity was measured using a differential scanning calorimeter (DSC) and sapphire reference standards. The samples were contained in stainless steel sample capsules of 75 μL (0.0046 in.³) capacity with an O-ring seal. Leakage during a calorimeter experiment is negligible. The capsules were filled using a micro-liter syringe in a cold room with a temperature below the boiling point of the sample (as low as -40°C [-40°F]). The DSC measurement was corrected for vapor volume and heat of vaporization effects due to changes in the relative sizes of the liquid and vapor phases as the temperature is scanned (Hwang et al. 1993). The data were also corrected to the constant pressure heat capacity, C_p , using formulas given in Reid et al. (1984). The vapor volume was kept at a minimum by using sample sizes of 60 mg (0.002 oz) or larger. For these sample sizes, the corrections (1%) were less than the estimated experimental error of 3%, or 0.04 kJ/ $^\circ\text{C}\cdot\text{kg}$ (0.01 Btu/ $^\circ\text{F}\cdot\text{lb}$).

MODIFIED CORRESPONDING STATES ESTIMATION OF VAPOR DENSITY AND VAPOR PRESSURE

In order to evaluate these compounds as refrigerants, vapor pressures and vapor densities are needed to temperatures approaching the critical point. It has already been noted that these may be estimated from the boiling point and measured critical parameters using various equations of state. In this section we demonstrate how the modified corresponding states method combined with the Benedict-

Webb-Rubin equations of state (1940) may be used for this evaluation. The modified corresponding states method is based on the following expressions for the compressibility, Z (Reid et al. 1984):

$$Z = \frac{P}{\rho RT}, \quad (5)$$

$$Z = Z^{(o)} + \omega Z^{(1)}, \quad (6)$$

$$Z^{(1)} = \frac{Z^{(R)} - Z^{(o)}}{\omega_R}, \quad (7)$$

where ω is the Pitzer acentric factor for the system of interest and ω_R is the same factor for a reference fluid, which was selected to be R-134a (an HFC). The quantity ρ is the density, P is the pressure, and T is the temperature. The quantity $Z^{(o)}$ is the compressibility of a simple fluid, which is defined to be the Benedict-Webb-Rubin equations with the simple fluid constants of Lee and Kesler (1975). The modified Benedict-Webb-Rubin equation of state (Jacobsen and Stewart 1973), with constants obtained by McLinden et al. (1989), was used to obtain the reference fluid compressibility $Z^{(R)}$. The acentric factor is calculated from the equations of Lee and Kesler (1975):

$$\omega = -\frac{\ln P_c + f^{(o)}(T_{br})}{f^{(1)}(T_{br})}, \quad (8)$$

where P_c is the critical pressure in units of atmospheres (101.325 kPa) and

$$f^{(o)}(T_r) = 5.92714 - \frac{6.09648}{T_r} - 1.28862 \ln(T_r) + 0.16934 T_r^6, \quad (9)$$

$$f^{(1)}(T_r) = 15.2518 - \frac{15.6875}{T_r} - 13.4721 \ln(T_r) + 0.43577 T_r^6. \quad (10)$$

The quantity $T_r (= T/T_c)$ is the reduced temperature and T_{br} is the reduced boiling point.

R-134a was picked as a reference fluid because excellent equation-of-state data (McLinden et al. 1989) have been obtained for this compound, and its acentric factor is comparable in value to the acentric factor for most of the fluorinated propane and butane derivatives. The latter fact increases the accuracy of the modified corresponding state methods because the correction from the reference fluid equation of state to that for the compounds being investigated is small. The latter fact becomes evident if one rewrites Equation 6 so that the reference fluid compressibility is the primary zero order term,

$$Z = Z^{(R)} + (\omega - \omega_R) Z^{(1)}, \quad (11)$$

in which the correction term, $(\omega - \omega_R) Z^{(1)}$, clearly is small when ω and ω_R are comparable in value.

TABLE 2a
Boiling Point, Melting Point, Heat of Vaporization at the Boiling Point,
Critical Properties, and Liquid-Phase Heat Capacity (SI Units)

Compound Code	$T_b(^{\circ}\text{C})$	$T_{\text{melt}}(^{\circ}\text{C})$	$\Delta H_{\text{vap}}(\text{kJ/mol})$	$T_c(^{\circ}\text{C})$	$P_c(\text{kPa})$	$\rho_c(\text{kg/m}^3)$	$C_p(\text{liq.})$ at 40°C $\left(\frac{\text{kJ}}{\text{kg}\cdot^{\circ}\text{C}}\right)$
HFE-125a	-34.6	-156.1	21.92	80.7	3253	584	1.33
HFC-227ea	-18.3	-126.8	22.29	102.8	2943	580	1.26
HFC-227ca	-16.3	-140.3	23.69	106.3	2870	594	1.25
HFC-236fa	-1.1	-94.2	25.66	130.6	3180	556	1.37
HFC-236ea	6.5	-146.1	26.83	141.1	3533	571	1.30
HFC-236cb	-1.4	-105.4	25.25	130.1	3120	545	1.44
HFC-236ca	12.6	-123.3	26.59	155.2	3410	558	- - -
HFC-245fa	15.3	-102.1	27.96	157.5	3640	529	1.42
HFC-245ca	25.0	-73.4	29.21	178.4	3860	529	1.45
HFC-245cb	-18.3	-81.1	23.59	108.5	3264	499	1.46
HFC-254cb	-0.8	-121.1	24.86	146.1	3750	467	1.59
HFC-329ccb	15.1	-122.3	26.71	140.2	2390	600	1.22
HFC-338eea	25.4	-91.5	27.79	148.5	2470	581	- - -
HFC-338cca	42.5	-91.0	31.13	186.4	2830	578	1.33
HFC-338ccb	27.8	-119.4	26.36	160.5	2550	562	1.34
HFC-347ccd	15.1	-124.9	25.82	144.2	2570	532	1.38
HCFC-226da	14.1	-119.6	24.64	158.2	3020	591	1.21
HCFC-226ea	17.6	-134.0	26.26	158.3	2950	584	1.20
HCFC-235ca	28.1	-85.0	27.57	170.3	3080	550	1.28
HCFC-244ca	54.8	-101.8	31.07	221.0	3710	525	1.16
HCFC-225da	50.8	-130.3	25.89	206.2	3010	589	1.09
HCFC-225ba	51.9	-132.7	29.38	212.9	3070	586	1.09
HCFC-234da	70.1	-98.0	31.70	242.5	- - -	- - -	1.17
HCFC-243da	76.7	-71.6	30.86	251.9	- - -	- - -	1.23
C-326d	38.1	-94.8	28.69	196.9	- - -	- - -	1.16

The procedure is to calculate $Z^{(o)}$ and $Z^{(1)}$ for the critical point (temperature, density, and pressure in reduced units being unity) and then solving Equations 8 through 10 and Equation 12,

$$Z_c = \frac{P_c}{\rho_c RT} = Z_c^{(o)} + \omega Z_c^{(1)}, \quad (12)$$

for the critical pressure and acentric factor using the measured value for the critical density ρ_c . The subscript c in Equation 12 refers to the critical point. The vapor pressure may then be evaluated from the following equation for reduced temperature T_r ,

$$\ln \left(\frac{P}{P_c} \right) = f^{(o)}(T_r) + \omega f^{(1)}(T_r). \quad (13)$$

The vapor pressure and temperature are then converted to density using Equations 5 through 7.

RESULTS AND DISCUSSION

In order to keep the body of this paper compact, comprehensive tabulations of saturated liquid densities, diameters for obtaining the critical density, and vapor pressures are given in Tables A-1 through A-6 of the appendix. The measured melting points, boiling points, critical properties, heat of vaporization at the boiling point, and the liquid-phase heat capacity are summarized in Table 2 (Table 2a is in SI units and Table 2b is in I-P units). All quantities in this table, except the critical pressures, are obtained from measured data. The critical pressures are

TABLE 2b
Boiling Point, Melting Point, Heat of Vaporization at the Boiling Point,
Critical Properties, and Liquid-Phase Heat Capacity (I-P Units)

Compound Code	$T_b(^{\circ}\text{F})$	$T_{\text{melt}}(^{\circ}\text{F})$	ΔH_{vap} (Btu/lb)	$T_c(^{\circ}\text{F})$	P_c (psia)	ρ_c lb/ft ³	$C_p(\text{liq.})$ at 104 $^{\circ}\text{F}$ (Btu/lb- $^{\circ}\text{F}$)
HFE-125a	-30.3	-249.0	69.32	177.3	471.8	36.4	0.318
HFC-227ea	-0.9	-196.2	56.39	217.0	426.9	36.2	0.301
HFC-227ca	2.7	-220.5	59.93	223.3	416	37.1	0.300
HFC-236fa	30.0	-137.6	72.61	267.1	461	34.7	0.328
HFC-236ea	43.7	-231.0	75.90	286.0	512.4	35.6	0.312
HCFC-236cb	29.4	-157.7	71.44	266.2	452	34.0	0.344
HFC-236ca	54.7	-189.9	75.25	311.4	494	34.8	- - -
HFC-245fa	59.5	-151.8	89.74	315.5	528	33.0	0.340
HFC-245ca	77.0	-100.1	93.75	353.1	560	33.0	0.348
HFC-245cb	-0.9	-114.0	75.72	227.3	473.4	31.2	0.348
HFC-254cb	30.6	-186.0	92.16	295.0	544	29.2	0.380
HFC-329ccb	59.2	-188.1	52.23	284.4	347	37.4	0.292
HFC-338eea	77.7	-132.7	59.16	299.3	358	36.2	- - -
HFC-338cca	108.5	-131.8	66.28	367.5	410	36.1	0.319
HFC-338ccb	82.0	-182.9	56.12	320.9	370	35.1	0.321
HFC-347ccd	59.2	-192.8	60.36	291.6	373	33.2	0.331
HCFC-226da	57.4	-183.3	56.84	316.8	438	36.9	0.289
HCFC-226ea	63.7	-209.2	60.59	316.9	428	36.4	0.288
HCFC-235ca	82.6	-121.0	70.40	338.5	447	34.3	0.305
HCFC-244ca	130.6	-151.2	88.80	429.8	538	32.7	0.277
HCFC-225da	123.4	-202.5	54.89	403.2	436	36.8	0.260
HCFC-225ba	125.4	-206.7	62.27	415.2	445	36.6	0.260
HCFC-234da	158.2	-144.4	73.74	468.5	- - -	- - -	0.281
HCFC-243da	170.1	-96.9	79.52	485.4	- - -	- - -	0.295
C-326d	100.6	-136.6	62.18	386.4	- - -	- - -	0.277

measured values for R-227ea, R-245cb, R-236ea, and R-125a; but for the remaining compounds, these were calculated from the measured critical temperature and critical density using modified corresponding state equations.

In order to judge the accuracy of the measured liquid densities and vapor pressures, these were measured for R-12 for comparison with literature data (Stoecker and Jones 1982). However, after completing this work, a search of the literature revealed very precise data for R-245cb, which were obtained by Shank (1967). Also during the course of this work, data were reported for R-125a (Wang et al. 1991; Adcock et al. 1991) and R-227ea (Hoechst 1991). Comparisons are made with these literature data in Tables 3 and 4. The liquid densities measured in this work are well within 1% of the literature values for R-12 (Stoecker and Jones 1982) and R-245cb (Shank 1967) presented in Table 3. For R-227ea, the discrepancy between our liquid densities and those reported by Hoechst (1991) is somewhat

larger, being 2.0% below 50 $^{\circ}\text{C}$ (122 $^{\circ}\text{F}$). This discrepancy may be related to the fact that our boiling point of -18.3 $^{\circ}\text{C}$ (-0.9 $^{\circ}\text{F}$) differs from the value of -17.3 $^{\circ}\text{C}$ (0.9 $^{\circ}\text{F}$) reported by Hoechst. Nevertheless, this still represents excellent agreement, and it verifies the estimated accuracy for the measured liquid densities. The measured liquid densities of this work (given in Table 3) for R-125a are within 1% of the values (Wang et al. 1991; Adcock et al. 1991) measured in van Hook's laboratory. Observations for the comparisons of vapor pressures of this work with literature values in Table 4 are similar to those made for liquid densities.

The critical temperature, pressure, and density of this work, 108.5 $^{\circ}\text{C}$ (227.3 $^{\circ}\text{F}$), 499 kg/m³ (31.2 lb/ft³), 3264 kPa (473.4 psia) and 102.8 $^{\circ}\text{C}$ (217.0 $^{\circ}\text{F}$), 580 kg/m³ (36.2 lb/ft³), 2943 kPa (426.9 psia) for R-245cb and R-227ea, respectively, are in very good agreement with the values of Shank (1967), 107.0 $^{\circ}\text{C}$ (224.6 $^{\circ}\text{F}$), 490 kg/m³ (30.6 lb/ft³),

TABLE 3a
Comparison of Measured Liquid Densities
and Modified Corresponding States Vapor
Densities with Literature Values (SI Units)

Temp (°C)	Liquid Density (kg/m ³)			Vapor Density (kg/m ³)		
	This Work	Litera- ture ^a	% Dev	Corre- ponding states	Litera- ture ^a	% Dev
CFC-12						
20	1313.	1329.0	-1.21	32.6	32.49	0.34
30	1286.	1292.2	-0.48	42.6	42.54	0.15
40	1250.	1253.1	-0.25	55.0	55.03	-0.06
50	1207.	1211.0	-0.33	70.3	70.57	-0.39
60	1156.	1165.3	-0.83	89.7	90.00	-0.33
70	1097.	1114.6	-1.62	114.2	114.61	-0.36
80	1030.	1056.9	-2.50	146.2	146.66	-0.27
HFC-245cb						
23.0	1185	1185.0	0.00	27.6	27.34	0.97
34.4	1142	1145.0	-0.22	38.3	38.10	0.48
43.3	1109	1111.5	-0.19	48.8	48.68	0.21
52.6	1074	1073.2	0.04	62.4	62.78	-0.50
61.5	1034	1033.1	0.08	79.0	79.49	-0.63
71.2	986	984.3	0.17	102.0	102.71	-0.59
81.2	924	925.4	-0.13	134.1	135.32	-0.86
HFC-227ea						
23.0	1380	1404	-1.74	35.3	35.19	0.30
35.0	1314	1347	-2.50	49.8	50.07	-0.60
45.0	1268	1294	-2.05	65.7	66.24	-0.75
55.0	1215	1234	-1.54	86.1	86.97	-1.03
65.0	1161	1168	-0.60	112.9	113.99	-0.96
75.0	1096	1094	0.18	149.2	150.42	-0.80
85.0	1013	1006	0.69	201.7	203.01	-0.64
HFE-125a						
9.7	1362	1345.1 ^a	1.26			
22.4	1298	1283.5 ^b	1.13			
32.1	1255	1238.7 ^b	1.37			
42.2	1196	1184.9 ^b	0.93			
51.4	1133	1133.4 ^b	0.00			
60.8	1051	1064.0 ^a	-1.22			

^a The literature data are taken from Stoecker and Jones (1982) for CFC-12, data of Shank (1967) for HFC-245cb, and Hoechst Chemical data [1991] for HFC-227ea. The literature values for HFE-125a labeled, a, are obtained from Adcock, et al. (1991) and data labeled, b, are obtained from Wang et al. (1991).

3137 kPa (455.0 psia), and Hoechst (1991), 101.9°C (215.4°F), 592 kg/m³ (36.9 lb/ft³), 2952 kPa (428.2 psia). The measured critical density for R-12, 567 kg/m³ (35.4 lb/ft³), which is obtained by extrapolation of density data ranging from temperatures of 20°C (68°F) to 85°C (185°F), is within 2% of the literature value (CRC 1989), 558 kg/m³ (34.8 lb/ft³).

Since no vapor densities were measured and a complete set of vapor pressures up to the critical point were measured for only four compounds, the accuracy of modified corresponding states methods using R-134a as a reference fluid was checked for estimating these properties by comparisons of the estimates with experimental data. Vapor densities estimated using this method and measured critical properties (density and temperature) and the boiling point are compared with the literature data for R-12 (Stoecker and Jones 1982), R-227ea (Hoechst 1991), and R-245cb (Shank 1967) in Table 3. The vapor densities estimated by modified corresponding states methods agree with the experimental literature values within 1%. We believe that the excellent agreement is the result of a good choice of reference fluid, R-134a (which has an acentric factor

TABLE 3b
Comparison of Measured Liquid Densities
and Modified Corresponding States Vapor
Densities with Literature Values (I-P Units)

Temp (°F)	Liquid Density (lb/ft ³)			Vapor Density (lb/ft ³)		
	This Work	Litera- ture ^a	% Dev	Corre- ponding states	Litera- ture ^a	% Dev
CFC-12						
68	82.0	82.97	-1.21	2.04	2.028	0.34
86	80.3	80.67	-0.48	2.66	2.655	0.15
104	78.0	78.23	-0.25	3.43	3.436	-0.06
122	75.4	75.60	-0.33	4.39	4.406	-0.39
140	72.1	72.75	-0.83	5.60	5.618	-0.33
158	68.5	69.58	-1.62	7.13	7.155	-0.36
176	64.3	65.98	-2.50	9.13	9.152	-0.27
HFC-245cb						
73.4	74.0	73.98	0.00	1.72	1.707	0.97
93.9	71.3	71.48	-0.22	2.39	2.379	0.48
109.9	69.2	69.39	-0.19	3.05	3.039	0.21
126.7	67.1	66.99	0.04	3.90	3.919	-0.50
142.7	64.6	64.49	0.08	4.93	4.962	-0.63
160.2	61.6	61.45	0.17	6.37	6.412	-0.59
178.2	57.7	57.77	-0.13	8.37	8.448	-0.86
HFC-227ea						
73.4	86.2	87.6	-1.74	2.20	2.197	0.30
95.0	82.0	84.1	-2.50	3.11	3.125	-0.60
113.0	79.2	80.8	-2.05	4.10	4.135	-0.75
131.0	75.9	77.0	-1.54	5.38	5.429	-1.03
149.0	72.5	72.9	-0.60	7.05	7.116	-0.96
167.0	68.4	68.3	0.18	9.31	9.390	-0.80
185.0	63.2	62.8	0.69	12.59	12.674	-0.64
HFE-125a						
48.6	85.0	83.97 ^a	1.3			
72.3	81.0	80.12 ^b	1.2			
89.8	78.4	77.33 ^b	1.3			
108.0	74.7	73.97 ^b	0.9			
124.5	70.7	70.73 ^b	0.0			
141.4	65.6	66.42 ^b	-1.2			

^a The literature data are taken from Stoecker and Jones (1982) for CFC-12, data of Shank (1967) for HFC-245cb, and Hoechst Chemical data [1991] for HFC-227ea. The literature values for HFE-125a labeled, a, are obtained from Adcock, et al. (1991) and data labeled, b, are obtained from Wang et al. (1991).

comparable to those of compounds being investigated), for the modified corresponding states method. These comparisons provide confidence for the modified corresponding states method as a means of estimating vapor densities.

The modified corresponding states method was used to estimate the critical pressure for most of the compounds investigated. In order to demonstrate the accuracy of the method for estimates of the critical pressure and vapor pressure between the boiling point and critical point, these are compared with experimental vapor pressures in Tables A-2 through A-5 of the appendix. The estimated vapor pressures for R-236ea, R-245cb, and R-125a are within 4% of the measured values. The deviations are somewhat larger (about 5%) for R-227ea but nevertheless still confirm that modified corresponding states methods are useful for estimating vapor pressures up to the critical point.

SUMMARY AND CONCLUSIONS

Data have been presented that can be used to evaluate fluorinated propane and butane derivatives as alternative refrigerants. Estimation methods for the vapor density and

TABLE 4
Comparison of Measured Vapor
Pressures with Literature Values

SI Units			IP Units			% Dev.
Temp (°C)	Measured This Work (kPa)	Literature* (kPa)	Temp (°F)	Measured This Work (psia)	Literature* (psia)	
CFC-12						
20.0	571	567.3	68.0	82.8	82.28	0.7
40.0	965	960.7	104.0	140.0	139.33	0.4
60.0	1529	1525.9	140.0	221.8	221.31	0.2
80.0	2291	2304.6	176.0	332.3	334.25	-0.6
95.0	3004	3056.9	203.0	435.8	443.36	-1.8
HFC-245cb						
10.1	293	289.2	50.2	42.4	41.95	1.2
20.0	402	398.5	68.0	58.3	57.80	0.8
40.1	715	711.0	104.3	103.7	103.12	0.6
60.1	1176	1169.1	140.2	170.6	169.57	0.6
80.3	1839	1837.9	176.5	266.8	266.57	0.1
106.9	---	3137.2	224.5	---	455.02	---
108.5	3264	---	227.3	473.4	---	3.9
HFC-227ea						
4.8	252	241.1	40.6	36.6	35.00	4.6
20.2	416	401.8	68.4	60.3	58.28	3.5
40.9	747	728.5	105.6	108.4	105.66	2.6
60.0	1201	1176.7	140.0	174.2	170.66	2.0
80.2	1883	1858.9	176.4	273.1	269.61	1.3
101.9	---	2952	215.4	---	428.2	---
102.8	2943	---	217.0	426.8	---	-0.3
HFE-125a						
5.4	500	491.5	41.7	72.5	71.29	1.7
20.0	777	772.4	68.0	112.7	112.03	0.6
40.0	1327	1324.0	104.0	192.5	192.08	0.2
59.9	2101	2123.2	139.8	304.7	307.95	-1.1
80.6	---	3326.1	177.1	---	482.42	---
80.7	3253	---	177.3	471.8	---	-2.2

* The literature data are taken from Stoeker and Jones (1982) for CFC-12, data of Shank (1967) for HFC-245cb, Hoechst Chemicals data (1991) for HFC227ea, and data of Wang et al. (1991) for HFE-125a.

vapor pressure that are based on boiling point and critical property measurements can provide a useful complement to the measured data. These conclusions are based on comparisons of the results of modified corresponding states estimation methods with measured data.

Qualitative judgments regarding the potential of the various chemicals as alternative refrigerants can be made by examining the physical property data in Table 2. The lowest-boiling-point propane chemicals—R245cb ($T_b = -18.3^\circ\text{C}$ [-0.9°F]), R-227ea ($T_b = -18.3^\circ\text{C}$ [-0.9°F]), and R-227ca ($T_b = -16.3^\circ\text{C}$ [2.7°F]) may be alternatives for R-12 ($T_b = -29.8^\circ\text{C}$ [-21.6°F]) and R-134a ($T_b = -26.5^\circ\text{C}$ [-15.7°F]) for some applications. The critical temperatures of these alternatives, which range from 102.8°C (217°F) to 108.5°C (227.3°F), compare well with the critical temperatures, 112.1°C (233.8°F) and 101.1°C (214.0°F) of R-12 and R-134a, respectively. The ether compound R-125a ($T_b = -34.6^\circ\text{C}$ [-30.3°F]) may in some instances also be an alternative for R-12 or R-134a, but its low critical temperature (80.7°C [177.3°F]) means that it is only marginally suitable for air-conditioning applications.

The compound R-245ca (an HFC), with a boiling point of 25.0°C (77°F) and a critical temperature of 178.4°C (353.1°F), appears to be a very likely alternative for R-11 ($T_b = 23.8^\circ\text{C}$ [74.8°F] and $T_c = 198^\circ\text{C}$ [388.4°F]). The chemical R-235ca (an HCFC), with a boiling point of 28.1°C (82.5°F) and critical temperature of 170.3°C (338.5°F), also appears to be an alternative for R-11. However, since the latter chemical contains chlorine, it is a much less desirable alternative than R-245ca (an HFC). The butanes, R-338ccb ($T_b = 27.8^\circ\text{C}$ [82.0°F]) and R-338eea ($T_b = 25.4^\circ\text{C}$ [77.7°F]), have boiling points that match the boiling point of R-11 very well, but their critical temperatures, 160.5°C (320.9°F) and 148.5°C (299.3°F), respectively, are significantly lower than that of R-11.

The HFC compounds, R-236ea ($T_b = 6.5^\circ\text{C}$ [43.7°F] and $T_c = 141.1^\circ\text{C}$ [286.0°F]) and R-236fa ($T_b = -1.1^\circ\text{C}$ [30.0°F] and $T_c = 130.6^\circ\text{C}$ [267.1°F]), are potential alternatives for R-114 ($T_b = 3.77^\circ\text{C}$ [38.8°F] and $T_c = 145.7^\circ\text{C}$ [294.3°F]). Other compounds, such as R-245fa, R-236ca, and R-329ccb, which have boiling points in the range 12°C (54°F) to 16°C (61°F), also may have applications as refrigerants. Chlorinated propane derivatives containing one chlorine atom per molecule have boiling points less than 30°C (86°F) and therefore would have potential refrigerant applications. The hydrogen-containing dichloropropane derivatives investigated in this work all have boiling points above 50°C (122°F), which are probably too high for refrigerant applications.

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APPENDIX

This appendix contains tabulations of the measured saturated liquid densities and vapor pressures between the boiling point and critical point for R-227ea, R-245cb, R-236ea, and R-125a in Tables A-1 through A-5. Since the presentation of measured vapor pressures below the boiling point would require extensive tabulations, only parameters for empirical representations of these data are given in Table A-6. The parameters are based on

$$\ln P = A - \frac{B}{T} - C \ln T, \quad (\text{A1})$$

where for SI units the pressure, P , is in kPa and T is the Kelvin temperature; in I-P units, P is in psia and T is the Rankine temperature. The parameters are calculated by least-squares methods from vapor pressures, measured at about 2°C (3.6°F) intervals over about a 30°C (54°F) temperature range from below the boiling point up to the boiling point. The RMS deviations of the measured vapor pressures from Equation A1 are about 0.7 kPa (0.1 psia). The exceptions to the above are the chemicals R-338eea and R-225da, for which data were obtained over a smaller 20°C (36°F) temperature range, and for these data only, the parameters A and B were included in the empirical representation. For the latter chemicals, the RMS deviation obtained from the least-squares calculation is 0.7 kPa (0.1 psia).

TABLE A-1a
Measured Diameters and Saturated
Liquid Densities (SI Units)

Temp. (°C)	Diameter ($\rho_l + \rho_g$)/2 (kg/m ³)	Liquid Density (kg/m ³)	Temp. (°C)	Diameter ($\rho_l + \rho_g$)/2 (kg/m ³)	Liquid Density (kg/m ³)	Temp. (°C)	Diameter ($\rho_l + \rho_g$)/2 (kg/m ³)	Liquid Density (kg/m ³)	Temp. (°C)	Diameter ($\rho_l + \rho_g$)/2 (kg/m ³)	Liquid Density (kg/m ³)
HFE-125a			HFC-227ea			HFC-338eea			HFC-338cca		
9.7	700	1362	23.0	705	1380	26.0	761	1510	22.0	766	1510
22.4	679	1298	35.0	686	1314	46.0	732	1455	40.0	754	1486
32.1	663	1255	45.0	670	1268	56.0	717	1404	60.0	729	1440
42.2	647	1196	55.0	654	1215	66.0	702	1360	80.0	707	1398
51.4	632	1133	65.0	638	1161	86.0	673	1281	100.0	683	1312
60.8	616	1051	75.0	622	1096	100.0	652	1216	120.0	656	1236
HFC-227ca			85.0	606	1013	110.0	637	1179	140.0	628	1148
24.5	717	1389	HFC-236fa			HFC-338ccb			HFC-347ccd		
37.6	697	1346	0.6	731	1449	22.0	763	1514	22.5	668	1324
42.0	691	1309	5.8	724	1427	42.0	734	1470	42.5	645	1271
60.7	662	1219	36.5	683	1330	62.0	705	1399	70.5	614	1183
71.6	646	1159	51.4	663	1269	82.0	676	1322	82.5	601	1145
86.8	623	1065	66.3	643	1214	102.0	647	1214	92.5	590	1105
HFC-236ea			83.5	620	1120	114.0	629	1139	102.5	578	1057
1.6	750	1471	97.5	601	1055	124.0	615	1079	112.5	567	1004
11.9	737	1421	HFC-236cb			HCFC-226da			HCFC-226ea		
22.7	723	1395	22.5	681	1331	25.6	741	1467	25.5	747	1478
32.4	711	1375	42.5	668	1309	36.3	729	1438	49.9	717	1417
44.6	695	1326	52.5	654	1265	53.7	709	1397	67.7	695	1357
64.4	670	1227	72.5	626	1191	69.5	691	1342	77.7	683	1316
75.2	656	1217	82.5	611	1149	78.2	681	1311	89.4	668	1268
94.6	631	1107	100.5	586	1026	89.6	669	1267	104.9	649	1212
HFC-236ca			HFC-245fa			HCFC-235ca			HCFC-244ca		
22.0	743	1484	11.3	688	1342	24.0	698	1382	21.0	719	1433
40.0	718	1420	30.6	667	1318	34.0	688	1371	41.5	699	1392
60.0	690	1339	44.1	652	1282	46.0	676	1344	61.0	680	1354
80.0	662	1268	57.3	638	1238	56.0	666	1317	84.5	657	1308
100.0	635	1189	75.0	618	1187	66.0	656	1289	104.2	638	1253
110.0	621	1148	84.5	608	1151	79.0	642	1250	113.5	629	1227
120.0	607	1084	HFC-245cb			95.5	626	1199	133.5	609	1170
HFC-245ca			23.0	611	1185	HCFC-225da			HFC-225ba		
22.0	688	1344	34.4	596	1142	24.3	783	1558	24.5	789	1559
60.0	650	1252	43.3	585	1109	34.7	772	1541	38.1	775	1547
80.0	629	1208	52.6	572	1074	59.3	746	1486	49.8	762	1528
100.0	609	1152	61.5	561	1034	73.6	731	1447	66.0	745	1487
120.0	589	1076	71.2	548	986	88.0	715	1406	77.8	732	1459
140.0	568	987	81.2	535	924	102.6	700	1364	96.7	712	1377
HFC-254cb			HFC-329ccb								
23.5	593	1171	25.0	766	1518						
43.5	573	1169	52.5	726	1413						
63.5	552	1083	66.6	706	1360						
73.5	542	1041	75.0	694	1333						
93.5	522	960	95.0	665	1230						
100.5	515	929	100.5	657	1208						
110.5	505	890	110.0	643	1143						

TABLE A-1b
Measured Diameters and Saturated
Liquid Densities (I-P Units)

Temp. (°F)	Diameter ($\rho_l + \rho_g$)/2 (lb/ft ³)	Liquid Density (lb/ft ³)	Temp. (°F)	Diameter ($\rho_l + \rho_g$)/2 (lb/ft ³)	Liquid Density (lb/ft ³)	Temp. (°F)	Diameter ($\rho_l + \rho_g$)/2 (lb/ft ³)	Liquid Density (lb/ft ³)	Temp. (°F)	Diameter ($\rho_l + \rho_g$)/2 (lb/ft ³)	Liquid Density (lb/ft ³)
HFE-125a			HFC-227ea			HFC-338eea			HFC-338cca		
49.5	43.7	85.0	73.4	44.0	86.2	78.8	47.5	94.3	71.6	47.8	94.2
72.3	42.4	81.0	95.0	42.8	82.0	114.8	45.7	90.8	104.0	47.1	92.8
89.8	41.4	78.4	113.0	41.8	79.2	132.8	44.8	87.6	140.0	45.5	89.9
108.0	40.4	74.7	131.0	40.8	75.9	150.8	43.8	84.9	176.0	44.1	87.3
124.4	39.5	70.7	149.0	39.8	72.5	186.8	42.0	80.0	212.0	42.6	81.9
141.5	38.5	65.6	167.0	38.8	68.4	212.0	40.7	75.9	248.0	41.0	77.2
			185.0	37.8	63.2	230.0	39.8	73.6	284.0	39.2	71.7
HFC-227ca			HFC-236fa			HFC-338ccb			HFC-347ccd		
76.1	44.8	86.7	33.1	45.6	90.5	71.6	47.6	94.5	72.5	41.7	82.6
99.7	43.5	84.0	42.5	45.2	89.1	107.6	45.8	91.8	108.5	40.3	79.4
107.6	43.1	81.7	97.7	42.6	83.0	143.6	44.0	87.4	158.9	38.3	73.8
141.3	41.3	76.1	124.5	41.4	79.2	179.6	42.2	82.5	180.5	37.5	71.5
161.9	40.3	72.4	151.3	40.1	75.8	215.6	40.4	75.8	198.5	36.8	69.0
188.2	38.9	66.5	182.3	38.7	69.9	237.2	39.3	71.1	216.5	36.1	66.0
			207.4	37.5	65.8	255.2	38.4	67.4	234.5	35.4	62.7
HFC-236ea			HFC-236cb			HCFC-226da			HCFC-226ea		
34.8	46.8	91.9	72.5	42.5	83.1	78.1	46.3	91.6	77.8	46.6	92.3
53.4	46.0	88.7	108.5	41.7	81.7	97.3	45.5	89.8	121.8	44.8	88.5
72.8	45.1	87.1	126.5	40.8	78.9	128.7	44.3	87.2	153.9	43.4	84.7
90.4	44.4	85.9	162.5	39.1	74.4	157.1	43.1	83.8	171.9	42.6	82.1
112.3	43.4	82.8	180.5	38.1	71.7	172.8	42.5	81.8	192.9	41.7	79.2
148.0	41.8	76.6	212.9	36.6	64.0	193.3	41.8	79.1	220.8	40.5	75.6
167.3	41.0	76.0							249.8	39.3	70.2
202.2	39.4	69.1									
Temp. (°F)	Diameter ($\rho_l + \rho_g$)/2 (lb/ft ³)	Liquid Density (lb/ft ³)	Temp. (°F)	Diameter ($\rho_l + \rho_g$)/2 (lb/ft ³)	Liquid Density (lb/ft ³)	Temp. (°F)	Diameter ($\rho_l + \rho_g$)/2 (lb/ft ³)	Liquid Density (lb/ft ³)	Temp. (°F)	Diameter ($\rho_l + \rho_g$)/2 (lb/ft ³)	Liquid Density (lb/ft ³)
HFC-236ca			HFC-245fa			HCFC-235ca			HCFC-244ca		
71.6	46.4	92.6	52.3	43.0	83.8	75.2	43.6	86.3	69.8	44.9	89.5
104.0	44.8	88.7	87.1	41.6	82.3	93.2	43.0	85.6	106.7	43.6	86.9
140.0	43.1	83.6	111.4	40.7	80.1	114.8	42.2	83.9	141.8	42.5	84.5
176.0	41.3	79.2	135.1	39.8	77.3	132.8	41.6	82.2	184.1	41.0	81.6
212.0	39.6	74.2	167.0	38.6	74.1	150.8	40.9	80.5	219.5	39.8	78.2
230.0	38.8	71.6	184.1	38.0	71.8	174.2	40.1	78.0	236.3	39.3	76.6
248.0	37.9	67.7				203.9	39.1	74.9	272.3	38.0	73.1
HFC-245ca			HFC-245cb			HCFC-225da			HFC-225ba		
71.6	42.9	83.9	73.3	38.1	74.0	75.7	48.9	97.3	76.1	49.3	97.3
140.0	40.6	78.2	93.9	37.2	71.3	94.5	48.2	96.2	100.6	48.4	96.6
176.0	39.3	75.4	109.9	36.5	69.2	138.7	46.6	92.7	121.6	47.6	95.4
212.0	38.0	71.9	126.7	35.7	67.1	164.5	45.6	90.3	150.8	46.5	92.8
248.0	36.8	67.2	142.7	35.0	64.6	190.5	44.6	87.8	172.0	45.7	91.1
284.0	35.5	61.6	160.2	34.2	61.6	216.7	43.7	85.1	206.1	44.4	86.0
			178.2	33.4	57.7						
HFC-254cb			HFC-329ccb								
74.3	37.0	73.1	77.0	47.8	94.8						
110.3	35.8	73.0	126.5	45.3	88.2						
146.3	34.5	67.6	151.9	44.1	84.9						
164.3	33.8	65.0	167.0	43.3	83.2						
200.3	32.6	59.9	203.0	41.5	76.8						
212.9	32.2	58.0	212.9	41.0	75.4						
230.9	31.5	55.6	230.0	40.1	71.4						

TABLE A-2
Measured Vapor Pressures for R-125a
Compared with Vapor Pressures Estimated
by Modified Corresponding States Methods

SI Units			IP Units			% Dev.
Temp (°C)	Measured This Work (kPa)	Corres. States (kPa)	Temp (°F)	Measured This Work (psia)	Corres. States (psia)	
5.4	500.	482	41.7	72.5	70.0	3.5
10.1	581	560	50.2	84.2	81.3	3.5
14.8	669	645	58.6	97.0	93.6	3.5
20.0	777	754	68.0	112.6	109.4	2.9
24.8	889	864	76.6	129.0	125.3	2.9
30.4	1034	1008	86.7	150.0	146.2	2.5
34.7	1160	1130	94.5	168.2	163.8	2.6
40.0	1327	1295	104.0	192.4	187.9	2.3
45.3	1509	1478	113.5	218.8	214.4	2.0
50.4	1703	1671	122.7	247.0	242.4	1.9
54.9	1881	1858	130.8	272.8	269.5	1.2
59.9	2100	2084	139.8	304.7	302.3	0.8
65.9	2393	2383	150.6	347.1	345.6	0.4
70.0	2610	2608	158.0	378.6	378.2	0.1
74.8	2892	2892	166.6	419.5	419.4	0.01
78.0	3087	3098	172.4	447.8	449.3	-0.4
80.0	3203	3229	176.0	464.6	468.3	-0.8
80.7	3253	3242	177.3	471.8	470.2	0.3

TABLE A-4
Measured Vapor Pressures for R-245cb
Compared with Vapor Pressures Estimated
by Modified Corresponding States Methods

SI Units			IP Units			% Dev.
Temp (°C)	Measured This Work (kPa)	Corres. States (kPa)	Temp (°F)	Measured This Work (psia)	Corres. States (psia)	
7.1	264	264	44.7	38.2	38.3	-0.1
10.1	293	293	50.2	42.4	42.5	-0.2
15.1	344	343	59.1	49.9	49.8	0.3
20.0	402	400	68.1	58.3	58.0	0.4
25.0	468	465	77.1	67.8	67.4	0.6
30.0	541	536	86.1	78.4	77.8	0.8
35.1	624	617	95.2	90.5	89.5	1.1
40.1	716	706	104.3	103.7	102.3	1.4
45.4	820	807	113.7	119.0	117.0	1.6
50.2	925	909	122.7	134.2	131.8	1.8
55.2	1047	1026	131.3	151.8	148.8	2.0
60.1	1176	1151	140.1	170.6	166.9	2.1
65.1	1320	1290	149.1	191.4	187.0	2.3
70.3	1483	1446	158.4	215.1	209.8	2.5
75.2	1651	1608	167.3	239.4	233.3	2.6
80.3	1839	1793	176.6	266.8	260.0	2.5
85.5	2044	1992	185.9	296.5	289.0	2.5
86.3	2099	2023	187.3	304.5	293.4	3.7
90.2	2244	2187	194.3	325.5	317.3	2.5
95.6	2497	2416	204.0	362.2	350.4	3.2
96.1	2557	2457	204.9	370.8	356.4	3.9
97.6	2610	2529	207.6	378.6	366.8	3.1
102.1	2877	2759	215.7	417.3	400.1	4.1
104.2	2995	2870	219.5	434.4	416.2	4.2
108.5	3264	3113	227.3	473.4	451.5	4.6

TABLE A-3
Measured Vapor Pressures for R-227ea
Compared with Vapor Pressures Estimated
by Modified Corresponding States Methods

SI Units			IP Units			% Dev.
Temp (°C)	Measured This Work (kPa)	Corres. States (kPa)	Temp (°F)	Measured This Work (psia)	Corres. States (psia)	
3.4	240	233	38.1	34.9	33.7	3.2
4.8	252	244	40.6	36.6	35.4	3.3
9.9	300	289	49.8	43.5	41.9	3.5
15.0	353	341	59.0	51.2	49.4	3.6
20.2	416	400	68.4	60.3	58.0	3.8
25.2	481	464	77.4	69.8	67.3	3.6
30.2	558	535	86.4	80.9	77.6	4.1
35.3	642	616	95.5	93.1	89.3	4.1
40.9	747	715	105.6	108.4	103.6	4.4
45.2	838	798	113.4	121.5	115.8	4.8
50.1	952	901	122.2	138.0	130.7	5.3
55.8	1091	1034	132.4	158.2	150.0	5.2
60.0	1201	1141	140.0	174.2	165.4	5.0
65.4	1361	1290	149.7	197.2	187.1	5.2
70.0	1510	1428	158.0	219.1	207.2	5.5
74.9	1680	1587	166.8	243.7	230.2	5.6
80.2	1883	1776	176.4	273.1	257.6	5.7
84.7	2067	1949	184.5	299.7	282.7	5.7
90.0	2297	2170	194.0	333.1	314.8	5.5
95.4	2525	2416	203.7	366.2	350.4	4.3
99.8	2752	2632	211.6	399.1	381.8	4.4
102.8	2943	2787	217.0	426.8	404.2	5.3

TABLE A-5
Measured Vapor Pressures for R-236ea
Compared with Vapor Pressures Estimated
by Modified Corresponding States Methods

SI Units			IP Units			% Dev.
Temp (°C)	Measured This Work (kPa)	Corres. States (kPa)	Temp (°F)	Measured This Work (psia)	Corres. States (psia)	
10.3	121	118	50.5	17.5	17.1	2.6
14.1	141	137	57.4	20.5	19.9	3.0
19.0	169	164	66.2	24.5	23.8	3.1
24.8	207	202	76.6	30.0	29.3	2.7
30.0	247	239	86.0	35.8	34.7	3.1
35.2	291	285	95.4	42.2	41.3	2.3
40.0	338	331	104.0	49.0	48.0	2.1
45.6	403	392	114.1	58.5	56.9	2.6
49.8	456	443	121.6	66.1	64.3	2.8
54.8	523	509	130.6	75.9	73.8	2.5
59.8	598	584	139.6	86.7	84.7	2.3
65.2	690	673	149.4	100.1	97.6	2.5
69.9	777	757	157.8	112.7	109.8	2.5
74.9	878	859	166.8	127.3	124.6	2.2
79.7	979	963	175.5	142.0	139.7	1.6
85.6	1124	1104	186.1	163.0	160.1	1.7
90.0	1227	1219	194.0	178.0	176.8	0.6
93.3	1325	1310	199.9	192.2	190.0	1.1
94.7	1359	1352	202.5	197.1	196.1	0.6
97.0	1463	1420	206.6	212.2	206.0	2.9
101.8	1626	1572	215.2	235.8	228.0	3.4
106.9	1808	1746	224.4	262.2	253.2	3.4
115.5	2158	2072	239.9	313.0	300.5	4.0
119.9	2350	2259	247.8	340.8	327.6	3.9
125.3	2609	2502	257.5	378.4	362.9	4.1
130.3	2870	2751	266.5	416.3	399.0	4.1
135.2	3146	3010	275.4	456.3	436.6	4.3
138.1	3313	3281	280.6	480.5	475.9	1.0
141.1	3533	3354	286.0	512.4	486.5	5.0

TABLE A-6
Parameters of Equation A1 Obtained
by a Least-Squares Calculation
of Vapor Pressures Measured Below
the Boiling Point

Compound	A		B		C
	SI units	(IP units)	SI units	(IP units)	SI or IP units
HFE-125a	48.950	(50.040)	3862.2	(6952.0)	5.1395
HFC-227ea	40.725	(41.112)	3613.1	(6503.6)	3.9579
HFC-227ca	38.971	(39.128)	3761.3	(6770.3)	3.5521
HFC-236fa	46.023	(46.767)	4324.3	(7783.8)	4.5497
HFC-236ea	45.842	(46.542)	4478.1	(8060.7)	4.4756
HFC-236cb	40.036	(40.262)	4034.0	(7261.1)	3.6704
HFC-236ca	44.047	(44.610)	4410.9	(7939.6)	4.2424
HFC-245fa	47.161	(47.954)	4700.0	(8460.0)	4.6342
HFC-245ca	7.970	(5.299)	3138.1	(5648.5)	-1.2597
HFC-245cb	18.204	(16.493)	2933.3	(5279.9)	0.3749
HFC-254cb	29.555	(28.866)	3565.6	(6418.0)	2.1126
HFC-329ccb	46.138	(46.886)	4526.6	(8147.9)	4.5579
HFC-338eea	15.809	(13.878)	3342.0	(6015.7)	- - -
HFC-338cca	50.452	(51.478)	5331.9	(9597.4)	5.0297
HFC-338ccb	76.357	(79.790)	5916.5	(10649.7)	9.1255
HFC-347ccd	33.917	(33.620)	3907.3	(7033.2)	2.7798
HCFC-226da	11.604	(9.967)	2819.6	(5075.3)	0.4999
HCFC-226ea	50.716	(51.889)	4691.9	(8445.4)	5.2817
HCFC-235ca	59.410	(61.316)	5282.9	(9509.2)	6.5274
HCFC-244ca	44.209	(44.718)	5098.1	(9176.5)	4.1512
HCFC-225da	14.224	(12.293)	3313.8	(5604.8)	- - -
HCFC-225ba	31.554	(31.016)	4303.1	(7745.6)	2.3681
HCFC-234da	70.182	(72.932)	6546.3	(11783.4)	7.9628
HCFC-243da	78.912	(82.443)	6962.6	(12532.6)	9.2916
cy-HCFC-326d	43.515	(44.009)	4735.1	(8523.1)	4.1260