UNIVERSITY OF JOHANNESBURG

PROGRAM	:	NATIONAL DIPLOMA *CHEMICAL ENGINEERING*
SUBJECT	:	**THERMODYNAMICS III**
CODE	:	**CIT3111**
DATE	:	SSA WINTER EXAMINATION 2019
DURATION	:	3 HRS
WEIGHT	:	40 : 60
TOTAL MARKS	:	90
EXAMINER(S)	:	DR T FALAYI
MODERATOR	:	DR A MAMVURA
NUMBER OF PAGES	:	PAGES
REQUIREMENTS	:	Use of scientific (non-programmable) calculator is permitted (only one per candidate); graph paper

HINTS AND INSTRUCTIONS TO CANDIDATE(S):

- Purpose of assessment is to determine not only if you can write down an answer, but also to assess whether you understand the concepts, principles and expressions involved. Set out solutions in a logical and concise manner with justification for the steps followed.
- **ATTEMPT ALL QUESTIONS**. Please answer each question to the best of your ability.
- Write your details (module name and code, ID number, student number etc.) on script(s).
- Number each question clearly; questions may be answered in any order.
- Make sure that you read each question carefully before attempting to answer the question.
- Show all steps (and units) in calculations; this is a 'closed book' test.
- Ensure your responses are legible, clear and include relevant units (where appropriate).
- **Round off all answers tom 3 decimal places**

Question One **[Total: 11 Marks]**

a) Name 4 types of thermodynamic equilibrium [4]
b) Define Saturated vapour [2]
c) Convert 35 K to ºC [1]
d) A slab of gold is at the bottom of a 50 cm column of mercury. If the density of mercury is 13.534 g/cm^3, g is 9.871 m/s^{2}and the atmospheric pressure is 1 bar, calculate the pressure on the slab of gold in kPa. [4]

Question Two **[Total: 19 Marks]**

Steam is leaving a 4 L pressure cooker whose operating pressure is 250 kPa. It is observed that the amount of liquid in the cooker has decreased by 0.8 L in 20 min after the steady operating conditions are established, and the cross-sectional area of the exit opening is 8 mm^2. Determine:

(a) the mass flow rate of the steam [7]

(b) the exit velocity [7]

(c) the flow energies of the steam per unit mass [5]

Note: Obtain water and steam properties from steam tables. Assume that flow is steady and initial start-up period is disregarded, KE and PE are negligible and Saturation conditions exist within the cooker at all times so that steam leaves the cooker as a saturated vapour at the cooker pressure

Question Three **[Total: 21 Marks]**

a) Calculate the heat required to raise the temperature of 5 moles of ethane from 300ºC to 600ºC in a steady-flow process at a pressure sufficiently low that ethane may be considered an ideal gas. [10]

b) N-Butane (C_4H_{10}) is burned completely with the stoichiometric amount of air during a steady-flow combustion process. If both the reactants and the products are maintained at 25°C and 1 atm and the water in the products exists in the liquid form, Calculate ΔH^o_{rxn} **.** [11]

Question Four **[Total: 17 Marks]**

a) Use Maxwell relation to determine the relationship for $\left(\frac{\partial S}{\partial V}\right)_T$ for a gas whose gas whose equation of state is $\left(P - {a}/{V^2}\right)(V - b) = RT$ [5]

b) Calculate $\left(\frac{\partial S}{\partial V}\right)_T$ for steam at 300ºC using ideal gas equation and appropriate Maxwell relation $v = 0.03619 m^3/kg$. Use R=8.314 m^{3}Pa/mol.K. [6]

c) For the same steam in (b) determine $\left(\frac{\partial S}{\partial V}\right)_T$ using Redlich-Kwong equation of state and an appropriate Maxwell relation $v = 0.03619 m^3/kg$ Use R=8.314 m^3Pa/mol.K. Redlich-Kwong equation of state $P = \frac{RT}{V-b}\left(\frac{a}{V(V+b)T^{1/2}}\right)$,

$a = 1.42 \times 10^4 Pa\left(\frac{m^3}{kmol}\right)^2 K^{\frac{1}{2}}$ $b = 0.0211\frac{m^3}{kmol}$ [6]

Question 5 **[22 marks]**

a) Estimate the fugacity isobutene at 20 bar and 87°C given that the compressibility factor is given as $Z = 1 + \frac{BP}{RT}$ where B -4.28×10^{-4} m^3/mol. Give your answer in kPa. [3]

b) Estimate the fugacity of a gaseous mixture consisting of 30% component 1 and 70% component 2 by mole, given that at 100°C and 50 bar, the fugacity coefficients of components 1 and 2 are 0.7 and 0.85 respectively. Give your answer in bars [6].

c) For SO_2 at 430.8 K and 394.45 bar, determine good estimate of fugacity using the using Lee/Kesler correlation charts. [13]

END **[Total: 90 Marks]**

USEFUL EQUATIONS AND FORMULAE

$PV = nRT$; $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$; $v = \frac{V^t}{m}$; $\dot{m} = uA\rho$; $\dot{n} = \frac{uA}{vM}$; $\rho = v^{-1}$; $\dot{V} = \frac{V}{t}$

t(°C) = T(K) – 273.15; t(°F) = T(R) – 459.67; t(°F) = 1.8t(°C) + 32;

$P_g = \frac{F}{A} = \frac{mg}{A} = \frac{\rho V g}{A} = \frac{Ah\rho g}{A}$; $P_{abs} = P_g(or\ \rho gh) + P_{atm}$

Interpolation: $M = \left(\frac{X_2 - X}{X_2 - X_1}\right)M_1 + \left(\frac{X - X_1}{X_2 - X_1}\right)M_2$ OR $M = \frac{M_1(X_2 - X) + M_2(X - X_1)}{X_2 - X_1}$

Double Interpolation:

	X_1	X	X_2
Y_1	$M_{1,1}$		$M_{1,2}$
Y		$M = ?$	
Y_2	$M_{2,1}$		$M_{2,2}$

$$M = \left[\left(\frac{X_2 - X}{X_2 - X_1}\right)M_{1,1} + \left(\frac{X - X_1}{X_2 - X_1}\right)M_{1,2}\right]\frac{Y_2 - Y}{Y_2 - Y_1} + \left[\left(\frac{X_2 - X}{X_2 - X_1}\right)M_{2,1} + \left(\frac{X - X_1}{X_2 - X_1}\right)M_{2,2}\right]\frac{Y - Y_1}{Y_2 - Y_1}$$

$\Delta E_{univ} = \Delta E_{syst} + \Delta E_{surr} = 0$; $\eta = \frac{W_{irreversible}}{W_{reversible}}$; $\frac{dm_{cv}}{dt} = \Delta m = \dot{m}_{out} - \dot{m}_{in}$

Energy balance for open systems: $\frac{d(mU)_{cv}}{dt} = -\dot{m}\Delta\left[U + \frac{1}{2}u^2 + gh\right] + \dot{Q} + \dot{W}$

Energy balance for steady-state flow processes: $\Delta\dot{m}\left(H+\frac{1}{2}u^2+gh\right)=\dot{Q}+\dot{W}_s$

Single Phase: $\ln\frac{V_2}{V_1}=\beta(T_2-T_1)-\kappa(P_2-P_1)$

Mechanically reversible closed system processes:

Constant V: $Q=n\Delta U=n\int_{T_1}^{T_2}C_v dT=nC_v\Delta T$

Constant P: $Q=n\Delta H=n\int_{T_1}^{T_2}C_p dT=nC_p\Delta T$; $W=-R(T_2-T_1)$

Constant T: $Q=-W=RT_1\ln\frac{V_2}{V_1}=-RT_1\ln\frac{P_2}{P_1}=P_1V_1\ln\frac{V_2}{V_1}=-P_1V_1\ln\frac{P_2}{P_1}$

Adiabatic: $\frac{T_2}{T_1}=\left(\frac{V_1}{V_2}\right)^{R/C_V}$; $\frac{T_2}{T_1}=\left(\frac{P_2}{P_1}\right)^{R/C_P}$; $\frac{P_2}{P_1}=\left(\frac{V_1}{V_2}\right)^{C_P/C_V}$; $\gamma=\frac{C_P}{C_V}$;

Adiabatic: $W=\Delta U=C_V\Delta T=\frac{R\Delta T}{\gamma-1}=\frac{R(T_2-T_1)}{\gamma-1}=\frac{P_2V_2-P_1V_1}{\gamma-1}=\frac{P_1V_1}{\gamma-1}\left[\left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma}-1\right]=\frac{RT_1}{\gamma-1}\left[\left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma}-1\right]$

For Carnot Cycle $\eta=1-\frac{Q_C}{Q_H}=1-\frac{T_c}{T_H}=\frac{W_{net}}{Q_H}$

Virial equation truncated to 2 terms: $Z=\frac{PV}{RT}=1+\frac{BP}{RT}$; truncated to 3 terms: $Z=1+\frac{B(T)}{V}+\frac{C(T)}{V^2}$;

Lee/ Kesler correlation: $Z=Z^o+\omega Z^1$;

Generalized Pitzer correlation: $Z=1+(B^0+\omega B^1)\frac{P_r}{T_r}$ $\left(B^0=0.083-\frac{0.422}{T_r^{1.6}};\quad B^1=0.139-\frac{0.172}{T_r^{4.2}}\right)$

IG: $Q=n\Delta H=n\int_{T_0}^{T_1}\frac{Cp^{ig}}{R}dT=n\left[AT_o(\tau-1)+\frac{B}{2}T_o^2(\tau^2-1)+\frac{C}{3}T_o^3(\tau^3-1)+\frac{D}{T_o}\left(\frac{\tau-1}{\tau}\right)\right]=n\frac{\langle C_P\rangle_H}{R}(T_1-T_0)$;

where, $\tau=\frac{T}{T_0}$

$$\langle C_P\rangle_H=R\left[A+\frac{B}{2}T_o(\tau+1)+\frac{C}{3}T_o^2(\tau^2+\tau+1)+\frac{D}{\tau T_o^2}\right]$$

Clapeyron equation: $\Delta H=T\Delta V\frac{dP^{sat}}{dT}$

General entropy change: $\Delta S=C_p\ln\frac{T_2}{T_1}-ln\frac{P_2}{P_1}$

Entropy change for IG: $\frac{\Delta S}{R}=\frac{\langle C_p^{ig}\rangle_S}{R}\ln\frac{T}{T_o}-\ln\frac{P}{P_o}$; $\frac{\langle C_p^{ig}\rangle_S}{R}=A+\left[BT_o+\left(CT_o^2+\frac{D}{\tau^2T_o^2}\right)\left(\frac{\tau+1}{\tau}\right)\right]\left(\frac{\tau-1}{\ln\tau}\right)$

For residual properties: $V^R=V-V^{ig}$; $H^R=H-H^{ig}$; $G^R=RT\ln\phi$

$S^R=S-(S^{ig}+\frac{R}{Mr}\ln\frac{P_2}{P_1})$; $\frac{H^R}{RT_c}=\left(\frac{H^R}{RT_c}\right)^0+\omega\left(\frac{H^R}{RT_c}\right)^1$; $\frac{S^R}{R}=\left(\frac{S^R}{R}\right)^0+\omega\left(\frac{S^R}{R}\right)^1$

$\frac{H^R}{RT_c}=P_r\left[\left(0.083-\frac{1.097}{T_r^{1.6}}\right)+\omega\left(0.139-\frac{0.894}{T_r^{4.2}}\right)\right]$; $\frac{S^R}{R}=-P_r\left[\frac{0.675}{T_r^{2.6}}+\omega\left(\frac{0.722}{T_r^{5.2}}\right)\right]$;

$$Z = 1 + \beta - q\beta \frac{(Z-\beta)}{(Z+\in\beta)(Z+\sigma\beta)}$$

<u>Fugacity and fugacity coefficient</u>: $\phi = (\phi^0)(\phi^1)^{\omega}$; $f = \phi P$; $\ln\phi = (B^0 + \omega B^1)\frac{P_r}{T_r}$; $\ln\phi = \sum_i X_i \ln\phi_i$

$$\ln\frac{f}{P} = \frac{BP}{RT}$$

<u>Raoult's law</u>: $y_i P = x_i P_i^{sat}$ where $P = \sum_i x_i P_i^{sat}$ or $P = \frac{1}{\sum_i y_i/P_i^{sat}}$

<u>Modified Raoult's law</u>: $y_i P = x_i \gamma_i P_i^{sat}$ where $P = \sum_i x_i \gamma_i P_i^{sat}$ or $P = \frac{1}{\sum_i y_i/\gamma_i P_i^{sat}}$

Maxwell Relations

- $\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V$
- $\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P$
- $\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T$
- $\left(\frac{\partial V}{\partial T}\right)_P = -\left(\frac{\partial S}{\partial P}\right)_T$

Table A.1: Conversion Factors

Quantity	Conversion
Length	1 m = 100 cm = 3.28084(ft) = 39.3701(in)
Mass	1 kg = 10^3 g = 2.20462(lb_m)
Force	1 N = 1 kg m s^{-2} = 10^5(dyne) = 0.224809(lb_f)
Pressure	1 bar = 10^5 kg m^{-1} s^{-2} = 10^5 N m^{-2} = 10^5 Pa = 10^2 kPa = 10^6(dyne) cm^{-2} = 0.986923(atm) = 14.5038(psia) = 750.061(torr)
Volume	1 m^3 = 10^6 cm^3 = 10^3 liters = 35.3147$(ft)^3$ = 264.172(gal)
Density	1 g cm^{-3} = 10^3 kg m^{-3} = 62.4278(lb_m)$(ft)^{-3}$
Energy	1 J = 1 kg m^2 s^{-2} = 1 N m = 1 m^3 Pa = 10^{-5} m^3 bar = 10 cm^3 bar = 9.86923 cm^3(atm) = 10^7(dyne) cm = 10^7(erg) = 0.239006(cal) = 5.12197 × $10^{-3}$$(ft)^3$(psia) = 0.737562(ft)($lb_f$) = 9.47831 × 10^{-4}(Btu) = 2.77778 × 10^{-7} kWhr
Power	1 kW = 10^3 W = 10^3 kg m^2 s^{-3} = 10^3 J s^{-1} = 239.006(cal) s^{-1} = 737.562(ft)(lb_f) s^{-1} = 0.947831(Btu) s^{-1} = 1.34102(hp)

Table A.2: Values of the Universal Gas Constant

R = 8.314 J mol^{-1} K^{-1} = 8.314 m^3 Pa mol^{-1} K^{-1}
= 83.14 cm^3 bar mol^{-1} K^{-1} = 8,314 cm^3 kPa mol^{-1} K^{-1}
= 82.06 cm^3(atm) mol^{-1} K^{-1} = 62,356 cm^3(torr) mol^{-1} K^{-1}
= 1.987(cal) mol^{-1} K^{-1} = 1.986(Btu)(lb mole)$^{-1}$(R)$^{-1}$
= 0.7302$(ft)^3$(atm)(lb mol)$^{-1}$(R)$^{-1}$ = 10.73$(ft)^3$(psia)(lb mol)$^{-1}$(R)$^{-1}$
= 1,545(ft)(lb_f)(lb mol)$^{-1}$(R)$^{-1}$

Table B.1 Properties of Pure Species

	Molar mass	ω	T_c/K	P_c/bar	Z_c	V_c cm^3 mol^{-1} or 10^{-3} m^3 kmol^{-1}	T_n/K
Methane	16.043	0.012	190.6	45.99	0.286	98.6	111.4
Ethane	30.070	0.100	305.3	48.72	0.279	145.5	184.6
Propane	44.097	0.152	369.8	42.48	0.276	200.0	231.1
n-Butane	58.123	0.200	425.1	37.96	0.274	255.	272.7
n-Pentane	72.150	0.252	469.7	33.70	0.270	313.	309.2
n-Hexane	86.177	0.301	507.6	30.25	0.266	371.	341.9
n-Heptane	100.204	0.350	540.2	27.40	0.261	428.	371.6
n-Octane	114.231	0.400	568.7	24.90	0.256	486.	398.8
n-Nonane	128.258	0.444	594.6	22.90	0.252	544.	424.0
n-Decane	142.285	0.492	617.7	21.10	0.247	600.	447.3
Isobutane	58.123	0.181	408.1	36.48	0.282	262.7	261.4
Isooctane	114.231	0.302	544.0	25.68	0.266	468.	372.4
Cyclopentane	70.134	0.196	511.8	45.02	0.273	258.	322.4
Cyclohexane	84.161	0.210	553.6	40.73	0.273	308.	353.9
Methylcyclopentane	84.161	0.230	532.8	37.85	0.272	319.	345.0
Methylcyclohexane	98.188	0.235	572.2	34.71	0.269	368.	374.1
Ethylene	28.054	0.087	282.3	50.40	0.281	131.	169.4
Propylene	42.081	0.140	365.6	46.65	0.289	188.4	225.5
1-Butene	56.108	0.191	420.0	40.43	0.277	239.3	266.9
cis-2-Butene	56.108	0.205	435.6	42.43	0.273	233.8	276.9
trans-2-Butene	56.108	0.218	428.6	41.00	0.275	237.7	274.0
1-Hexene	84.161	0.280	504.0	31.40	0.265	354.	336.3
Isobutylene	56.108	0.194	417.9	40.00	0.275	238.9	266.3
1,3-Butadiene	54.092	0.190	425.2	42.77	0.267	220.4	268.7
Cyclohexene	82.145	0.212	560.4	43.50	0.272	291.	356.1
Acetylene	26.038	0.187	308.3	61.39	0.271	113.	189.4
Benzene	78.114	0.210	562.2	48.98	0.271	259.	353.2
Toluene	92.141	0.262	591.8	41.06	0.264	316.	383.8
Ethylbenzene	106.167	0.303	617.2	36.06	0.263	374.	409.4
Cumene	120.194	0.326	631.1	32.09	0.261	427.	425.6
o-Xylene	106.167	0.310	630.3	37.34	0.263	369.	417.6
m-Xylene	106.167	0.326	617.1	35.36	0.259	376.	412.3
p-Xylene	106.167	0.322	616.2	35.11	0.260	379.	411.5
Styrene	104.152	0.297	636.0	38.40	0.256	352.	418.3
Naphthalene	128.174	0.302	748.4	40.51	0.269	413.	
Biphenyl	154.211	0.365	789.3	38.50	0.295	502.	528.2
Formaldehyde	30.026	0.282	408.0	65.90	0.223	115.	254.1
Acetaldehyde	44.053	0.291	466.0	55.50	0.221	154.	294.0
Methyl acetate	74.079	0.331	506.6	47.50	0.257	228.	330.1
Ethyl acetate	88.106	0.366	523.3	38.80	0.255	286.	350.2
Acetone	58.080	0.307	508.2	47.01	0.233	209.	329.4
Methyl ethyl ketone	72.107	0.323	535.5	41.50	0.249	267.	352.8
Diethyl ether	74.123	0.281	466.7	36.40	0.263	280.	307.6
Methyl t-butyl ether	88.150	0.266	497.1	34.30	0.273	329.	328.4
Methanol	32.042	0.564	512.6	80.97	0.224	118.	337.9

Table B.1 (Continued)

	Molar mass	ω	T_c/K	P_c/bar	Z_c	V_c cm^3 mol^{-1} or 10^{-3} m^3 kmol^{-1}	T_n/K
Ethanol	46.069	0.645	513.9	61.48	0.240	167.	351.4
1-Propanol	60.096	0.622	536.8	51.75	0.254	219.	370.4
1-Butanol	74.123	0.594	563.1	44.23	0.260	275.	390.8
1-Hexanol	102.177	0.579	611.4	35.10	0.263	381.	430.6
2-Propanol	60.096	0.668	508.3	47.62	0.248	220.	355.4
Phenol	94.113	0.444	694.3	61.30	0.243	229.	455.0
Ethylene glycol	62.068	0.487	719.7	77.00	0.246	191.0	470.5
Acetic acid	60.053	0.467	592.0	57.86	0.211	179.7	391.1
n-Butyric acid	88.106	0.681	615.7	40.64	0.232	291.7	436.4
Benzoic acid	122.123	0.603	751.0	44.70	0.246	344.	522.4
Acetonitrile	41.053	0.338	545.5	48.30	0.184	173.	354.8
Methylamine	31.057	0.281	430.1	74.60	0.321	154.	266.8
Ethylamine	45.084	0.285	456.2	56.20	0.307	207.	289.7
Nitromethane	61.040	0.348	588.2	63.10	0.223	173.	374.4
Carbon tetrachloride	153.822	0.193	556.4	45.60	0.272	276.	349.8
Chloroform	119.377	0.222	536.4	54.72	0.293	239.	334.3
Dichloromethane	84.932	0.199	510.0	60.80	0.265	185.	312.9
Methyl chloride	50.488	0.153	416.3	66.80	0.276	143.	249.1
Ethyl chloride	64.514	0.190	460.4	52.70	0.275	200.	285.4
Chlorobenzene	112.558	0.250	632.4	45.20	0.265	308.	404.9
Tetrafluoroethane	102.030	0.327	374.2	40.60	0.258	198.0	247.1
Argon	39.948	0.000	150.9	48.98	0.291	74.6	87.3
Krypton	83.800	0.000	209.4	55.02	0.288	91.2	119.8
Xenon	131.30	0.000	289.7	58.40	0.286	118.0	165.0
Helium 4	4.003	−0.390	5.2	2.28	0.302	57.3	4.2
Hydrogen	2.016	−0.216	33.19	13.13	0.305	64.1	20.4
Oxygen	31.999	0.022	154.6	50.43	0.288	73.4	90.2
Nitrogen	28.014	0.038	126.2	34.00	0.289	89.2	77.3
Air†	28.851	0.035	132.2	37.45	0.289	84.8	
Chlorine	70.905	0.069	417.2	77.10	0.265	124.	239.1
Carbon monoxide	28.010	0.048	132.9	34.99	0.299	93.4	81.7
Carbon dioxide	44.010	0.224	304.2	73.83	0.274	94.0	
Carbon disulfide	76.143	0.111	552.0	79.00	0.275	160.	319.4
Hydrogen sulfide	34.082	0.094	373.5	89.63	0.284	98.5	212.8
Sulfur dioxide	64.065	0.245	430.8	78.84	0.269	122.	263.1
Sulfur trioxide	80.064	0.424	490.9	82.10	0.255	127.	317.9
Nitric oxide (NO)	30.006	0.583	180.2	64.80	0.251	58.0	121.4
Nitrous oxide (N_2O)	44.013	0.141	309.6	72.45	0.274	97.4	184.7
Hydrogen chloride	36.461	0.132	324.7	83.10	0.249	81.	188.2
Hydrogen cyanide	27.026	0.410	456.7	53.90	0.197	139.	298.9
Water	18.015	0.345	647.1	220.55	0.229	55.9	373.2
Ammonia	17.031	0.253	405.7	112.80	0.242	72.5	239.7
Nitric acid	63.013	0.714	520.0	68.90	0.231	145.	356.2
Sulfuric acid	98.080	...	924.0	64.00	0.147	177.	610.0

†Pseudoparameters for $y_{N_2} = 0.79$ and $y_{O_2} = 0.21$. See Eqs. (6.88)–(6.90).

Table E.I Values of Z^0

$P_r =$ / T_r	0.0100	0.0500	0.1000	0.2000	0.4000	0.6000	0.8000	1.0000
0.30	*0.0029*	*0.0145*	*0.0290*	*0.0579*	*0.1158*	*0.1737*	*0.2315*	0.2892
0.35	*0.0026*	*0.0130*	*0.0261*	*0.0522*	*0.1043*	*0.1564*	*0.2084*	0.2604
0.40	*0.0024*	*0.0119*	*0.0239*	*0.0477*	*0.0953*	*0.1429*	*0.1904*	0.2379
0.45	*0.0022*	*0.0110*	*0.0221*	*0.0442*	*0.0882*	*0.1322*	*0.1762*	0.2200
0.50	*0.0021*	*0.0103*	*0.0207*	*0.0413*	*0.0825*	*0.1236*	*0.1647*	0.2056
0.55	0.9804	*0.0098*	*0.0195*	*0.0390*	*0.0778*	*0.1166*	*0.1553*	0.1939
0.60	0.9849	*0.0093*	*0.0186*	*0.0371*	*0.0741*	*0.1109*	*0.1476*	0.1842
0.65	0.9881	0.9377	*0.0178*	*0.0356*	*0.0710*	*0.1063*	*0.1415*	0.1765
0.70	0.9904	0.9504	0.8958	*0.0344*	*0.0687*	*0.1027*	*0.1366*	0.1703
0.75	0.9922	0.9598	0.9165	*0.0336*	*0.0670*	*0.1001*	*0.1330*	0.1656
0.80	0.9935	0.9669	0.9319	0.8539	*0.0661*	*0.0985*	*0.1307*	0.1626
0.85	0.9946	0.9725	0.9436	0.8810	*0.0661*	*0.0983*	*0.1301*	0.1614
0.90	0.9954	0.9768	0.9528	0.9015	0.7800	*0.1006*	*0.1321*	0.1630
0.93	0.9959	0.9790	0.9573	0.9115	0.8059	0.6635	*0.1359*	0.1664
0.95	0.9961	0.9803	0.9600	0.9174	0.8206	0.6967	*0.1410*	0.1705
0.97	0.9963	0.9815	0.9625	0.9227	0.8338	0.7240	0.5580	0.1779
0.98	0.9965	0.9821	0.9637	0.9253	0.8398	0.7360	0.5887	0.1844
0.99	0.9966	0.9826	0.9648	0.9277	0.8455	0.7471	0.6138	0.1959
1.00	0.9967	0.9832	0.9659	0.9300	0.8509	0.7574	0.6355	0.2901
1.01	0.9968	0.9837	0.9669	0.9322	0.8561	0.7671	0.6542	0.4648
1.02	0.9969	0.9842	0.9679	0.9343	0.8610	0.7761	0.6710	0.5146
1.05	0.9971	0.9855	0.9707	0.9401	0.8743	0.8002	0.7130	0.6026
1.10	0.9975	0.9874	0.9747	0.9485	0.8930	0.8323	0.7649	0.6880
1.15	0.9978	0.9891	0.9780	0.9554	0.9081	0.8576	0.8032	0.7443
1.20	0.9981	0.9904	0.9808	0.9611	0.9205	0.8779	0.8330	0.7858
1.30	0.9985	0.9926	0.9852	0.9702	0.9396	0.9083	0.8764	0.8438
1.40	0.9988	0.9942	0.9884	0.9768	0.9534	0.9298	0.9062	0.8827
1.50	0.9991	0.9954	0.9909	0.9818	0.9636	0.9456	0.9278	0.9103
1.60	0.9993	0.9964	0.9928	0.9856	0.9714	0.9575	0.9439	0.9308
1.70	0.9994	0.9971	0.9943	0.9886	0.9775	0.9667	0.9563	0.9463
1.80	0.9995	0.9977	0.9955	0.9910	0.9823	0.9739	0.9659	0.9583
1.90	0.9996	0.9982	0.9964	0.9929	0.9861	0.9796	0.9735	0.9678
2.00	0.9997	0.9986	0.9972	0.9944	0.9892	0.9842	0.9796	0.9754
2.20	0.9998	0.9992	0.9983	0.9967	0.9937	0.9910	0.9886	0.9865
2.40	0.9999	0.9996	0.9991	0.9983	0.9969	0.9957	0.9948	0.9941
2.60	1.0000	0.9998	0.9997	0.9994	0.9991	0.9990	0.9990	0.9993
2.80	1.0000	1.0000	1.0001	1.0002	1.0007	1.0013	1.0021	1.0031
3.00	1.0000	1.0002	1.0004	1.0008	1.0018	1.0030	1.0043	1.0057
3.50	1.0001	1.0004	1.0008	1.0017	1.0035	1.0055	1.0075	1.0097
4.00	1.0001	1.0005	1.0010	1.0021	1.0043	1.0066	1.0090	1.0115

Table E.2 Values of Z^1

$P_r =$	0.0100	0.0500	0.1000	0.2000	0.4000	0.6000	0.8000	1.0000
T_r								
0.30	−0.0008	−0.0040	−0.0081	−0.0161	−0.0323	−0.0484	−0.0645	−0.0806
0.35	−0.0009	−0.0046	−0.0093	−0.0185	−0.0370	−0.0554	−0.0738	−0.0921
0.40	−0.0010	−0.0048	−0.0095	−0.0190	−0.0380	−0.0570	−0.0758	−0.0946
0.45	−0.0009	−0.0047	−0.0094	−0.0187	−0.0374	−0.0560	−0.0745	−0.0929
0.50	−0.0009	−0.0045	−0.0090	−0.0181	−0.0360	−0.0539	−0.0716	−0.0893
0.55	−0.0314	−0.0043	−0.0086	−0.0172	−0.0343	−0.0513	−0.0682	−0.0849
0.60	−0.0205	−0.0041	−0.0082	−0.0164	−0.0326	−0.0487	−0.0646	−0.0803
0.65	−0.0137	−0.0772	−0.0078	−0.0156	−0.0309	−0.0461	−0.0611	−0.0759
0.70	−0.0093	−0.0507	−0.1161	−0.0148	−0.0294	−0.0438	−0.0579	−0.0718
0.75	−0.0064	−0.0339	−0.0744	−0.0143	−0.0282	−0.0417	−0.0550	−0.0681
0.80	−0.0044	−0.0228	−0.0487	−0.1160	−0.0272	−0.0401	−0.0526	−0.0648
0.85	−0.0029	−0.0152	−0.0319	−0.0715	−0.0268	−0.0391	−0.0509	−0.0622
0.90	−0.0019	−0.0099	−0.0205	−0.0442	−0.1118	−0.0396	−0.0503	−0.0604
0.93	−0.0015	−0.0075	−0.0154	−0.0326	−0.0763	−0.1662	−0.0514	−0.0602
0.95	−0.0012	−0.0062	−0.0126	−0.0262	−0.0589	−0.1110	−0.0540	−0.0607
0.97	−0.0010	−0.0050	−0.0101	−0.0208	−0.0450	−0.0770	−0.1647	−0.0623
0.98	−0.0009	−0.0044	−0.0090	−0.0184	−0.0390	−0.0641	−0.1100	−0.0641
0.99	−0.0008	−0.0039	−0.0079	−0.0161	−0.0335	−0.0531	−0.0796	−0.0680
1.00	−0.0007	−0.0034	−0.0069	−0.0140	−0.0285	−0.0435	−0.0588	−0.0879
1.01	−0.0006	−0.0030	−0.0060	−0.0120	−0.0240	−0.0351	−0.0429	−0.0223
1.02	−0.0005	−0.0026	−0.0051	−0.0102	−0.0198	−0.0277	−0.0303	−0.0062
1.05	−0.0003	−0.0015	−0.0029	−0.0054	−0.0092	−0.0097	−0.0032	0.0220
1.10	0.0000	0.0000	0.0001	0.0007	0.0038	0.0106	0.0236	0.0476
1.15	0.0002	0.0011	0.0023	0.0052	0.0127	0.0237	0.0396	0.0625
1.20	0.0004	0.0019	0.0039	0.0084	0.0190	0.0326	0.0499	0.0719
1.30	0.0006	0.0030	0.0061	0.0125	0.0267	0.0429	0.0612	0.0819
1.40	0.0007	0.0036	0.0072	0.0147	0.0306	0.0477	0.0661	0.0857
1.50	0.0008	0.0039	0.0078	0.0158	0.0323	0.0497	0.0677	0.0864
1.60	0.0008	0.0040	0.0080	0.0162	0.0330	0.0501	0.0677	0.0855
1.70	0.0008	0.0040	0.0081	0.0163	0.0329	0.0497	0.0667	0.0838
1.80	0.0008	0.0040	0.0081	0.0162	0.0325	0.0488	0.0652	0.0814
1.90	0.0008	0.0040	0.0079	0.0159	0.0318	0.0477	0.0635	0.0792
2.00	0.0008	0.0039	0.0078	0.0155	0.0310	0.0464	0.0617	0.0767
2.20	0.0007	0.0037	0.0074	0.0147	0.0293	0.0437	0.0579	0.0719
2.40	0.0007	0.0035	0.0070	0.0139	0.0276	0.0411	0.0544	0.0675
2.60	0.0007	0.0033	0.0066	0.0131	0.0260	0.0387	0.0512	0.0634
2.80	0.0006	0.0031	0.0062	0.0124	0.0245	0.0365	0.0483	0.0598
3.00	0.0006	0.0029	0.0059	0.0117	0.0232	0.0345	0.0456	0.0565
3.50	0.0005	0.0026	0.0052	0.0103	0.0204	0.0303	0.0401	0.0497
4.00	0.0005	0.0023	0.0046	0.0091	0.0182	0.0270	0.0357	0.0443

Table E.15 Values of ϕ^0

P_r =	1.0000	1.2000	1.5000	2.0000	3.0000	5.0000	7.0000	10.000
T_r								
0.30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.35	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.40	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002	0.0003
0.45	0.0016	0.0014	0.0012	0.0010	0.0008	0.0008	0.0009	0.0012
0.50	0.0055	0.0048	0.0041	0.0034	0.0028	0.0025	0.0027	0.0034
0.55	0.0146	0.0127	0.0107	0.0089	0.0072	0.0063	0.0066	0.0080
0.60	0.0321	0.0277	0.0234	0.0193	0.0154	0.0132	0.0135	0.0160
0.65	0.0611	0.0527	0.0445	0.0364	0.0289	0.0244	0.0245	0.0282
0.70	0.1045	0.0902	0.0759	0.0619	0.0488	0.0406	0.0402	0.0453
0.75	0.1641	0.1413	0.1188	0.0966	0.0757	0.0625	0.0610	0.0673
0.80	0.2404	0.2065	0.1738	0.1409	0.1102	0.0899	0.0867	0.0942
0.85	0.3319	0.2858	0.2399	0.1945	0.1517	0.1227	0.1175	0.1256
0.90	0.4375	0.3767	0.3162	0.2564	0.1995	0.1607	0.1524	0.1611
0.93	0.5058	0.4355	0.3656	0.2972	0.2307	0.1854	0.1754	0.1841
0.95	0.5521	0.4764	0.3999	0.3251	0.2523	0.2028	0.1910	0.2000
0.97	0.5984	0.5164	0.4345	0.3532	0.2748	0.2203	0.2075	0.2163
0.98	0.6223	0.5370	0.4529	0.3681	0.2864	0.2296	0.2158	0.2244
0.99	0.6442	0.5572	0.4699	0.3828	0.2978	0.2388	0.2244	0.2328
1.00	0.6668	0.5781	0.4875	0.3972	0.3097	0.2483	0.2328	0.2415
1.01	0.6792	0.5970	0.5047	0.4121	0.3214	0.2576	0.2415	0.2500
1.02	0.6902	0.6166	0.5224	0.4266	0.3334	0.2673	0.2506	0.2582
1.05	0.7194	0.6607	0.5728	0.4710	0.3690	0.2958	0.2773	0.2844
1.10	0.7586	0.7112	0.6412	0.5408	0.4285	0.3451	0.3228	0.3296
1.15	0.7907	0.7499	0.6918	0.6026	0.4875	0.3954	0.3690	0.3750
1.20	0.8166	0.7834	0.7328	0.6546	0.5420	0.4446	0.4150	0.4198
1.30	0.8590	0.8318	0.7943	0.7345	0.6383	0.5383	0.5058	0.5093
1.40	0.8892	0.8690	0.8395	0.7925	0.7145	0.6237	0.5902	0.5943
1.50	0.9141	0.8974	0.8730	0.8375	0.7745	0.6966	0.6668	0.6714
1.60	0.9311	0.9183	0.8995	0.8710	0.8222	0.7586	0.7328	0.7430
1.70	0.9462	0.9354	0.9204	0.8995	0.8610	0.8091	0.7907	0.8054
1.80	0.9572	0.9484	0.9376	0.9204	0.8913	0.8531	0.8414	0.8590
1.90	0.9661	0.9594	0.9506	0.9376	0.9162	0.8872	0.8831	0.9057
2.00	0.9727	0.9683	0.9616	0.9528	0.9354	0.9183	0.9183	0.9462
2.20	0.9840	0.9817	0.9795	0.9727	0.9661	0.9616	0.9727	1.0093
2.40	0.9931	0.9908	0.9908	0.9886	0.9863	0.9931	1.0116	1.0568
2.60	0.9977	0.9977	0.9977	0.9977	1.0023	1.0162	1.0399	1.0889
2.80	1.0023	1.0023	1.0046	1.0069	1.0116	1.0328	1.0593	1.1117
3.00	1.0046	1.0069	1.0069	1.0116	1.0209	1.0423	1.0740	1.1298
3.50	1.0093	1.0116	1.0139	1.0186	1.0304	1.0593	1.0914	1.1508
4.00	1.0116	1.0139	1.0162	1.0233	1.0375	1.0666	1.0990	1.1588

Table E.16 Values of ϕ^1

$P_r =$	1.0000	1.2000	1.5000	2.0000	3.0000	5.0000	7.0000	10.000
T_r								
0.30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.35	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.40	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.45	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001
0.50	0.0013	0.0013	0.0013	0.0012	0.0011	0.0009	0.0008	0.0006
0.55	0.0063	0.0062	0.0061	0.0058	0.0053	0.0045	0.0039	0.0031
0.60	0.0210	0.0207	0.0202	0.0194	0.0179	0.0154	0.0133	0.0108
0.65	0.0536	0.0527	0.0516	0.0497	0.0461	0.0401	0.0350	0.0289
0.70	0.1117	0.1102	0.1079	0.1040	0.0970	0.0851	0.0752	0.0629
0.75	0.1995	0.1972	0.1932	0.1871	0.1754	0.1552	0.1387	0.1178
0.80	0.3170	0.3133	0.3076	0.2978	0.2812	0.2512	0.2265	0.1954
0.85	0.4592	0.4539	0.4457	0.4325	0.4093	0.3698	0.3365	0.2951
0.90	0.6166	0.6095	0.5998	0.5834	0.5546	0.5058	0.4645	0.4130
0.93	0.7145	0.7063	0.6950	0.6761	0.6457	0.5916	0.5470	0.4898
0.95	0.7798	0.7691	0.7568	0.7379	0.7063	0.6501	0.6026	0.5432
0.97	0.8414	0.8318	0.8185	0.7998	0.7656	0.7096	0.6607	0.5984
0.98	0.8730	0.8630	0.8492	0.8298	0.7962	0.7379	0.6887	0.6266
0.99	0.9036	0.8913	0.8790	0.8590	0.8241	0.7674	0.7178	0.6546
1.00	0.9311	0.9204	0.9078	0.8872	0.8531	0.7962	0.7464	0.6823
1.01	0.9462	0.9462	0.9333	0.9162	0.8831	0.8241	0.7745	0.7096
1.02	0.9572	0.9661	0.9594	0.9419	0.9099	0.8531	0.8035	0.7379
1.05	0.9840	0.9954	1.0186	1.0162	0.9886	0.9354	0.8872	0.8222
1.10	1.0162	1.0280	1.0593	1.0990	1.1015	1.0617	1.0186	0.9572
1.15	1.0375	1.0520	1.0814	1.1376	1.1858	1.1722	1.1403	1.0864
1.20	1.0544	1.0691	1.0990	1.1588	1.2388	1.2647	1.2474	1.2050
1.30	1.0715	1.0914	1.1194	1.1776	1.2853	1.3868	1.4125	1.4061
1.40	1.0814	1.0990	1.1298	1.1858	1.2942	1.4488	1.5171	1.5524
1.50	1.0864	1.1041	1.1350	1.1858	1.2942	1.4689	1.5740	1.6520
1.60	1.0864	1.1041	1.1350	1.1858	1.2883	1.4689	1.5996	1.7140
1.70	1.0864	1.1041	1.1324	1.1803	1.2794	1.4622	1.6033	1.7458
1.80	1.0839	1.1015	1.1298	1.1749	1.2706	1.4488	1.5959	1.7620
1.90	1.0814	1.0990	1.1272	1.1695	1.2618	1.4355	1.5849	1.7620
2.00	1.0814	1.0965	1.1220	1.1641	1.2503	1.4191	1.5704	1.7539
2.20	1.0765	1.0914	1.1143	1.1535	1.2331	1.3900	1.5346	1.7219
2.40	1.0715	1.0864	1.1066	1.1429	1.2190	1.3614	1.4997	1.6866
2.60	1.0666	1.0814	1.1015	1.1350	1.2023	1.3397	1.4689	1.6482
2.80	1.0641	1.0765	1.0940	1.1272	1.1912	1.3183	1.4388	1.6144
3.00	1.0593	1.0715	1.0889	1.1194	1.1803	1.3002	1.4158	1.5813
3.50	1.0520	1.0617	1.0789	1.1041	1.1561	1.2618	1.3614	1.5101
4.00	1.0471	1.0544	1.0691	1.0914	1.1403	1.2303	1.3213	1.4555

Table C.1 Heat Capacities of Gases in the Ideal-Gas State†

Constants in equation $C_P^{ig}/R = A + BT + CT^2 + DT^{-2}$ T (kelvins) from 298.15 to T_{max}

Chemical species		T_{max}	$C_{P_{298}}^{ig}/R$	A	$10^3\ B$	$10^6\ C$	$10^{-5}\ D$
Paraffins:							
Methane	CH_4	1500	4.217	1.702	9.081	−2.164	
Ethane	C_2H_6	1500	6.369	1.131	19.225	−5.561	
Propane	C_3H_8	1500	9.001	1.213	28.785	−8.824	
n-Butane	C_4H_{10}	1500	11.928	1.935	36.915	−11.402	
iso-Butane	C_4H_{10}	1500	11.901	1.677	37.853	−11.945	
n-Pentane	C_5H_{12}	1500	14.731	2.464	45.351	−14.111	
n-Hexane	C_6H_{14}	1500	17.550	3.025	53.722	−16.791	
n-Heptane	C_7H_{16}	1500	20.361	3.570	62.127	−19.486	
n-Octane	C_8H_{18}	1500	23.174	4.108	70.567	−22.208	
1-Alkenes:							
Ethylene	C_2H_4	1500	5.325	1.424	14.394	−4.392	
Propylene	C_3H_6	1500	7.792	1.637	22.706	−6.915	
1-Butene	C_4H_8	1500	10.520	1.967	31.630	−9.873	
1-Pentene	C_5H_{10}	1500	13.437	2.691	39.753	−12.447	
1-Hexene	C_6H_{12}	1500	16.240	3.220	48.189	−15.157	
1-Heptene	C_7H_{14}	1500	19.053	3.768	56.588	−17.847	
1-Octene	C_8H_{16}	1500	21.868	4.324	64.960	−20.521	
Miscellaneous organics:							
Acetaldehyde	C_2H_4O	1000	6.506	1.693	17.978	−6.158	
Acetylene	C_2H_2	1500	5.253	6.132	1.952	......	−1.299
Benzene	C_6H_6	1500	10.259	−0.206	39.064	−13.301	
1,3-Butadiene	C_4H_6	1500	10.720	2.734	26.786	−8.882	
Cyclohexane	C_6H_{12}	1500	13.121	−3.876	63.249	−20.928	
Ethanol	C_2H_6O	1500	8.948	3.518	20.001	−6.002	
Ethylbenzene	C_8H_{10}	1500	15.993	1.124	55.380	−18.476	
Ethylene oxide	C_2H_4O	1000	5.784	−0.385	23.463	−9.296	
Formaldehyde	CH_2O	1500	4.191	2.264	7.022	−1.877	
Methanol	CH_4O	1500	5.547	2.211	12.216	−3.450	
Styrene	C_8H_8	1500	15.534	2.050	50.192	−16.662	
Toluene	C_7H_8	1500	12.922	0.290	47.052	−15.716	
Miscellaneous inorganics:							
Air		2000	3.509	3.355	0.575	......	−0.016
Ammonia	NH3	1800	4.269	3.578	3.020	......	−0.186
Bromine	Br_2	3000	4.337	4.493	0.056	......	−0.154
Carbon monoxide	CO	2500	3.507	3.376	0.557	......	−0.031
Carbon dioxide	CO_2	2000	4.467	5.457	1.045	......	−1.157
Carbon disulfide	CS_2	1800	5.532	6.311	0.805	......	−0.906
Chlorine	Cl_2	3000	4.082	4.442	0.089	......	−0.344
Hydrogen	H_2	3000	3.468	3.249	0.422	......	0.083
Hydrogen sulfide	H_2S	2300	4.114	3.931	1.490	......	−0.232
Hydrogen chloride	HCl	2000	3.512	3.156	0.623	......	0.151
Hydrogen cyanide	HCN	2500	4.326	4.736	1.359	......	−0.725
Nitrogen	N_2	2000	3.502	3.280	0.593	......	0.040
Nitrous oxide	N_2O	2000	4.646	5.328	1.214	......	−0.928
Nitric oxide	NO	2000	3.590	3.387	0.629	......	0.014
Nitrogen dioxide	NO2	2000	4.447	4.982	1.195	......	−0.792
Dinitrogen tetroxide	N_2O_4	2000	9.198	11.660	2.257	......	−2.787
Oxygen	O_2	2000	3.535	3.639	0.506	......	−0.227
Sulfur dioxide	SO_2	2000	4.796	5.699	0.801	......	−1.015
Sulfur trioxide	SO3	2000	6.094	8.060	1.056	......	−2.028
Water	H_2O	2000	4.038	3.470	1.450	......	0.121

†Selected from H. M. Spencer, *Ind. Eng. Chem.*, vol. 40, pp. 2152–2154, 1948; K. K. Kelley, *U.S. Bur. Mines Bull. 584*, 1960; L. B. Pankratz, U.S. *Bur. Mines Bull. 672*, 1982.

Table C.4 Standard Enthalpies and Gibbs Energies of Formation at 298.15 K (25°C)†

Joules per mole of the substance formed

Chemical species		State (Note 2)	$\Delta H^{\circ}_{f_{298}}$ (Note 1)	$\Delta G^{\circ}_{f_{298}}$ (Note 1)
Paraffins:				
Methane	CH_4	(*g*)	−74 520	−50 460
Ethane	C_2H_6	(*g*)	−83 820	−31 855
Propane	C_3H_8	(*g*)	−104 680	−24 290
n-Butane	C_4H_{10}	(*g*)	−125 790	−16 570
n-Pentane	C_5H_{12}	(*g*)	−146 760	−8 650
n-Hexane	C_6H_{14}	(*g*)	−166 920	150
n-Heptane	C_7H_{16}	(*g*)	−187 780	8 260
n-Octane	C_8H_{18}	(*g*)	−208 750	16 260
1-Alkenes:				
Ethylene	C_2H_4	(*g*)	52 510	68 460
Propylene	C_3H_6	(*g*)	19 710	62 205
1-Butene	C_4H_8	(*g*)	−540	70 340
1-Pentene	C_5H_{10}	(*g*)	−21 280	78 410
1-Hexene	C_6H_{12}	(*g*)	−41 950	86 830
1-Heptene	C_7H_{14}	(*g*)	−62 760	
Miscellaneous organics:				
Acetaldehyde	C_2H_4O	(*g*)	−166 190	−128 860
Acetic acid	$C_2H_4O_2$	(*l*)	−484 500	−389 900
Acetylene	C_2H_2	(*g*)	227 480	209 970
Benzene	C_6H_6	(*g*)	82 930	129 665
Benzene	C_6H_6	(*l*)	49 080	124 520
1,3-Butadiene	C_4H_6	(*g*)	109 240	149 795
Cyclohexane	C_6H_{12}	(*g*)	−123 140	31 920
Cyclohexane	C_6H_{12}	(*l*)	−156 230	26 850
1,2-Ethanediol	$C_2H_6O_2$	(*l*)	−454 800	−323 080
Ethanol	C_2H_6O	(*g*)	−235 100	−168 490
Ethanol	C_2H_6O	(*l*)	−277 690	−174 780
Ethylbenzene	C_8H_{10}	(*g*)	29 920	130 890
Ethylene oxide	C_2H_4O	(*g*)	−52 630	−13 010
Formaldehyde	CH_2O	(*g*)	−108 570	−102 530
Methanol	CH_4O	(*g*)	−200 660	−161 960
Methanol	CH_4O	(*l*)	−238 660	−166 270
Methylcyclohexane	C_7H_{14}	(*g*)	−154 770	27 480
Methylcyclohexane	C_7H_{14}	(*l*)	−190 160	20 560
Styrene	C_8H_8	(*g*)	147 360	213 900
Toluene	C_7H_8	(*g*)	50 170	122 050
Toluene	C_7H_8	(*l*)	12 180	113 630

Table C.4 (Continued)

Chemical species		State (Note 2)	$\Delta H^\circ_{f_{298}}$ (Note 1)	$\Delta G^\circ_{f_{298}}$ (Note 1)
Miscellaneous inorganics:				
Ammonia	NH_3	(g)	−46 110	−16 450
Ammonia	NH_3	(aq)		−26 500
Calcium carbide	CaC_2	(s)	−59 800	−64 900
Calcium carbonate	$CaCO_3$	(s)	−1206 920	−1128 790
Calcium chloride	$CaCl_2$	(s)	−795 800	−748 100
Calcium chloride	$CaCl_2$	(aq)		−8101900
Calcium chloride	$CaCl_2 \cdot 6H_2O$	(s)	−2607 900	
Calcium hydroxide	$Ca(OH)_2$	(s)	−986 090	−898 490
Calcium hydroxide	$Ca(OH)_2$	(aq)		−868 070
Calcium oxide	CaO	(s)	−635 090	−604 030
Carbon dioxide	CO_2	(g)	−393 509	−394 359
Carbon monoxide	CO	(g)	−110525	−137 169
Hydrochloric acid	HCl	(g)	−92 307	−95 299
Hydrogen cyanide	HCN	(g)	135 100	124 700
Hydrogen sulfide	H_2S	(g)	−20 630	−33 560
Iron oxide	FeO	(s)	−272 000	
Iron oxide (hematite)	Fe_2O_3	(s)	−824 200	−742 200
Iron oxide (magnetite)	Fe_3O_4	(s)	−1118400	−1015400
Iron sulfide (pyrite)	FeS_2	(s)	−178 200	−166 900
Lithium chloride	$LiCl$	(s)	−408 610	
Lithium chloride	$LiCl \cdot H_2O$	(s)	−712 580	
Lithium chloride	$LiCl \cdot 2H_2O$	(s)	−1012 650	
Lithium chloride	$LiCl \cdot 3H_2O$	(s)	−1311 300	
Nitric acid	HNO_3	(l)	−174 100	−80 710
Nitric acid	HNO_3	(aq)		−111 250
Nitrogen oxides	NO	(g)	90 250	86 550
	NO_2	(g)	33 180	51 310
	N_2O	(g)	82 050	104 200
	N_2O_4	(g)	9 160	97 540
Sodium carbonate	Na_2CO_3	(s)	−1130 680	−1044 440
Sodium carbonate	$Na_2CO_3 \cdot 10H_2O$	(s)	−4081 320	
Sodium chloride	$NaCl$	(s)	−411 153	−384 138
Sodium chloride	$NaCl$	(aq)		−393 133
Sodium hydroxide	$NaOH$	(s)	−425 609	−379 494
Sodium hydroxide	$NaOH$	(aq)		−419 150
Sulfur dioxide	SO_2	(g)	−296 830	−300 194
Sulfur trioxide	SO_3	(g)	−395 720	−371 060
Sulfur trioxide	SO_3	(l)	−441 040	
Sulfuric acid	H_2SO_4	(l)	−813 989	−690 003
Sulfuric acid	H_2SO_4	(aq)		−744 530
Water	H_2O	(g)	−241 818	−228 572
Water	H_2O	(l)	−285 830	−237 129

†From TRC Thermodynamic Tables—Hydrocarbons, Thermodynamics Research Center, Texas A & M Univ. System, College Station, TX; "The NBS Tables of Chemical Thermodynamic Properties," *J. Phys. and Chem. Reference Data*, vol. 11, supp. 2, 1982.

Notes

1. The standard property changes of formation $\Delta H^\circ_{f_{298}}$ and $\Delta G^\circ_{f_{298}}$ are the changes occurring when 1 mol of the listed compound is formed from its elements with each substance in its standard state at 298.15 K (25°C).
2. Standard states: *(a)* Gases (g): pure ideal gas at 1 bar and 298.15 K (25°C). (b) Liquids (*l*) and solids (s): pure substance at 1 bar and 298.15 K (25°C). (c) Solutes in aqueous solution (*aq*): Hypothetical ideal 1-molal solution of solute in water at 1 bar and 298.15 K (25°C).

TABLE A–5

Saturated water—Pressure table

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7	0.1059	8.8690	8.9749
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7	0.1956	8.6314	8.8270
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9	0.2606	8.4621	8.7227
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4	0.3118	8.3302	8.6421
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9073
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5	0.8932	6.9370	7.8302
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6	0.9441	6.8234	7.7675
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1	1.0261	6.6430	7.6691
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2	1.0912	6.5019	7.5931
75	91.76	0.001037	2.2172	384.36	2111.8	2496.1	384.44	2278.0	2662.4	1.2132	6.2426	7.4558
100	99.61	0.001043	1.6941	417.40	2088.2	2505.6	417.51	2257.5	2675.0	1.3028	6.0562	7.3589
101.325	99.97	0.001043	1.6734	418.95	2087.0	2506.0	419.06	2256.5	2675.6	1.3069	6.0476	7.3545
125	105.97	0.001048	1.3750	444.23	2068.8	2513.0	444.36	2240.6	2684.9	1.3741	5.9100	7.2841
150	111.35	0.001053	1.1594	466.97	2052.3	2519.2	467.13	2226.0	2693.1	1.4337	5.7894	7.2231
175	116.04	0.001057	1.0037	486.82	2037.7	2524.5	487.01	2213.1	2700.2	1.4850	5.6865	7.1716
200	120.21	0.001061	0.88578	504.50	2024.6	2529.1	504.71	2201.6	2706.3	1.5302	5.5968	7.1270
225	123.97	0.001064	0.79329	520.47	2012.7	2533.2	520.71	2191.0	2711.7	1.5706	5.5171	7.0877
250	127.41	0.001067	0.71873	535.08	2001.8	2536.8	535.35	2181.2	2716.5	1.6072	5.4453	7.0525
275	130.58	0.001070	0.65732	548.57	1991.6	2540.1	548.86	2172.0	2720.9	1.6408	5.3800	7.0207
300	133.52	0.001073	0.60582	561.11	1982.1	2543.2	561.43	2163.5	2724.9	1.6717	5.3200	6.9917
325	136.27	0.001076	0.56199	572.84	1973.1	2545.9	573.19	2155.4	2728.6	1.7005	5.2645	6.9650
350	138.86	0.001079	0.52422	583.89	1964.6	2548.5	584.26	2147.7	2732.0	1.7274	5.2128	6.9402
375	141.30	0.001081	0.49133	594.32	1956.6	2550.9	594.73	2140.4	2735.1	1.7526	5.1645	6.9171
400	143.61	0.001084	0.46242	604.22	1948.9	2553.1	604.66	2133.4	2738.1	1.7765	5.1191	6.8955
450	147.90	0.001088	0.41392	622.65	1934.5	2557.1	623.14	2120.3	2743.4	1.8205	5.0356	6.8561
500	151.83	0.001093	0.37483	639.54	1921.2	2560.7	640.09	2108.0	2748.1	1.8604	4.9603	6.8207
550	155.46	0.001097	0.34261	655.16	1908.8	2563.9	655.77	2096.6	2752.4	1.8970	4.8916	6.7886
600	158.83	0.001101	0.31560	669.72	1897.1	2566.8	670.38	2085.8	2756.2	1.9308	4.8285	6.7593
650	161.98	0.001104	0.29260	683.37	1886.1	2569.4	684.08	2075.5	2759.6	1.9623	4.7699	6.7322
700	164.95	0.001108	0.27278	696.23	1875.6	2571.8	697.00	2065.8	2762.8	1.9918	4.7153	6.7071
750	167.75	0.001111	0.25552	708.40	1865.6	2574.0	709.24	2056.4	2765.7	2.0195	4.6642	6.6837