Appendix A
Answers to Unsolved Problems

Chapter 1

1.1A (a) 26.82 m/s; (b) 0.626 lb_f/ft^2, (c) 1.548×10^{-2} Btu, (d) 4.21×10^3 J/s

1.1B (a) 0.518 lb, (b) 21.5 ft^3, (c) 1.87 lb/ft^3, (d) 1.034 kg/cm^2

1.1C 2.40×10^5 (ft) (lb_f)

1.1D 1.4×10^3 (ft) (lb_f)

1.1E Btu/(hr) (ft^2) (°F)

1.1F cm/s or cm^2/(s) (cm of height)

1.1G (a) A is g/cm^3, B is g (cm^3)(°C), C is atm^{-1}; (b) A is 68.4 lb_m/ft^3, B is 0.055 $lb_m/(ft^3)$(°R), C is 0.0000648/(lb_f/in^2)

1.2A (a) 2.27 g mol, (b) 0.22 lb N_2

1.2 B (a) 3.18×10^6 g, (b) 15.4 lb, (c) 932 g mol, (d) 4.54×10^{-3} lb mol

1.3A (a) 0.0311 lb mol/gal, (b) 22.9 lb/ft^3, (c) 366 g/L, (d) 0.428 lb H_2SO_4/lb H_2O, (e) 0.927 lb mol H_2O/lb mol total solution

1.3B (a) 0.659, (b) 15 gal

1.3C 18.2 ppm

1.3D (a) 17.5° API, (b) 7.94 lb/gal, (c) 59.3 lb/ft^3

1.4A 72.2 lb

1.4B 21.8 lb/ lb mol

1.4C CO_2:21.7, CO:10.9, CH_4:49.5, H_2:17.9

1.5A (a) –30°C, (b) 243.2K

1.5B (a) 356.8°C, (b) 675°F, (c) 1135°R

1.6A 1.07×10^4 lb_f/in^2

1.6B 2.06 psia

1.6C 4.49 psia

1.6D (a) $h_3 = 7.15$ in., (b) $h_2 = 20.65$ in.

1.7A 0.945 g Cr_2S_3

1.7B (a) $BaSO_4$ is limiting reactant, C is excess reactant, (b) % xs = 50.6%, (c) degree of completion = 0.901

Chapter 2

2.1A At 100°C (because phenol freezes at 42.5°C!)

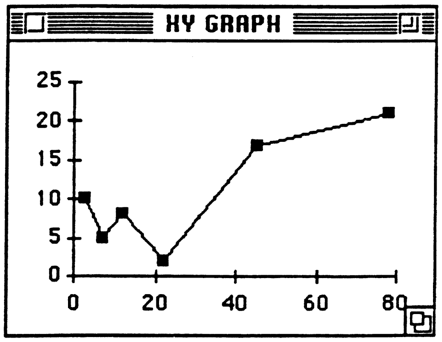
2.1B Pick up the second beaker from the left, pour all the ethanol into the fifth beaker from the left, and replace the second beaker in its original location.

2.1C The other team's catcher and the umpire.

2.2A x = 1, y = 2, z = 3

2.2B x = 4, y = 32

2.2C



Chapter 3

3.1A (a) closed, (b) open, (c) open, (d) open if it leaks, closed otherwise

3.2A rank = 3

3.2B No; you have 3 unknown variables and two independent equations

3.2C No.

3.3A $51.90/ton

3.3B (a) Na_2SO_4 28%, H_2O 72%, (b) 33.3 g crystals/100 g solution

3.3C Overhead: C_2H_4 (7.8%), C_2H_6 (11.7%), C_3H_6 (19.4%), C_3H_8 (56.0%), iC_4H_{10} (5.1%). Bottoms: C_3H_8 (0.8%), iC_4H_6 (31.9%), nC_4H_{10} (47.1%), nC_5H_{12} (20.2%)

3.4C CO_2:17.82%, O_2:1.18%, N_2:81.0%

3.4B 686%

3.4C 8.98%

3.5A (a) 87.6%, (b) 25.0%

3.5B (a) 17,650 bbl, (b) 1:52.45%, 2:40.20%, 3:6.67%, 4:0.68%; (c) 1:49.90%, 2:44.05%, 3:6.05%; (d) 22.14 bbl

3.6A (a) 1 mol NO/1 mol NH_3 in, (b) R = 42.9 mol NH_3/mol NH_3 fed

3.6B (a) R = 111 lb Ca $(Ac)_2$ /hr, (b) 760 lb HAc/hr

3.6C (a) 75.1 kg C_2H_2, (b) 250 kg, (c) 454 kg (d) 2.00

Chapter 4

4.1A 248 gal/hr

4.1B A leak occurred. The CO_2 balance indicates the analysis is correct.

4.1C (a) C_6H_6:1.13 mol/min, C_6H_{12}:11.5 mol/min, H_2:11.5 mol/min; (b) C_6H_6:44.5 L/min, C_6H_{12}:452.5L/min, H_2:452L/min; (c) C_6H_6:6.4 mol/min (200L/min), H_2:25.8 mol/min (799L/min)

4.1D (a) all kN/m^2:CH_4 (80), C_2H_4 (10), N_2 (10); (b) No.

4.2A (a) RK:1193.1 cm^3/g mol, (b) PR:1168.9 cm^3/g mol

4.2B (a) van der Waals: 18.3lb, (b) 23.4 lb

4.2C (a) Eq. of State: 0.862 ft^3, (b) compressibility factor: 0.877 ft^3

4.3A (a) 20 atm

4.3B 50 psia (340 kPa)

4.4A 70.7L

4.4B O_2:296 ft^3 at 745 mm Hg and 25°C; C_2H_2: 54 ft^3 at 745 mm Hg and 25°C

4.4C 7.2L at SC

4.4D 44°C (111°F)

4.5A L/V = 1.59

4.5B Hexane 0.545, heptane 0.280, octane 0.180

4.5C (a) 75.2 lb H_2O/100 lb feed, (b) 48.4 wt% nonvolatile

4.5D Yes

4.6A (a) 43.6%, (b) 0.0136 mol Tol/mol H_2, (c) 0.043, (d) 42.9%, (e) 1.34%

4.6B (a) 219 psia, (b) 0.00435 lb mol H_2O/lb mol N_2, (c) 0.999

4.6C (a) 20.5°C, (b) 0.024, (c) 0.805

4.7A The solution is wrong. The problem is underspecified. No unique solution is possible.

4.7B (a) 50.5%, (b) 200 kPa, (c) 11°C, (d) 7%, (e) No

4.7C (a) 103.6°F, (b) 80.3 in. Hg, (c) 84%

4.7D (a) 89 ft^3/min, (b) 1180 mm Hg

Chapter 5

5.1A (a) system: can plus water, $Q = 0$, $W \neq 0$; (b) system: H_2 plus bomb, $W = 0$, $Q \neq 0$; (c) system: motor, $Q \neq 0$, $W \neq 0$; (d) system: pipe plus water, $Q = 0$, $W \neq 0$.

5.1B All are intensive except the volume

5.1C (a) 240 J, (b) 177 $(ft)(lb_f)$, (c) 0.226 Btu

5.1D (a) KE = 25 $(ft)(lb_f)$, for reference of the ground level, PE = –25 $(ft)(lb_f)$; (b) KE = 0, PE = 0

5.1E Yes. The reference for enthalpy changes is arbitrary.

5.2A $C_p = 8.78 + 0.00963T - 0.00000529T^2$

5.2B $C_p = 6.852 + 1.62 \times 10^{-3}\, T_{^\circ C} - 0.26 \times 10^{-6}\, T^2_{^\circ C}$

5.2B $C_p = 27.5 + 6.78 \times 10^{-3}\, T_{^\circ C} - 1.09 \times 10^{-6}\, T^2_{^\circ C}$, J/(g mol) (°C)

5.2C (a) 39.8 cal, (b) 34.2 cal, (c) 5.6 cal

5.2D (a) 1955 J/g mol, (b) 1640 J/g mol, (c) 1937 J/g mol

5.2E –2020 Btu

5.2F 376 J/g vs. 357 J/g by experiment

5.3A (a) $W_{rev} = -79.5$ Btu/lb mol, $Q = 280$ Btu/lb mol, $\Delta U = 200.5$ Btu/lb mol; (b) $\Delta H = Q = -280$ Btu/lb mol, $W = +79.5$ Btu/lb mol, $\Delta U = -200.5$ Btu/lb mol; (c) Q and W are zero, and $\Delta H = \Delta U = O$

5.3B (a) $\Delta H = Q$, (b) $\Delta H = 0$

5.3C (a) $T_2 = 250K$, (b) $v_2 = 3.2$ ft/s

5.3D No

5.3E (a) air = 3915 lb/min (b) humidity = 0.0425 lb H_2O/lb BDA

5.3F (a) 6.37×10^4 lb/hr, (b) 1.72×10^4 lb/hr, (c) 4.65×10^4 lb/hr, (d) $L = 3.16 \times 10^4$ lb/hr, $V = 3.21 \times 10^4$ lb/hr

5.4A –156.47 kJ

5.4B 57.5 kg

5.4C –122.2 kJ

5.4D (a) 488 lb/hr, (b) 31,240 ft^3 at SC

5.4E –28,240 J (heat evolved)

5.4F $T = 1278°F < 1500°F$

5.4G $T = 982K$

5.4H 276%

5.5A About –1.8°F

5.5B (a) Before = 0, (b) After = 0.0024 m^3

5.5C (a) 0.37 gas and 0.63 liquid, (b) 98 Btu/lb, (c) –173 Btu/lb, (d) \$$6.76 \times 10^{-4}$/lb

5.6A (a) $T_o = 210°F$, $T_f = 295°F$

5.6B (a) 653 lb, (b) 8.85 lb, (c) 355.9 lb, (d) 300°F, (e) 10^5 Btu

5.6C Masses in lb: A = 71.5, B = 28.5, ΔH = Btu/lb; III and IV are impossible to exist

5.7A (a) 0.078, (b) 0.871 atm, (c) 99°F, (d) 100°F

5.7B (a) $T_B = 166°F$, $T_c = 85.2$ °F; (b) $\Delta H_I = 3080$ Btu, $\Delta H_{II} = 860$ Btu

5.7C Refrigeration = 4830 Btu/min; Reheating = 124.5 Btu/min

Appendix B
Data

TABLE B1 Typical Dry Gas Analyses

Type	Analysis (vol. %—excluding water vapor)									
	CO_2	O_2	N_2	CO	H_2	CH_4	C_2H_6	C_3H_8	C_4H_{10}	$C_5H_{12}+$
Natural gas	6.5					77.5	16.0			
Natural gas, dry*	0.2		0.6			99.2				
Natural gas, wet*	1.1					87.0	4.1	2.6	2.0	3.4
Natural gas, sour†	(H_2S 6.4)					58.7	16.5	9.9	5.0	3.5
Butane							2.0	3.5	75.4 *n*-butane 18.1 isobutane	
									Illuminants	
Reformed refinery oil	2.3	0.7	4.9	20.8	49.8	12.3	5.5	5.5	3.7	
Coal gas, by-product	2.1	0.4	4.4	13.5	51.9	24.3			3.4	
Producer gas	4.5	0.6	50.9	27.0	14.0	3.0				
Blast furnace gas	5.4	0.7	8.3	37.0	47.3	1.3				
Sewage gas	22.0		6.0		2.0	68.0				

*Dry gas contains much less propane (C_3H_8) and higher hydrocarbons than wet gas does.

†*Sour* implies that the gas contains significant amounts of hydrogen sulfide.

SOURCE: *Fuel Flue Gases*, American Gas Association, New York, 1941, p. 20.

TABLE B2 Ultimate Analysis of Petroleum Crude

Type	Sp Gr	At °C	Weight %				
			C	H	N	O	S
Pennsylvania	0.862	15	85.5	14.2			
Humbolt, Kan.	0.921		85.6	12.4			0.37
Beaumont, Tex.	0.91		85.7	11.0	2.61		0.70
Mexico	0.97	15	83.0	11.0	1.7		
Baku USSR	0.897		86.5	12.0		1.5	

SOURCE: Data from W.L. Nelson, *Petroleum Refinery Engineering*, 4th ed., McGraw-Hill, New York, 1958.

TABLE B3 Chemical Analyses of Various Wastes

Material	Raw paper	Charred paper	Tire rubber	Dry sewage sludge	Charred sewage sludge	Charred animal manure	Garbage composite *A*	Garbage composite *B*
Moisture	3.8	0.8	0.5	13.6	1.2	0.0	3.4	12.3
Hydrogen*	6.9	3.1	4.3	6.7	1.4	5.4	6.6	7.0
Carbon	45.8	84.9	86.5	28.7	48.6	41.2	57.3	44.4
Nitrogen	—	0.1	—	2.6	3.7	1.5	0.5	0.4
Oxygen*	46.8	8.5	4.6	26.5	—	26.0	22.1	42.1
Sulfur	0.1	0.1	1.2	0.6	—	0.4	0.4	0.2
Ash	0.4	2.5	3.4	34.9	45.7	25.5	10.2	5.9

* The hydrogen and oxygen values reflect that due to both the presence of water and that contained within the moisture-free material.

TABLE B4 Refinery Biological Treatment

	Ranges reported*
Chlorides (mg/L)	200–960
COD (mg/L)	140–640
BOD_5 (mg/L)	97–280
Suspended solids (mg/L)	80–450
Alkalinity (mg/L as $CaCO_3$)	77–210
Temperature, (°F)	69–100
Ammonia, nitrogen (mg/L)	56–120
Oil (mg/L)	23–130
Phosphate (mg/L)	20–97
Phenolics (mg/L)	7.6–61
pH	7.1–9.5
Sulfides (mg/L)	1.3–38
Chromium (mg/L)	0.3–0.7

*Values are the averages of the minima and maxima reported by 12 refineries treating total effluent. Individual plants have reported data well outside many of these ranges.

SOURCE: *Manual on Disposal of Refinery Wastes,* American Petroleum Institute, New York, 1969, pp. 2–4.

TABLE B5 Higher Heating Value of Municipal Refuse (kJ/kg)

Refuse component	As delivered	Dry basis	Refuse component	As delivered	Dry basis
Lawn grass	4,780	19,320	Average	—	20,050
Meat scraps, cooked	32,260	32,260	Mail	14,150	14,820
Newspaper	18,530	19,710	Cardboard	16,370	17,260
Shrub cuttings	6,290	20,300	Ripe tree leaves	18,550	20,610
Vegetable food waste	4,170	19,220	Magazine	12,210	12,730

TABLE B6 Calorie Counts in Various Foods

Food	Portion	Kilo-calories	Food	Portion	Kilo-calories
Beer	12 oz	165	Orange juice	$\frac{1}{2}$ glass	56
Chicken, broiled	$\frac{1}{2}$	308	Soft drink	1 can	73
Coffee	1 cup	0	Toast	2 pieces	120
Martini	1 oz	168	Trout	1 lb	224

TABLE B7 Higher Heating

Class	kJ/kg	Btu/lb
Meta-anthracite	26,680	11,480
Anthracite	33,110	14,250
Low-volatile bituminous	35,370	15,220
High-volatile bituminous	27,790	11,960
Subituminous	23,330	10,040
Lignite	17,290	7,440

TABLE B8 Heating Values of Fuels

Class	Btu/gal
Kerosene	134,000
No. 2 burner fuel oil	140,000
No. 4 heavy fuel oil	144,000
No. 5 heavy fuel oil	150,000
No. 6 heavy fuel oil, 2.7% sulfur	152,000
No. 6 heavy fuel oil, 0.3% sulfur	143,800
natural gas	*1,000
liquefied butane	103,300
liquefied propane	91,6000

*10^3 Btu/ft^3 at SCNGI

TABLE B9 Elemental Compositions and Heating Values of Raw and Hydrotreated Coal Liquids

	Boiling range (C)	Specific gravity	Heating value, (kJ/kg)	H	C	O	S	N
liquid organic liquid	65-205	0.847	42212	11.33	83.77	4.0	0.60	0.30
liquid organic liquid	110-230	0.918	40068	9.93	84.44	5.0	0.40	0.23
SRC-Illinois No. 6 coal	340+	1.184	37090	5.72	88.50	3.5	0.57	1.71
distillate≅syncrude mode	190-350	0.968	42056	9.14	88.87	1.5	0.10	0.39
fuel oil≅Illinois No. 6 coal	260+		40498	7.94	88.77	2.1	0.42	0.77
distillate syncrude	180-330	0.942	43326	10.46	89.12	0.3	<0.01	0.12

Source: R. H. Heck and M. J. Dabkowski, "Heating Value Correlation for Coal," *Ind. Eng. Chem. Res*, **27**, 1922 (1988).

TABLE B10 Thermodynamic Charts Showing Enthalpy Data for Pure Compounds*

Compound	Reference†
Acetone	2
Acetylene	1
Air	V.C. Williams, *AIChE Trans.*, v. 39, p. 93 (1943); *AIChE J.*, v. 1, p. 302 (1955).
Benzene	1
1,3-Butadiene	C.H. Meyers, *J. Res. Natl. Bur. Stand.*, v. A39, p. 507 (1947).
i-Butane	1, 3
n-Butane	1, 3, 4
n-Butanol	L.W. Shemilt, in *Proceedings of the Conference on Thermodynamic Transport Properties of Fluids,* London, 1957, Institute of Mechanical Engineers, London, 1958.
t-Butanol	F. Maslan, *AIChE J.*, v. 7, p. 172 (1961).
n-Butene	1
Chlorine	R.E. Hulme and A.B. Tilman, *Chem. Eng.* (January 1949).
Ethane	1, 3, 4
Ethanol	R.C. Reid and J.M. Smith, *Chem. Eng. Prog.*, v. 47, p. 415 (1951).
Ethyl ether	2
Ethylene	1, 3
Ethylene oxide	J.E. Mock and J.M. Smith, *Ind. Eng. Chem.*, v. 42, p. 2125 (1950).
Fatty acids	J.D. Chase, *Chem. Eng.*, p. 107 (March 24, 1980).
n-Heptane	E.B. Stuart et al., *Chem Eng. Prog.*, v. 46, p. 311 (1950).
n-Hexane	1
Hydrogen sulfide	J.R. West, *Chem. Eng. Prog.*, v. 44, p. 287 (1948).
Isopropyl ether	2
Mercury	General Electric Company Report GET-1879A, 1949.
Methane	1, 3, 4
Methanol	J.M. Smith, *Chem. Eng. Prog.*, v. 44, p. 52 (1948).
Methyl ethyl ketone	2
Monomethyl hydrazine	F. Bizjak and D.F. Stai, *AIAA J.*, v. 2, p. 954 (1964).
Neon	Cryogenic Data Center, National Bureau of Standards, Boulder, Colo.
Nitrogen	G.S. Lin, *Chem. Eng. Prog.*, v. 59, no. 11, p. 69 (1963).

*For mixtures, see V.F. Lesavage et al., *Ind. Eng. Chem.*, v. 59, no. 11, p. 35 (1967).

†1. L.N. Cajar et al., *Thermodynamic Properties and Reduced Correlations for Gases,* Gulf Publishing Company, Houston, 1967. (Series of articles which appeared in the magazine *Hydrocarbon Processing* from 1962 to 1965.)

2. P.T. Eubank and J.M. Smith, *J. Chem. Eng. Data,* v. 7, p. 75 (1962).

3. W.C. Edmister, *Applied Hydrocarbon Thermodynamics,* Gulf Publishing Company, Houston, 1987.

4. K.E. Starling et al., *Hydrocarbon Processing,* 1971 and following. *Note:* Charts available separately from Gulf Publishing Company, Houston.

Heat capacity of hydrogen vapor[1]

$$C_p = (0.0450K - 0.233) + (0.440 + 0.0177K)(10^{-3}t) - 0.1520(10^{-6}t^2)$$

where C_p = specific heat of vapor, Btu/(lb$_m$)(°F)
t = temperature, °F
K = characterization factor

Heat capacity of hydrocarbon liquids[1]

$$C_p = [(0.355 + 0.128 \times 10^{-2}\mathrm{API}) + (0.503 + 0.117 \times 10^{-2}\mathrm{API})(10^{-3}t)] \times (0.05K + 0.41)$$

where API = gravity degrees API and the other units are the same as for vapor heat capacity.

Specific gravity

$$\text{sp gr} = \frac{141.5}{131.5 + {}^\circ\mathrm{API}}$$

where sp gr = specific gravity, 60/60°F
°API = degrees API

Pseudo critical temperature[2]

$$t'_c = a_0 + a_1T + a_2T^2 + a_3AT + a_4T^3 + a_5T^2 + a_6A^2T^2$$

where t'_c = pseudo-critical temperature, °R
T = molal average boiling point, °F
A = degrees API
a_i = constants in the correlation (see Table K.3)

Pseudo critical pressure[2]

$$p'_c = b_0 + b_1T + b_2T^2 + b_3AT + b_4T^3 + b_5AT^2 + b_6A^2T + b_7A^2T^2$$

where p'_c = pseudo-critical pressure psia
T = mean average boiling point, °F
A = degrees API
b_i = constants in the correlation

Constants for Cavett Correlations

i	a_i	b_i
0	768.07121	2.8290406
1	(0.17133693) (10)	(0.94120109) (10^{-3})
2	(−0.10834003) (10^{-2})	(−0.30474749) (10^{-5})
3	(−0.89212579) (10^{-2})	(−0.20876110) (10^{-4})
4	(0.38890584) (10^{-6})	(0.15184103) (10^{-8})
5	(0.53094920) (10^{-5})	(0.11047899) (10^{-7})
6	(0.32711600) (10^{-7})	(−0.48271599) (10^{-7})
7		(0.13949619) (10^{-9})

Enthalpy. Calculated as

$$\Delta H = \int_{T_{\mathrm{ref}}}^{\bar{T}_1} C_{p_{\mathrm{liq}}}\,dt + \Delta H_{\mathrm{vaporization\ at}\ \bar{T}_1} + \int_{\bar{T}_1}^{T} C_{p_{\mathrm{vap}}}\,dt$$

where $\overline{T_1}$ is the mean average boiling point.

Heat of vaporization[1]

$$\Delta H_{vap} = 2.303\ \{(z_g - z_l)R(T_c)[A + 40T_r^2(T_r - b)e^{-20}(T_r - b)^2]\}$$

where H_{vap} = latent heat of vaporization, Btu/lb$_{\mathrm{m}}$
$z_g - z_l$ = pressure correction (see Fallon and Watson for table of values)
R = universal gas constant
T_c = critical temperature, °R

T_r = reduced temperature
A, b = constants (see Fallon and Watson for ways to calculate values)

or (a somewhat less accurate equation) [3]

$$\Delta H_{\mathrm{vap}} = 0.95RT_B\left(\frac{T_B}{T_B - 43}\right)^2\left(\frac{1 - T_r}{1 - T_{rB}}\right)^{0.38}$$

where T_B = molal average boiling point, °R
T_r = reduced temperature
T_{rB} = reduced T_B

Boiling-point relations

(a)

$$\bar{t}_v = \sum_{i=1}^{n} X_{vi}t_{bi}$$

where X_{vi} = volume fraction of the ith component of the petroleum fraction
t_{bi} = normal boiling point of the midpoint of the ith volume fraction, °F or °R
n = number of volume fractions in the distillation curve to characterize the petroleum product

(b)

$$\bar{t} = (V_1t_1^{1/3} + V_2t_2^{1/3} + \cdots + V_nt_n^{1/3})^3$$

where $\bar{t}$ = cubic average boiling point, °F
V_i = volume fraction i of a petroleum product having a normal boiling point of t_i
t_i = temperature, °F

(c)

$$\bar{t}_x = x_1t_1 + x_2t_2 + \cdots + x_nt_n$$

where $\bar{t}_x$ = molar average boiling point, °F
x_i = the mole fractions of the narrow boiling range with normal boiling points t_i
t_i = temperature, °F

(d)

$$\bar{t}_M = \frac{\bar{t}_x + \bar{t}}{2}$$

where $\bar{t}_M$ is the mean average boiling point, °F.

Sources of Equations

1. J. F. Fallon and K. M. Watson, "Thermal Properties of Hydrocarbons," *Nat. Pet. News (Tech. Sec.)*, p. R-372 (June 7,1944).
2. R. H. Cavett. "Physical Data for Distillation Calculations-Vapor-Liquid Equilibria," *Proc. Am. Pet. Inst. Div. Refining*. v. 42, p. 351 (1962).
3. K. M. Watson, "Thermodynamics of the Liquid State," *Ind. Eng. Chem.*, v. 35, p. 398 (1943).