

LITERATURE DATA

The experimental technique developed to calculate viscosities of ternary mixtures was used to check the only other available data on ternary systems. Ruby and Kawai (13) measured viscosities in the ternary NaCl-KCl-H₂O system at 25°C., and Ezrokhi (3) published data on this system at 25°, 40°, and 60°C. The data given by Ruby and Kawai were correlated with an average deviation of $\pm 0.19\%$ and those of Ezrokhi with an average deviation of $\pm 0.55\%$ up to an ionic strength of 3.0.

Unfortunately, available data on sea water viscosity cover only a narrow temperature and concentration range. Dorsey (1) summarized Krümmel's (8) data over the 0° to 30°C. temperature range for salinities from 5 to 40, and Myake and Koizumi (10) gave new results over the same temperature and concentration range. Their data are compared with the calculated results for the synthetic sea water in Table VII. The average deviation between the given and calculated data is $\pm 0.21\%$.

CONCLUSIONS

Since all other data on the viscosity of sea water and its concentrates are estimated data, based on sodium chloride solutions of equivalent chloride content or on some other assumption, it is felt that the present measurements on calcium-free sea water represent the best available information, and Equations 10 can be used for the calculation of sea water viscosities. Deviations between calculated viscosities of the calcium-free sea water and calcium-containing sea water were within the precision of the

method. Table VIII gives the interpolated data on sea water and its concentrates as a function of chlorinity and salinity.

Additional tables on salt and sea water solutions containing density, vapor pressure, and viscosity data were prepared for the Office of Saline Water (4).

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Thermal Properties of Propane

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This contribution summarizes the results of an experimental investigation of the thermal properties of propane as part of a continuing effort to determine such properties for materials that are gases under normal conditions, light hydrocarbons, and their mixtures. New data on the isobaric heat capacity are presented. These data are compared with previously published experimental data in regions where such comparisons are possible. Published data on propane, including PVT determinations, isobaric heat capacity, latent heat, isothermal throttling coefficient, and Joule-Thomson data, were used together with the new data to determine values of enthalpy in the liquid, critical, super-critical, gaseous, and two-phase regions in the temperature range from -280° to $+300^\circ$ F., at pressures up to 2000 p.s.i.a. These results were checked for thermodynamic consistency and are believed to be accurate to better than 0.5%. The BWR equation of state was used, together with published data on isothermal enthalpy departures, to extend the upper limit of the tabulation of thermal properties to $+500^\circ$ F. A table of enthalpy values is presented.

TABLES and charts of thermodynamic properties of propane have been published (2, 3, 4, 6, 18, 28, 32, 34, 38). The ranges in temperature and pressure covered by these published tables are indicated in Figure 1. The values of the thermal properties, enthalpy and entropy, presented in these tables were calculated using heat capacity data at low pressure and volumetric (PVT) data. This general procedure has been followed as there are few calorimetric data for propane at elevated pressures, with the exception of data on the latent heat of vaporization (6, 13, 30) and results of Joule-Thomson experiments (31).

Recently, results of direct experimental determinations of the effect of both pressure and temperature on the thermal properties of propane have been published (9, 12, 35, 37). These data extend over a considerable range of temperatures (-250° to $+400^\circ$ F.) at pressures up to 2000 p.s.i.a. However, information was sketchy in the regions near the critical point and in the vicinity of the two-phase region—i.e., where rapid changes in properties are encountered. Therefore, the purposes of this contribution are to present the results of experimental determinations in these regions and to summarize all published experimental data on the

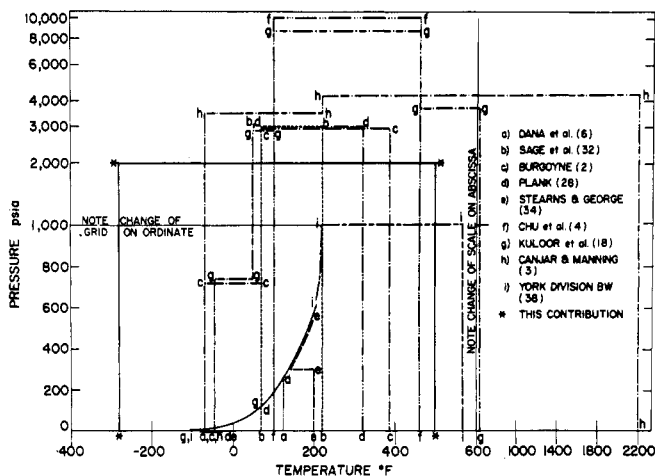


Figure 1. Range of tables and charts of thermodynamic properties of propane

thermal properties of propane in terms of the enthalpy function.

THERMODYNAMIC RELATIONS

The thermodynamic relations which are used to interpret the experimental data have been summarized in detail elsewhere (25, 37). The equations which were applied to calculate enthalpy differences are summarized in the following paragraphs.

Change of Phase. For a pure component, vaporization occurs at a constant temperature and pressure, and values of the enthalpy change associated with the change from liquid to vapor are determined directly from experimental data.

Changes within a Single Phase. ISOBARIC. Changes in enthalpy which occur at constant pressure within the single phase region are calculated from values of the isobaric heat capacity determined at that pressure.

$$\Delta H_P = \int C_P dT_P \quad (1)$$

ISOTHERMAL. At temperatures for which experimental values of the isothermal throttling coefficient, $\phi \equiv (\partial H / \partial P)_T$, have been reported, isothermal differences in enthalpy are calculated.

$$\Delta H_T = \int \phi dP_T \quad (2)$$

Such differences can also be estimated from *PVT* data or an equation of state.

$$\Delta H_T = \int \left[V - T \left(\frac{\partial V}{\partial T} \right)_P \right] dP_T \quad (3)$$

The terms in Equation 3 represent a difference, often relatively small, in large numbers.

Values of the isothermal throttling coefficient at zero pressure, ϕ^0 , are directly related to the second virial coefficient, *B*.

$$\phi^0 = B - T dB/dT \quad (4)$$

ISENTHALPIC. Isobaric and isenthalpic data can be used together to calculate isothermal differences in enthalpy. Consider a closed loop on a pressure-temperature-enthalpy (*PTH*) diagram consisting of isobaric (ΔH_P), isothermal (ΔH_T), and isenthalpic (ΔH_H) portions. The last term is identically zero [$(\Delta H)_H = 0$], and therefore

$$\Sigma \Delta H_i = 0 = \Delta H_P + \Delta H_T \quad (5)$$

from which ΔH_T can be determined from known values of ΔH_P .

The basic thermal properties resulting from calorimetric determinations, C_P , ϕ , and the Joule-Thomson coefficient, μ , are related by the mathematical identity

$$\phi = -\mu C_P \quad (6)$$

EXPERIMENTS

The recycle flow facility (25) and both the isobaric (10, 11, 15) and throttling (21, 22, 24) calorimeters, as well as the operating procedures and methods of interpreting the basic results (25, 37), have been described in detail elsewhere. The gas used in the investigation was 99.75 mole % propane, with impurities of nitrogen (0.15%), oxygen (0.04%), methane (0.02%), ethane (0.03%), and propylene (0.01%), as determined by mass spectrometer analysis.

Results from several experimental runs at 700 p.s.i.a. are presented on Figure 2. The solid horizontal lines represent mean values of heat capacity, $\Delta H_P / \Delta T$, over the experimentally observed temperature interval. The dashed horizontal lines were obtained by difference from the basic experimental data. An equal-area curve was drawn through the data, with more emphasis on agreement with the basic data than with the values obtained by difference.

Experimental values of the isobaric heat capacity, C_P , determined from experimental data obtained in regions of rapid change with respect to temperature are presented in Table I. Only a part of the data obtained at 700 p.s.i.a. are represented on Figure 2. In the interval from 200° to 219° F., C_P at 700 p.s.i.a. changes by a factor of 4.2, and from 219° to 250° F., C_P varies by a factor of 5.3! Figure 3 summarizes the experimental values from Table I and from a complementary investigation (37). Figure 4 similarly summarizes values of ϕ as presented in the complementary investigation.

COMPARISON WITH OTHER PUBLISHED DATA

Isobaric data at pressures in excess of 1 atm. have only recently become available (9, 12, 37). Figure 2 summarizes the results of Finn (12) and of this investigation at 700 p.s.i.a., only about 80 p.s.i. above the critical point. There

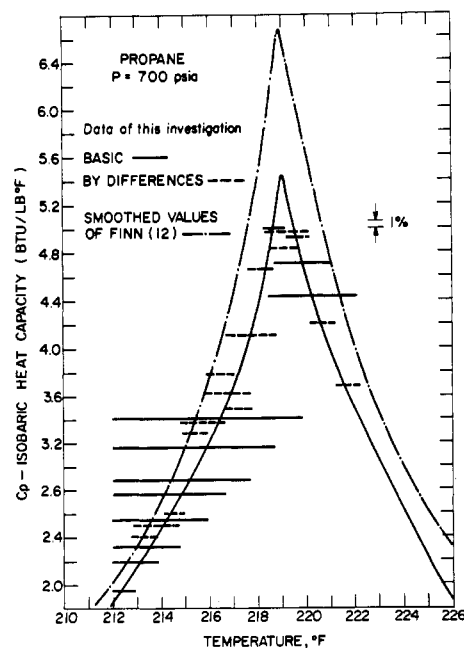


Figure 2. Experimental data at 700 p.s.i.a. and comparison with results of Finn (12)

Table I. Experimental Values of Isobaric Heat Capacity, C_p , Near the Saturation Curve and in the Vicinity of $C_p(T)$ Maxima

Temp., °F.	C_p ($\frac{\text{B.t.u.}}{\text{Pound} \cdot \text{°F.}}$)	Temp., °F.	C_p ($\frac{\text{B.t.u.}}{\text{Pound} \cdot \text{°F.}}$)
250 P.S.I.A.			
100	0.696		
105	0.7047		
110	0.7159	240	0.84
115	0.7290	245	0.79
119.9(l.)	0.7424	250	0.76
122.4(g.)	0.5794		
125	0.5756		
130	0.5684	200	1.265
135	0.5629	207	1.410
140	0.5586	213	2.150
400 P.S.I.A.			
160	0.912	217	3.795
161.1(l.)	0.943	219	5.280
163.5(g.)	0.8214	220	3.910
165	0.8078	225	2.018
170	0.7693	230	1.351
175	0.7399	240	1.061
180	0.7157	250	0.986
190	0.6769		
200	0.6478		
220	0.6130		
500 P.S.I.A.			
165	0.8970	220	0.980
170	0.9347	235	1.134
175	0.9889	245	1.272
180	1.11	250	1.345
185.3(l.)		255	1.436
186.0(g.)	(1.54) ^a	257	1.466
190	1.32	260	1.439
195	0.985	265	1.377
200	0.8543	270	1.314
205	0.8069	280	1.189
617 P.S.I.A.			
202	1.84	225	1.050
203	2.37	260	1.077
204	3.09	270	1.121
205	4.3	275	1.139
206	29	280	1.161
206.3(c.p.)		284	1.177
207	6.5	285	1.172
208	4.0	290	1.118
209	2.95	295	1.070
210	2.35	300	
212	1.88		
214	1.68		
217	1.30		
220	1.17		
225	1.06		
230	0.97		
235	0.90		
700 P.S.I.A.			
1000 P.S.I.A.			
1200 P.S.I.A.			
1500 P.S.I.A.			

^a Value for saturated vapor not known to accuracy of other values in the table.

is excellent agreement between the two investigations with respect to the temperature of the maximum in C_p (219° F.), but the values reported by Finn are between 7 and 26% higher than those reported in this contribution, with the maximum deviation occurring at the peak.

Ernst (9) reports values of C_p in the temperature range from 68° to 176° F. at pressures up to 118 p.s.i.a. This is below the lowest pressure used for isobaric determinations in the present investigation (250 p.s.i.a.), and also at temperatures lower than any used in the determination of ϕ for propane as a gas (201° F.), so that direct comparisons cannot be made. However, when values of C_p from the

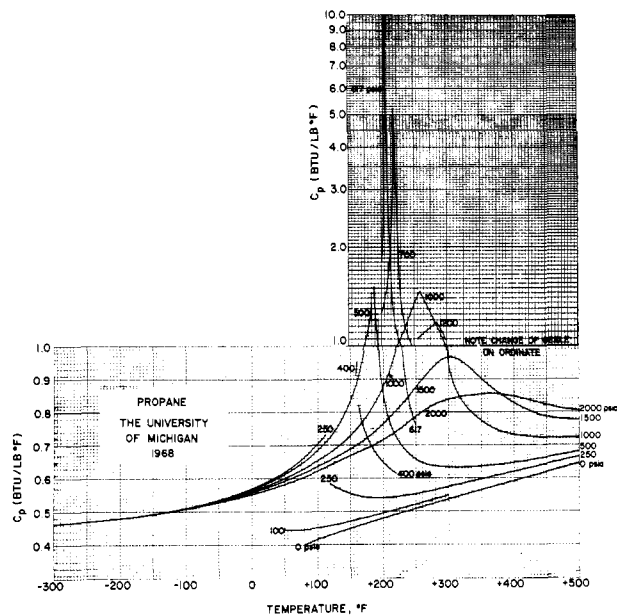


Figure 3. Isobaric heat capacity, C_p , of propane

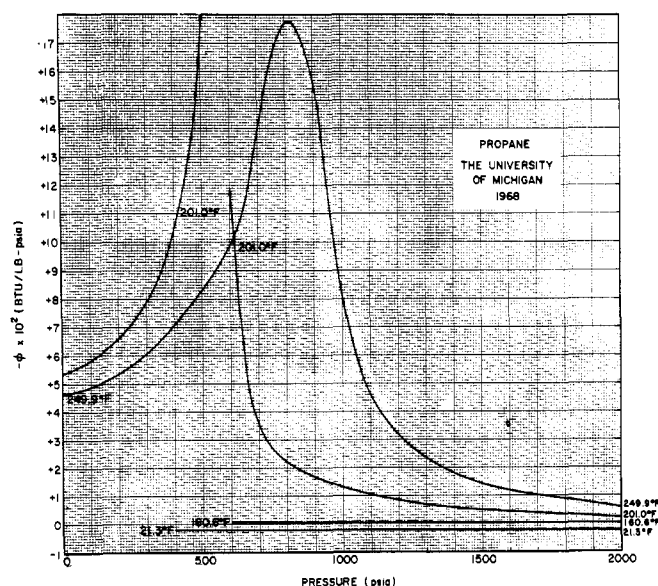


Figure 4. Isothermal throttling coefficient, ϕ , of propane

two investigations and the complementary investigation (37) were plotted *vs.* either T or P , smooth isobaric and isothermal curves could be passed through all the data.

Data on the enthalpy change on vaporization (ΔH_{vap}) reported in the complementary publication (37) have been compared with other published data (6, 13, 30). The four values determined in this experiment agree with experimental values recently reported by Helgeson and Sage (13) within 1.5 B.t.u. per pound except at 588 p.s.i.a. (200° F.), where our value is about 2 B.t.u. per pound (4%) lower than the interpolated value which appears in their publication. Values from the other sources vary from the authors' results by as much as 10 B.t.u. per pound (11%).

A rough comparison with the isothermal data of Yarborough and Edmister (35) at 200° F. has been presented elsewhere (37). Quantitative comparisons are presented in Table II. Note that the values presented for comparison at 300° F. were calculated from values of ϕ at 249.9° F. in combination with values of C_p at pressures ranging from 0 to 2000 p.s.i.a., as reported in Table I and elsewhere (29, 37). There is better agreement at 300° F. than at

Table II. Comparison of Experimental Values of Enthalpy Departure for Propane

Pressure, P.S.I.A.	200° F.			300° F.		
	$H^\circ - H$, B.t.u./lb.		Dev., %	$H^\circ - H$, B.t.u./lb.		Dev., %
	Yarborough, Edmister (35) (average value)	Yesavage <i>et al.</i> ^a (37) (smoothed value) ^b		Yarborough, Edmister (35) (average value)	Yesavage <i>et al.</i> ^a (37) (calcd. from data) ^c	
200	11.65	11.83	-1.5	8.0	8.2	+2.5
500	43.87(v.)	41.55(v.)	+5.6	22.6	23.8	+5.0
600	116.2(l.)	112(l.)	+3.5	...	30.	...
750	124.3	119.96	+3.6	40.6	40.1	-1.2
1000	...	124.5	...	63.0	60.4	-4.3
1500	...	128.4	92.2	...
2000	...	130.0	102.5	...

^aAll values from Yesavage *et al.* are sensitive to method of estimating ϕ° (See Equation 4), especially at low pressures. ^bCalculated by integration of $\phi(P)$ values at 200° F. ^cCalculated by integration of $\phi(P)$ values at 249.9° F. and integration of $C_p(T)$ values at elevated pressures.

200° F. The agreement at the lower temperature is remarkable, as it is within 7° of the critical temperature, and the data extend from low pressures through the two-phase region to above the critical pressure.

No data are available for the direct comparison of the isenthalpic data reported previously (37). However, Equation 6 has been applied to permit comparison of data on C_p and ϕ from this investigation with values of the Joule-Thomson coefficient, μ , reported by Sage *et al.* (31). As

reported elsewhere (37), the comparison was only moderately successful, with deviations of $\pm 8\%$ occurring, with a maximum deviation of +12%.

Science *et al.* (33) recently published calculated values of the properties of the saturated phases of propane. Comparison of his reported values with values of C_p for the saturated vapor determined in the course of this study and reported in Table I, together with a value from the investigation of Ernst (9), indicates that the values reported by Science *et al.* are uniformly high by about 0.02 B.t.u. per pound ° F. ($\approx 4\%$).

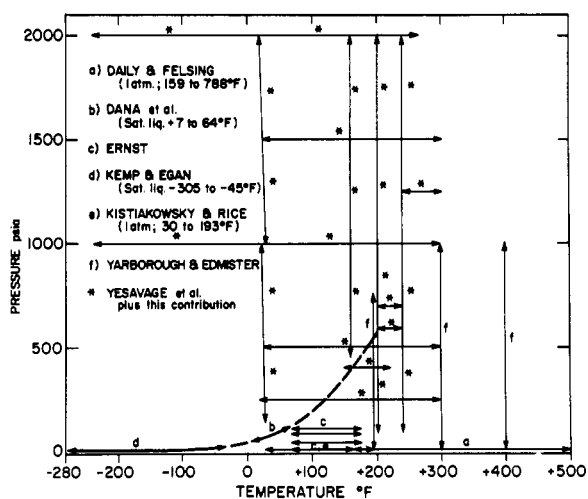


Figure 5. Range of calorimetric data used in preparation of Table IV

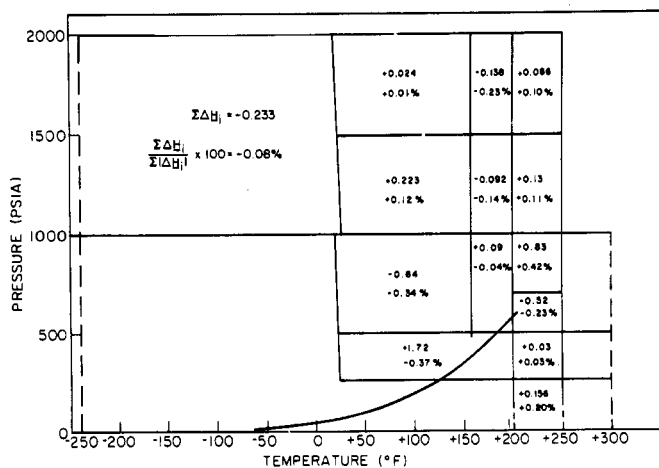


Figure 6. Checks of thermodynamic consistency of thermal data for propane

INTERPRETATION

The reference for enthalpy was taken as $H = 0$ at $T = -280^\circ \text{F.}$ for liquid propane at its saturation pressure. This is consistent with the reference previously used in reporting enthalpy values for mixtures of methane and propane (19, 20, 21, 23, 26, 27, 36). Values of the enthalpy of propane as a gas at zero pressure were calculated using data on the liquid phase heat capacity (16), the latent heat of vaporization at 1 atm. (16), the BWR equation of state (1) to correct from 1 atm. to zero pressure at the normal boiling point, and values of the ideal heat capacity (29) to account for a change in temperature from the normal boiling point to other temperatures at zero pressure. The calculations of the enthalpy at 250° F. and zero pressure are summarized on page 202.

Table III. Tabulated Values of Enthalpy for Propane at Saturated Conditions

Pressure, P.S.I.A.	Temp., ° F.	Satd. Liquid Enthalpy, B.t.u./Lb.	Satd. Vapor Enthalpy, B.t.u./Lb.	Latent Heat of Vaporization, B.t.u./Lb.
14.7	-43.7	116.2	299.4	183.2
50	14.1	147.2	314.5	167.3
100	55.0	172.2	325.7	153.5
150	82.7	190.1	332.7	142.6
200	104.5	204.6	337.6	133.0
250	122.5	217.4	340.8	123.4
300	137.6	230.0	343.4	113.4
350	151.4	241.4	344.6	103.2
400	163.5	252.0	344.8	92.8
450	174.7	261.4	343.4	82.0
500	184.8	270.4	340.8	70.4
550	194.4	279.8	337.1	57.3
588	201.0	289.7	333.1	43.4
600	203.5	296.4	330.7	34.3
617	206.3	315.0	315.0	0.0

Table IV. Tabulated Values of Enthalpy for Propane ($H = \text{B.t.u./Lb.}$)

Temp., ° F.	Pressure, P.S.I.A.									
	0	100	200	250	300	350	400	450	500	550
-280		0.1	.2	.3	.4	.5	.6	.7	.8	.9
-270		4.8	4.9	5.0	5.0	5.0	5.1	5.1	5.2	5.4
-260		9.3	9.5	9.6	9.7	9.6	9.7	9.8	10.0	10.1
-250	242.9	14.0	14.1	14.2	14.3	14.3	14.4	14.5	14.5	14.7
-240	245.4	18.5	18.6	18.8	18.9	19.0	19.1	19.2	19.4	19.5
-230	248.0	23.2	23.3	23.4	23.5	23.5	23.6	23.8	23.9	24.0
-220	250.5	28.0	28.1	28.2	28.3	28.4	28.5	28.6	28.7	28.9
-210	253.1	32.9	33.0	33.0	33.1	33.0	33.1	33.2	33.4	33.5
-200	255.7	37.5	37.6	37.6	37.7	37.8	37.9	38.0	38.0	38.2
-190	258.3	42.2	42.3	42.4	42.5	42.5	42.7	42.8	43.0	43.0
-180	261.0	46.9	47.0	47.1	47.2	47.3	47.5	47.6	47.7	47.9
-170	263.7	51.7	51.8	51.9	52.0	52.0	52.1	52.2	52.4	52.5
-160	266.4	56.7	56.8	56.9	57.0	57.0	57.1	57.2	57.4	57.5
-150	269.2	61.5	61.6	61.6	61.7	61.7	61.8	62.0	62.1	62.4
-140	272.0	66.5	66.6	66.6	66.7	66.8	66.9	67.0	67.1	67.2
-130	274.8	71.4	71.5	71.6	71.7	71.8	71.9	72.0	72.1	72.3
-120	277.7	76.4	76.5	76.6	76.7	76.8	76.9	76.9	77.0	77.0
-110	280.6	81.4	81.5	81.5	81.6	81.7	81.8	81.8	81.9	82.0
-100	283.6	86.5	86.7	86.7	86.8	86.8	86.9	87.0	87.0	87.0
-90	286.6	91.5	91.7	91.7	91.8	91.8	91.9	91.9	92.0	92.0
-80	289.7	96.5	96.6	96.6	96.7	96.7	96.8	96.9	97.0	97.1
-70	292.8	101.8	101.9	102.0	102.0	102.0	102.0	102.0	102.1	102.3
-60	296.0	106.8	106.9	107.0	107.0	107.0	107.1	107.2	107.4	107.5
-50	299.2	112.2	112.2	112.3	112.4	112.3	112.4	112.5	112.6	112.8
-40	302.5	117.5	117.5	117.5	117.5	117.7	117.8	117.8	118.0	118.1
-30	305.8	123.0	123.0	123.0	123.0	123.1	123.1	123.2	123.4	123.5
-20	309.2	128.5	128.5	128.5	128.5	128.6	128.7	128.7	128.7	128.9
-10	312.6	133.9	134.0	134.0	134.0	134.1	134.1	134.1	134.2	134.3
0	316.1	139.2	139.4	139.5	139.5	139.6	139.6	139.7	139.8	139.9
10	319.7	145.1	145.2	145.3	145.3	145.3	145.3	145.3	145.4	145.5
20	323.3	150.4	150.5	150.6	150.7	150.8	150.8	150.9	151.1	151.2
21.3				151.2	151.3	151.4	151.5	151.6	151.7	151.9
30	327.0	156.5	156.5	156.5	156.6	156.7	156.8	156.9	157.0	157.1
40	330.7	162.5	162.5	162.5	162.6	162.7	162.7	162.7	162.8	162.9
50	334.5	169.0	168.8	168.7	168.5	168.4	168.4	168.3	168.4	168.4
60	338.3	327.6	174.9	174.8	174.8	174.8	174.8	174.8	174.9	175.0
70	342.2	332.9	181.5	181.3	181.2	181.1	181.1	181.1	181.1	181.1
80	346.2	337.5	187.8	187.6	187.5	187.3	187.2	187.2	187.2	187.3
90	350.2	342.1	195.0	194.4	194.1	193.9	193.7	193.7	193.7	193.8
100	354.3	346.6	201.3	201.0	200.7	200.5	200.4	200.3	200.2	200.2
110	358.5	351.3	340.5	208.2	207.9	207.6	207.3	207.1	206.9	206.8
120	362.7	355.5	346.0	215.5	215.2	214.9	214.5	214.3	214.0	214.0
130	367.0	360.2	351.2	344.8	223.1	222.5	222.0	221.6	221.3	221.1
140	371.3	364.7	356.1	350.6	344.7	230.8	229.9	229.2	228.8	228.6
150	375.7	369.1	361.0	356.0	350.4	240.0	238.5	237.4	236.8	236.5
160	380.2	373.7	366.3	361.7	356.6	350.5	248.9	246.4	245.2	244.8
160.6			368.2	363.8	358.7	352.5	249.8	247.0	245.9	245.3
170	384.7	378.6	371.7	367.5	362.3	356.5	349.6	346.4	345.2	345.2
180	389.3	383.3	376.4	372.5	368.1	363.0	356.7	348.2	346.3	346.3
190	394.0	388.1	381.6	378.1	374.1	369.5	363.9	356.8	347.1	347.5
200	398.7	392.9	386.6	383.4	379.7	375.6	370.8	364.8	356.9	356.9
201.0	399.2	393.5	387.5	384.0	380.3	376.4	371.4	365.4	357.8	347.0
210	403.5	398.0	392.1	388.8	385.2	381.2	376.7	371.5	365.2	357.1
220	408.3	403.0	397.3	394.2	390.8	387.1	383.0	378.4	372.7	366.2
230	413.2	408.2	402.7	399.7	396.3	392.8	388.8	384.6	379.6	374.0
240	418.1	413.1	407.9	405.0	401.8	398.6	395.0	391.2	386.8	381.9
250	423.1	418.3	413.3	410.6	407.5	404.3	401.0	397.3	393.3	389.1
260	428.2	423.5	418.7	416.0	413.3	410.3	407.0	403.6	399.8	395.5
270	433.3	428.7	424.0	421.5	419.0	416.2	413.1	409.9	406.3	402.4
280	438.5	434.1	429.6	427.2	424.6	421.8	418.9	415.8	412.6	409.0
290	443.7	439.6	435.1	432.8	430.3	427.7	425.0	421.9	418.8	415.5
300	449.0	445.2	440.8	438.5	436.1	433.5	430.9	428.1	425.2	422.2
310	454.4	450.7	446.4	444.1	441.7	439.2	436.6	434.0	431.2	428.4
320	459.8	455.9	451.8	449.9	447.5	445.2	442.8	440.3	437.7	435.1
330	465.3	461.7	457.7	455.6	453.4	451.1	448.8	446.3	443.9	441.4
340	470.9	467.2	463.4	461.5	459.4	457.2	455.0	452.7	450.2	447.8
350	476.5	473.0	469.3	467.3	465.3	463.1	460.9	458.7	456.4	454.1
360	482.1	478.8	475.2	473.3	471.3	469.2	467.1	464.9	462.8	460.5
370	487.9	484.5	481.1	479.2	477.3	475.4	473.3	471.3	469.1	467.1
380	493.6	490.5	487.0	485.2	483.3	481.4	479.4	477.4	475.3	473.3
390	499.5	496.3	492.9	491.2	489.4	487.5	485.7	483.7	481.7	479.8
400	505.4	502.2	498.9	497.3	495.4	493.6	491.7	489.8	487.8	486.1

(Continued on page 202)

Table IV. Tabulated Values of Enthalpy for

Temp., ° F.	Pressure, P.S.I.A.									
	0	100	200	250	300	350	400	450	500	550
410	511.3	508.3	505.1	503.5	501.8	500.0	498.3	496.5	494.6	492.8
420	517.3	514.4	511.3	509.7	508.0	506.3	504.6	502.8	501.1	499.3
430	523.4	520.4	517.4	515.9	514.3	512.7	511.0	509.4	507.6	506.0
440	529.5	526.7	523.7	522.3	520.7	519.1	517.5	515.7	514.0	512.5
450	535.6	532.9	530.0	527.5	527.0	525.5	523.9	522.4	520.7	519.1
460	541.8	539.3	536.4	535.0	533.5	532.0	530.5	528.9	527.3	525.8
470	548.0	545.4	542.7	541.3	539.8	538.4	536.9	535.5	534.0	532.5
480	554.3	551.7	549.2	547.8	546.5	545.1	543.7	542.3	540.8	539.4
490	560.7	558.2	555.6	554.3	553.0	551.6	550.2	548.8	547.4	546.0
500	567.1	564.7	562.2	561.0	559.7	558.3	556.9	555.5	554.1	552.8
Temp., ° F.	Pressure, P.S.I.A.									
	600	617	700	800	900	1000	1250	1500	1750	2000
-280	1.0	1.1	1.4	1.7	1.9	2.5	3.4	4.0	4.4	4.6
-270	5.5	5.5	6.0	6.3	6.7	7.1	8.0	8.8	9.2	9.3
-260	10.2	10.3	10.5	10.9	11.4	11.7	12.6	13.3	13.7	13.9
-250	14.9	15.0	15.1	15.5	15.9	16.3	17.2	18.0	18.5	18.6
-240	19.7	19.8	20.0	20.5	20.8	21.1	22.0	22.6	23.1	23.3
-230	24.3	24.4	24.7	25.1	25.5	25.8	26.8	27.5	27.7	27.9
-220	29.0	29.0	29.4	29.7	30.0	30.4	31.4	32.0	32.5	32.6
-210	33.7	33.7	34.0	34.5	34.9	35.3	36.1	36.9	37.2	37.4
-200	38.5	38.5	38.7	39.1	39.5	39.8	40.8	41.4	42.0	42.2
-190	43.3	43.4	43.6	44.0	44.3	44.7	45.7	46.3	46.8	47.0
-180	48.0	48.1	48.4	48.6	49.0	49.4	50.4	51.0	51.5	51.8
-170	52.7	52.8	53.1	53.5	53.8	54.1	55.2	55.9	56.3	56.6
-160	57.7	57.8	58.0	58.4	58.7	59.0	60.2	60.8	61.3	61.5
-150	62.5	62.5	62.9	63.1	63.5	63.9	65.0	65.5	66.1	66.5
-140	67.4	67.5	67.8	68.1	68.5	68.9	69.8	70.4	71.0	71.3
-130	72.4	72.5	72.8	73.1	73.5	73.8	74.6	75.3	75.8	76.2
-120	77.2	77.2	77.6	78.0	78.3	78.6	79.6	80.3	80.9	81.2
-110	82.0	82.1	82.5	82.8	83.2	83.5	84.5	85.4	85.9	86.0
-100	87.1	87.2	87.5	87.8	88.2	88.5	89.5	90.3	90.8	91.0
-90	92.1	92.2	92.5	92.9	93.2	93.5	94.5	95.3	95.8	96.2
-80	97.3	97.4	97.6	98.0	98.3	98.6	99.7	100.5	100.9	101.3
-70	102.5	102.5	102.8	103.1	103.4	103.7	104.7	105.5	106.1	106.5
-60	107.6	107.7	108.0	108.4	108.7	109.0	110.0	110.7	111.3	111.7
-50	113.0	113.0	113.3	113.6	113.9	114.3	115.4	115.9	116.4	116.9
-40	118.2	118.3	118.5	118.9	119.2	119.5	120.6	121.2	121.7	122.0
-30	123.5	123.6	123.9	124.2	124.5	124.9	125.8	126.5	127.0	127.5
-20	129.0	129.0	129.3	129.6	129.9	130.3	131.1	131.7	132.3	132.7
-10	134.4	134.5	134.8	135.0	135.4	135.8	136.5	137.1	137.7	138.1
0	140.0	140.0	140.3	140.7	141.0	141.2	142.0	142.6	143.0	143.5
10	145.6	145.7	146.0	146.3	146.6	146.9	147.6	148.1	148.5	149.0
20	151.3	151.4	151.7	152.0	152.4	152.5	153.1	153.5	154.0	154.6
21.3	152.1	152.1	152.5	152.7	153.0	153.2	153.8	154.0	154.6	155.2
30	157.3	157.3	157.6	157.9	158.1	158.3	158.9	159.4	160.0	160.4
40	163.0	163.0	163.4	163.6	163.9	164.2	164.9	165.3	165.9	166.2

	ΔH (B.t.u. per pound)
Saturated liquid (at -280° F.)	0
Saturated liquid (-280° to -43.7° F.)	115.30
Enthalpy change on vaporization (at -43.7° F.)	183.17
Effect of pressure on enthalpy (14.7 to 0 p.s.i.a.)	2.70
Effect of temperature on zero pressure enthalpy (-43.7° to $+250^\circ$ F.)	121.93
H° (Propane at zero pressure and $+250^\circ$ F.)	423.1

Isobaric enthalpy differences at elevated pressures were calculated using Equation 1 with the data presented in Table I plus other published values of C_p (9, 37). The pressures at which such data are available are indicated by horizontal lines on Figure 5. The values of C_p recently reported by Ernst (9) are in excellent agreement with those at 1 atm. previously published by Kistiakowsky and Rice (17).

Above 100 p.s.i.a., published values of ϕ (37) were used in Equation 2 to determine the effect of pressure on

enthalpy. These basic data were supplemented by published experimental values of enthalpy departures, $(H^\circ - H)$ (35). The temperatures at which such data are available are indicated by vertical lines on Figure 5. In connection with the published data on ϕ (37), the effect of pressure on enthalpy at low pressures (<100 p.s.i.a.) was estimated, using published experimental values of the pressure dependence of enthalpy (35) together with values of ϕ° estimated from published correlations of the second virial coefficient, B , its temperature dependence (7, 14) (Equation 4), and estimates made using the BWR equation of state (1). Primary reliance was placed on the correlation of experimental values of B , as made available by Diaz Peña (8).

The isenthalpic data in the compressed liquid region ($T \approx 22^\circ$ F.) (37) were interpreted using Equation 5, together with heat capacity data in this region (37), to yield isothermal differences in enthalpy.

In establishing the enthalpy change on vaporization, experimental data from Dana *et al.* (6) and Yesavage *et al.* (37) were used, together with "critically chosen values" reported by Helegeson and Sage (13). The values from

Propane ($H = \text{B.t.u./Lb.}$) (Continued)

Temp., ° F.	Pressure, P.S.I.A.									
	600	617	700	800	900	1000	1250	1500	1750	2000
50	168.5	168.6	168.9	169.3	169.6	170.0	170.8	171.3	171.7	171.9
60	175.1	175.2	175.4	175.6	175.9	176.1	176.9	177.2	177.4	177.7
70	181.2	181.2	181.4	181.6	181.9	182.2	182.9	183.2	183.2	183.5
80	187.3	187.4	187.6	187.9	188.1	188.4	188.9	189.3	189.5	189.5
90	193.9	193.9	194.1	194.2	194.5	194.6	194.9	195.4	195.8	195.8
100	200.2	200.2	200.4	200.6	200.9	201.0	201.3	201.6	201.8	201.9
110	206.8	206.8	207.0	207.1	207.4	207.5	207.5	208.0	208.0	208.0
120	213.9	213.9	214.0	214.1	214.1	214.2	214.3	214.5	214.6	214.5
130	221.0	220.9	220.8	220.8	220.9	220.9	221.0	221.0	221.0	220.8
140	228.4	228.4	228.2	228.0	227.9	228.0	228.0	227.8	227.6	227.4
150	236.2	236.1	235.8	235.4	235.1	235.0	234.7	235.5	234.2	233.9
160	244.3	244.2	243.7	243.2	242.6	242.4	241.5	241.2	240.8	240.4
160.6	244.9	244.8	244.3	243.7	243.1	242.9	242.0	241.7	241.5	241.1
170	252.5	252.3	251.4	250.7	250.3	250.0	249.2	248.4	247.9	247.4
180	261.1	260.8	259.8	258.9	258.1	257.5	256.5	255.6	255.0	254.4
190	272.7	272.1	269.9	268.1	267.0	266.0	264.0	262.7	261.9	261.4
200	286.3	285.2	280.8	277.6	275.6	274.1	271.5	270.1	269.2	268.4
201.0	287.8	286.6	282.4	278.5	276.6	275.1	272.6	271.1	270.0	269.3
210	345.3	340.3	295.1	289.1	285.6	283.1	279.6	277.9	276.7	275.6
220	357.8	354.7	326.2	303.1	296.4	292.6	287.9	285.7	284.3	283.0
230	367.6	365.3	350.5	318.8	308.0	302.8	296.2	293.8	291.9	290.3
240	376.3	374.5	362.4	342.5	321.9	314.2	305.7	302.1	299.6	298.1
250	384.2	382.5	372.9	357.4	339.2	326.8	315.3	310.5	307.8	305.8
260	391.0	389.3	381.2	369.3	355.2	341.0	326.0	319.3	315.8	313.7
270	398.2	396.7	389.1	378.6	367.1	354.7	337.0	328.4	324.1	321.8
280	405.2	403.8	397.1	388.5	378.9	367.2	348.2	337.8	332.9	330.0
290	412.2	411.1	405.2	397.4	388.5	378.4	358.6	347.1	341.4	338.3
300	419.0	418.0	412.5	405.3	397.4	388.6	368.1	356.8	350.8	346.5
310	425.5	424.5	419.5	413.0	406.0	398.0	378.6	366.4	359.7	355.0
320	432.4	431.5	426.8	420.8	414.1	406.6	388.3	375.8	368.5	363.4
330	438.8	437.8	433.3	427.5	421.5	415.0	398.1	385.3	377.5	371.8
340	445.3	444.4	440.1	434.7	429.0	423.0	407.1	394.6	386.5	380.3
350	451.6	450.8	446.6	441.6	436.3	430.8	416.3	403.9	395.2	388.7
360	458.3	457.5	453.5	448.6	443.6	438.4	424.7	412.7	403.9	397.4
370	464.9	464.2	460.5	455.8	451.0	445.8	432.7	421.4	412.8	405.8
380	471.2	470.5	467.0	462.6	458.1	453.3	441.0	430.1	421.5	414.2
390	477.7	477.0	473.6	469.4	465.1	460.7	449.1	438.5	430.0	422.7
400	484.0	483.5	480.1	476.1	472.0	467.8	456.9	446.7	438.4	431.1
410	491.0	490.3	487.1	483.2	479.3	475.4	465.0	455.0	447.2	439.7
420	497.4	496.8	493.7	489.9	486.2	482.5	472.8	463.2	455.3	448.1
430	504.3	503.6	500.7	497.2	493.6	490.0	480.5	471.2	463.5	456.2
440	510.8	510.2	507.4	504.0	500.6	497.1	488.1	479.2	471.5	464.8
450	517.6	517.0	514.2	511.0	507.6	504.2	495.6	487.0	479.5	473.0
460	524.2	523.7	521.2	518.0	514.8	511.5	503.1	494.9	487.5	481.2
470	531.1	530.6	528.0	525.0	521.8	518.6	510.6	502.6	495.7	489.3
480	538.0	537.5	535.0	532.0	531.5	525.9	518.2	510.5	503.8	497.5
490	544.6	544.1	541.7	538.8	536.0	533.0	525.7	518.2	511.6	505.5
500	551.3	550.9	548.6	545.8	543.0	540.1	533.0	525.9	519.5	513.5

these latter two sources are in excellent agreement (better than $\pm 1\%$) in the region of overlap.

No attempt was made to correlate the extensive vapor pressure data reported in the literature. Instead, values were taken from recent tabulations (3, 18).

Redundant thermal data are available between 21° and 300° F. at pressures up to 2000 p.s.i.a. (Figure 5). Consistency checks were made as permitted by these redundancies, and the results are summarized in Figure 6. Consider the loop between the pressures of 500 and 1000 p.s.i.a. and the temperatures of 21.2° and 160.5° F. There is some error in the constituent experimental determinations because the algebraic sum of the enthalpy differences around the complete loop, $\Sigma \Delta H_i$, is not zero, but instead is -0.64 B.t.u. per pound. The percentage deviation, defined as

$$\frac{\sum_i \Delta H_i}{\sum_i |\Delta H_i|} \times 100 \quad (12)$$

is determined to be -0.34% . The maximum percentage deviation for any loop is $+0.42\%$, and the average absolute

deviation of all such checks is 0.18% . This is indicative of the accuracy of the enthalpy differences in this region.

The differences in enthalpy at a point calculated from different experimental data are small, but nevertheless it was necessary to make minor adjustments in preparing the final compilation. This was done by adjusting individual values of isobaric and isothermal enthalpy differences to make each loop thermodynamically consistent. These adjustments were made within the limits of experimental uncertainty of the data. In general, the uncertainty in ΔH_p is 0.3% , except near the critical and through and near the two-phase region. The uncertainty in ΔH_T is $\pm 1\%$, except at pressures below 200 p.s.i.a.

In extending the calculation of enthalpy down to -280°F. , use was made of experimental values of C_p for the saturated liquid (16), and values at 1000 and 2000 p.s.i.a. at temperatures of -240°F. and above (37) were extrapolated graphically to the lower temperatures. The variation in value of C_p over the range of extrapolation was about 1% .

Above 300°F. , primary reliance was placed on the C_p data of Daily and Felsing (5) at 1 atm. Between 300°

and 400° F. and at elevated pressures, smoothed curves were drawn to blend experimental values at 300° F. (37) with values calculated using the BWR equation of state (1) with the low pressure data. The blending was carried out so that the results were consistent with the experimental values of Yarborough and Edmister at 400° F. (35). Between 400° and 500° F., enthalpy departures were calculated using the BWR equation of state (1).

After all adjustments and extrapolations had been made as described above, a skeleton table of values of enthalpy was prepared. These values were then plotted on a diagram and smooth curves drawn to connect all points and to represent interpolated values. Values were then read from the master plot and are reported in Tables III and IV. From -250° to +300° F. at the temperatures and pressures of measurement as indicated on Figure 5, little or no interpolation is involved, and therefore the numbers listed for these temperatures and pressures can be considered to be smoothed experimental values. (The results in the form of two 11 × 17 graphs which can be read to 0.2 B.t.u. per pound and 0.2 p.s.i.a. are available for \$1.00 per set from J. E. Powers.)

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NOMENCLATURE

- B = second virial coefficient, cubic feet per pound mole or B.t.u. per pound mole-p.s.i.a.
 C_p = heat capacity, B.t.u. per pound-° F.
 H = specific enthalpy, B.t.u. per pound
 P = pressure, p.s.i.a.
 T = temperature, ° F.
 V = specific volume, cubic feet per pound
 μ = $(\partial T/\partial P)_H$ Joule-Thomson coefficient, ° F. per p.s.i.
 ϕ = $(\partial H/\partial P)_T$ isothermal throttling coefficient, B.t.u. per pound-p.s.i.

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