Chemical Engineering Thermodynamics

CHE 3062

Class meets MTWR from 12:20 to 1:15 Baldwin 755
Help sessions W 3-5 405 ERC

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Introductory Chemical Engineering Thermodynamics Second Edition
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ISBN 978-0-13-606854-9http://chethermo.net/

Chemical Engineering Thermodynamics

Course Logistics

Quizzes: Weekly quiz composed of questions similar to homework and example problems.
~Every Thursday

Group Homework: Weekly Group Homework. We will go through homework in a work session.
~Every Wednesday. (Every Wednesday **3 to 5 pm Baldwin 764 (Me)**
and **6 to 9 pm Rec Center 3250 (Alex and Zinhui**.)
Homework is due Wednesday night at **midnight**. E-mail a pdf of the homework to chethermouc@gmail.com
(You can use a smart phone app like "instapdf" to make pdf of homework.)

Final: Comprehensive Final composed of questions from weekly quizzes.
(Weighted as 8 quizzes.)

Grade is 90% Average of Final and Quizzes and 10% Homework.

Chemical Engineering Thermodynamics

Course Logistics

Final letter grades will be based on class grade using the following scale: A is between 90.0 and 100.0;
B is between 80.0 and 89.9;
C is between 70.0 and 79.9;
D is between 60.0 and 69.

Only whole grades will be given, i.e. the grade is B for 80 or 89.

Those with a "natural" 90 or above from quiz grades before the final do not need to take the final.

The comprehensive final is worth eight quiz grades.

Homework Group Options

A) Form your own group
   Send an email to chethermouc@gmail.com with list of homework group members and time that you meet. Put in subject of email: HOMEWORK GROUP Meets Monday at 6pm.

B) Need a group
   Send an email requesting a group and a time that you are available to meet. Put in subject: REQUEST GROUP Monday at 6 pm.

C) Prefer to work on your own (not recommended).
   Send an email to chethermouc@gmail.com
   Subject: WORK ON OWN

Please do this by Tuesday January 15 (tomorrow).

First Homework is due Wednesday January 16 at midnight.

Plant Tours

We will have non-mandatory plant tours.

The purpose is to see some of the processes we will study.

Attendance at a plant tour counts for 50 replacement points on a quiz. For instance, if your low grade is 30/100 this becomes a 65/100.

If you arrange a plant tour for the class you get 100 replacement points.

The timing for plant tours is variable.

Friday afternoon is a good time for me.

<u>The tours can cover a maximum of 500 quiz points (five quizzes</u>).

Plant Tours in 2017

Rheingeist Brewery

Miller Brewery (near Dayton)

Nease (Harrison)

Shepherd Catalysts (Norwood)

Steam Plant West Campus
Steam Plant East Campus

Kraus Maffei (Covington)

Cincinnati Water Plant

Este Oleo Chemicals (Ivorydale)

Outline of Class:


Week	Topic	Text	Homework	ppt, pdf	Quiz
1	Background	Chapter 1	P.34 First 10 Test Yourself Problems; Practice Problems P1.1,P1.2; Homework Problems 1.3-1.6,1.8,1.9,1.11-1.19 (ans)	ppt, pdf	Quiz 1, Quiz 1 2016
2	Energy Balance A	Chapter 2 Laminar Flow	1,2,5 Test yourself, write answers not explain to family...; Practice problems 1-3; P2.10,12,14,15; Homework Problems 2.2, 4, 6, 7, 8 (ans)	ppt, pdf	Quiz 2, Quiz 2 2016
2a	**MLK Week**		Chapter 2 Homework Problems **15, 17, 18, 21, 23** ***Don't do:*** *(3,4,6 Test yourself, write answers not explain to family...; Practice problems 8; P2.16, 17 Homework Problems 2.12, 13, 16, 22)*		
3	Energy Balance B	Chapter 2 & 3	Chapter 3 P3.1; Homework Problems 3.4,3.5, 3.6, 3.7, 3.9, 3.11, 3.13 (ans)	ppt, pdf	Quiz 3, Quiz 3 2016, Answer
4	Entropy Space Junk	Chapter 4	Chapter 4 Practice Problems: 1-7; Homework Problems: 2,3,5,6,9 (total of 12 problems ans, Practice Problem Solutions)	ppt, pdf	Quiz 4; Quiz 4 2016
5	Entropy and Processes	Chapter 4	Practice Problems Chapter 4: 8,9,12,14,15,18; Homework Problems Chapter 4: 14,16,18,22,27,30,32,33,40,43 (total of 16 problems ans, Practice Problem Solutions) ***Don't do:*** (4.37)	Part of Chap. 4, End of Chap. 4	Quiz 5; Quiz 5 2016
6	Processes	Chapters 5, start of 6	Practice Problems Chapter 5: 1,3,4,6; Homework Problems Chapter 5: 2,4,5,7,8,13,14,15,17,18,19 (15 problems Practice Problem Solutions, ans) Test Yourself P. 248 Problem 1; Practice Problems Chapter 6: 1; (2 problems Practice Problem Solution)	ppt, pdf	Quiz 6 mon.; Quiz 2016
7	Fluids and PVT Equation of State Webpage Penn State	Chapters 6 and 7 Chapters 7 (Molecular Simulators)	Test Yourself P. 236; Problems Chapter 6: 3,4,6,7,8,11 (7 problems, ans) Chapter 7 Practice Problems: 1,2,3,4,5; Chapter 7 Homework: 1,3,4,6,8 (10 Problems) (Practice Problem Solution, ans) *(Do not do: Chapter 7 Homework: 12,15,17,21,22,26,28,31 (8 problems) (ans))*	Chapter 6 ppt, pdf Chapter 6A video, Chapter 6B in class Chapter 7A Video Chapter 7B Video ppt, pdf	Quiz 7 thurs.; Quiz 2016
8	Non Ideal Fluids Departure Functions	Chapter 8 Quiz 8 HelpSession2016	Chapter 8 Practice Problems: 1,2,3,4 (4 problems) (PP Solutions) Chapter 8 Homework: 1,3,4,6,7 (5 problems) (ans) Chapter 8 Practice Problems: 5,7,9 (3 problems) (PP Solutions) Chapter 8 Homework: 8,10,14,15,18,19,28,34 (8 problems) (ans) *(Do not do: ,38)*	Chapter 8A Video, Chapter 8B Video, Chapter 8 ppt, pdf Chapter 8B Video,	Quiz 8 Thurs. Mar.26 Quiz 2016
9	One Component Equilibria	Chapters 9	Chapter 9 Practice Problems: 1 (use 8 MPa not 1.5, CO2 boiling point is 78.5°C), 2 (PP Solutions) CO2 Chart Pressure Enthalpy; Another Chart Ethane P H Diagram Chapter 9 Homework: 1,2,4,6 (ans) Chapter 9 Homework: 7,8,10,13,16,18 (6 Problems) (ans) In calculating the fugacity make sure you first determine the state of the material (vapor, liquid, solid). *(Do not do Chapter 9 Practice Problems: 4)*	Chapter 9 ppt, pdf	Quiz 9 Quiz 2016
10	Multicomponent Systems Models for Interaction	Chapters 10 example 10.2 matlab Matlab/Excel Folder.zip DePriester Chart	Chapter 10 Practice Problems: 1, 4 (PP Solutions) Chapter 10 Homework: 1,3,5 (ans) Problem 10.3 Mark Ellsberry.xls Chapter 10 Homework: 10,11,12,14,15 (you choose video for 15) (ans)One Video Lower Flamability Limit Article AIChE Journal Ammonium Nitrate VP, Ammonium Nitrate MSDS 93C FP	Chapter 10 ppt, pdf	Quiz 10; Quiz 10 2016
11	Equation of State for Mixing	Chapter 11	Chapter 11 Practice Problems: 1, 2 (PP Solutions) Chapter 11 Homework: 2,4,6,8,11,14,16,21,22,29 (ans)	Chapter 11 ppt, pdf	Quiz 11, Quiz 11 2016
12	Liquid/Liquid Phase Equilibria	Chapter 14 Matlab/Excel Folder.zip	Chapter 14 Practice Problems: 1,2,3,4 (PP Solutions) Chapter 14 Homework: 3,4,7,11,17,19,21,25,28,31,35 (ans) My Answers for Chapter 14 PP and HW Problems	Chapter 14 ppt, pdf	Quiz 12, Quiz 12 2016
13	Reaction Thermo	Chapter 17	Chapter 17 Test Yourself: 1,2,3,4,5,6 Chapter 17 Practice Problems: 1,4,9 (PP Solutions) Chapter 17 Homework: 1,2,5,7,12,16,21,22,25,27 (ans)	Chapter 17 ppt, pdf	Quiz 13 Quiz 13 Help Session

Chapter 1   Background

Energy is the capacity to do work.
Potential, kinetic, molecular, bond, nuclear, magnetic, Coloumbic.

You use energy to do work. You can store energy or expend energy.
You do work.

Work is the integral of force times change in distance.

Surface Energy, it requires energy to make a surface.

Kinetic energy of a gas atom $E = 3/2\ k_B T$.
(T is in absolute units otherwise we would have negative kinetic energy.)

Ground state for energy.

We could consider T = 0 but this is inconvenient (impossible to achieve) and ignores atomic energy, $E = mc^2$, and chemical bond energy.

Often we define the ground state at STP.

In the end we are only interested in changes in energy for an event or process so the ground state is only important in so far as we use the same ground state for all components of a calculation.

First Law of Thermodynamics (basis of energy balance)

For any spontaneous process the total energy is constant. That is, in order for energy to increase we require work or heat to be added to the system.

$E = PV$ for a gas,

to increase the pressure at constant number of gas atoms requires force and a change in distance, compression, that leads to a reduction in volume. Or you need to heat the system.

More Definitions:

Internal Energy, U.
Thermal and repulsive/attractive enthalpy of molecular interaction.

Ignores center of mass energy.

Enthalpy, H.
Energy related to specific bonding/reactions, and PV work. So the sum of internal energy and PV.

Entropy, S.

If you mix two ideal gasses at constant pressure there is no enthalpic interaction so the enthalpy of the system does not change. However, the system has changed since it requires a significant amount of work to separate the two ideal gasses and return to the pure states. This change is a change in entropy. The entropy change in this case is given by $\Delta S = nk_B(\phi_a \ln\phi_a + \phi_b \ln\phi_b)$ and the energy change $\Delta E = -T\Delta S$.

More Definitions:

At a given temperature T

A “system” has

- Kinetic energy associated with motion *KE*,
- Potential energy associated with its position in a field (gravity) *PE*
- Internal energy, *U*, associated with microscopic kinetic energies and the energy of interactions between microscopic components. The microscopic kinetic energy increases with temperature.

At absolute 0 the “system” has only one state, a perfect and infinite crystal. This condition is defined as having zero microscopic kinetic energy. At higher temperatures the “system” has more possible configurations, Ω. Boltzmann proposed that the number of states could be related to the energy of the system through a thermodynamic parameter, the entropy,

$$S = k_B \ln \Omega.$$

The entropy has a value of 0 at absolute 0 where only one state is possible. It increases with temperature and contributes $-T\Delta S$ to the energy.

More Definitions:

Work is the change in energy for the “system”

$W = \Delta KE + \Delta PE + \Delta U$

Mass added to the system results in a change in internal energy associate with the internal energy and potential energy of the mass transferred ($u\Delta M$) = ΔU

Heat, Q, flows from hot to cold. $\Delta U = Q$

Philosophically How Thermodynamics Works:

We consider a subset of the universe called **the system** or **the control volume**. The system contains many molecular elements that are each subject to 3/2 $k_B T$ kinetic energy. There are so many of these elementary units that they are almost uncountable. The most important step at the start of solving a problem in thermodynamics is to carefully define the system boundaries.

Closed System:

Thermal transfer but no mass transfer, say an ice cube melts into a puddle and the ice cube is the system.

Open System:

Mass and thermal transfer occurs, a system is a section of a river.

Isolated System:

No heat or mass transfer. A perfectly insulated box in which a match is lit.

Free Energy:

The energy that is available to do work.

Equilibrium:

A system is at equilibrium when the free energy is at a minimum. Two systems are at equilibrium with each other when every component of the two systems have the same chemical potential. (**Dynamic equilibrium** indicates that there are always fluctuations about an equilibrium composition due to thermal motion.)

The **chemical potential** is the change in free energy when one element (molecule or mole) of that component is introduced to the system.

Heat Sink/Heat Reservoir:

A component with infinite capacity to absorb or generate heat (transfer of thermal energy). The heat sink is at a constant temperature. That is, it is isothermal

Intensive Properties: (Not underlined, *V*)

Pressure, Temperature, Free Energy, Internal Energy, Specific Volume
Things that do not depend on system size.

State Properties:

These are intensive properties that specify the state of the system.

This is *F* in the Gibbs Phase Rule.

Extensive Properties: (Underlined in the book, *V*)

Volume, Mass, Total Energy
Things that are determined by the system size.

How is thermodynamic equilibrium achieved?

Thermodynamics assumes that large population of small objects, each of which has energy $3k_BT/2$ and moves randomly by thermal diffusion, interact with each other and transfer energy. The system is random in space and time so that fluctuations in density and speed occur at random in space and time. These random thermal fluctuations allow the molecules to probe the conditions at higher and lower concentration, to compare the favorability of conditions at these different densities and to find the state with the lowest free energy.

Thermodynamics relies on random fluctuations in density, and molecular motion.

The first stage of considering random fluctuations is the kinetic theory of gasses

Ideal Gas Law

A gas is viewed as a collection of particles each with momentum $p = mv$ in a box of size L.

The x-component of momentum is $p_x = mv_x$.

On collision with a wall the change in momentum is $2p_x$ for a wall normal to the x direction.

The particle impacts the wall every $\langle \Delta t \rangle = 2L/\langle v_x \rangle$.

The force is given by $F = ma = \Delta p_x/\Delta t = Nm\langle v_x^2 \rangle/L$ for N particles.

We have $\langle v_x^2 \rangle = \langle v^2 \rangle/3$ for random motions (x, y, and z are indistinguishable).

So, $F = Nm\langle v^2 \rangle/(3L)$ for 3d.

The pressure, $P = F/L^2 = Nm\langle v^2 \rangle/(3V)$.

We have $m\langle v^2 \rangle/2$ = Kinetic Energy = $3k_B T/2$.

So, $PV = Nk_B T$.

Ideal Gas Law

$F=ma=m(dv/dt)=dp/dt$

from before Δp is $2\ p_x$ And $\Delta t = 2L/v_x$

So $F = m\langle v_x\text{^}2\rangle/L$

For 3d and N atoms $F = 1/3\ N\ m\ \langle v^2\rangle/L$

$E = 3/2\ kT = ½\ m\langle v^2\rangle$

So $m\langle v^2\rangle = 3kT$

$P=F/A = 1/3\ N\ m\ \langle v^2\rangle/(LA) = NkT/V$

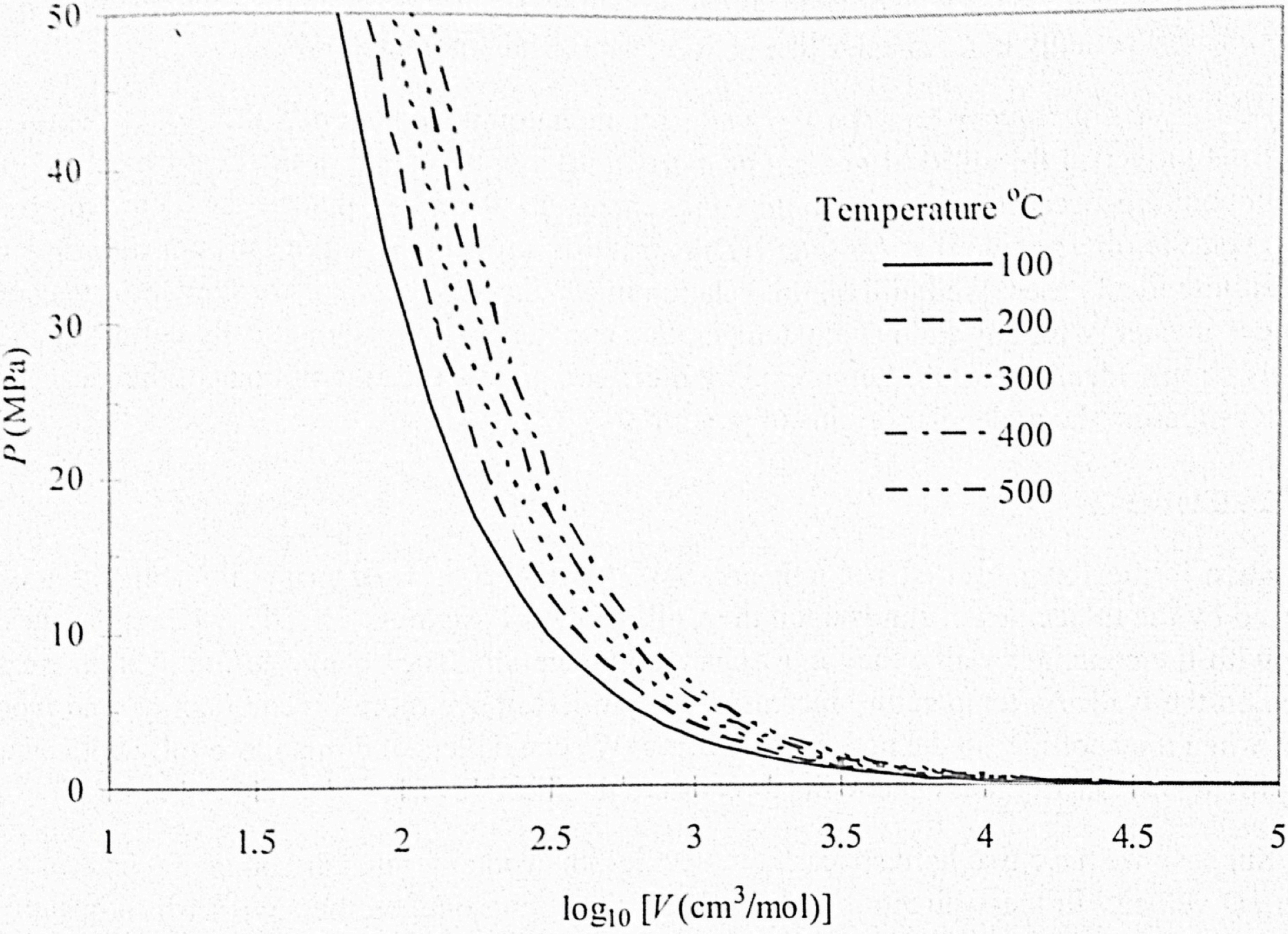


Figure 1.3 *Ideal gas behavior at five temperatures.*

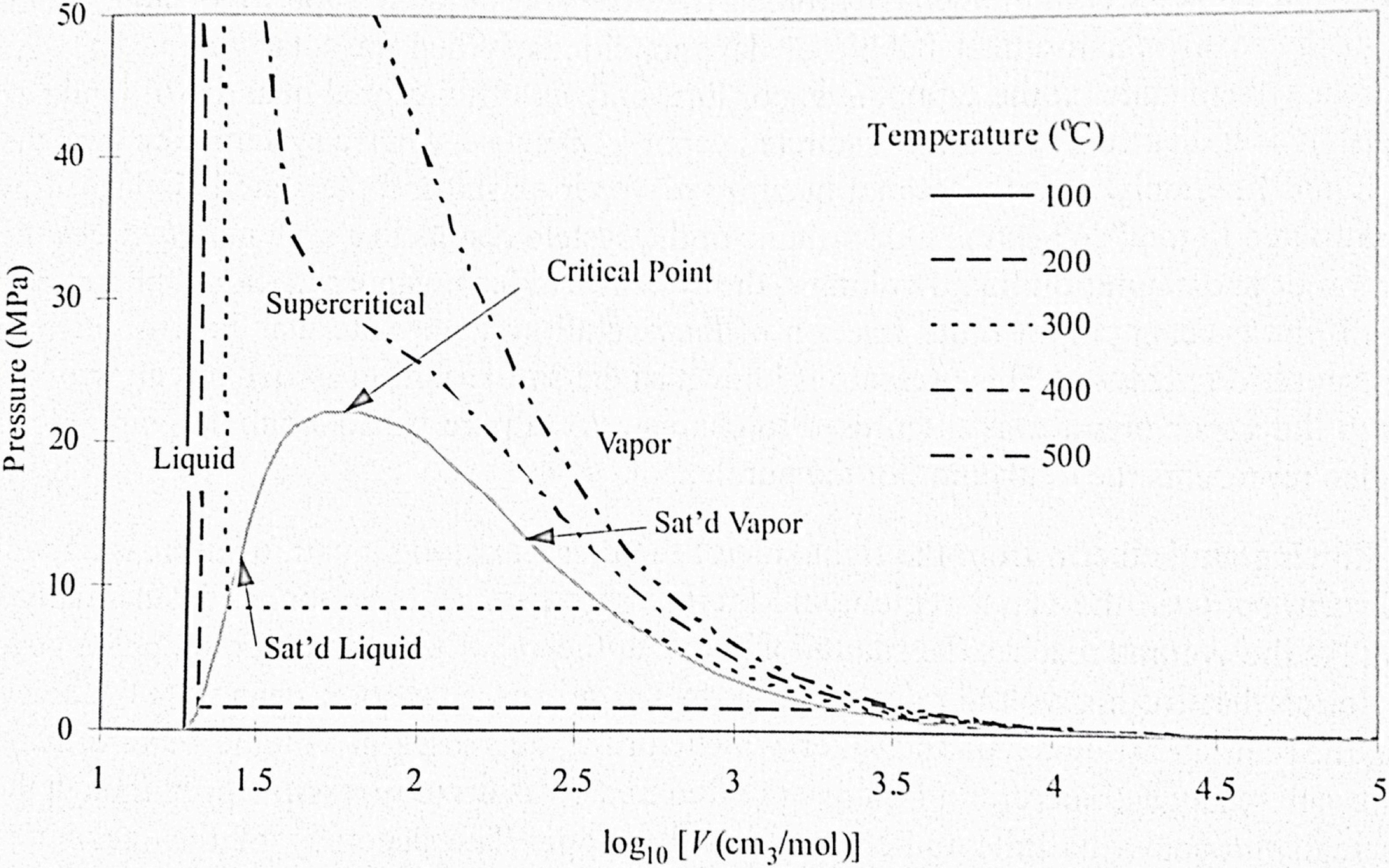


Figure 1.4 *P-V-T behavior of water at the same temperatures used in Fig. 1.3. The plot is prepared from the steam tables in Appendix E.*

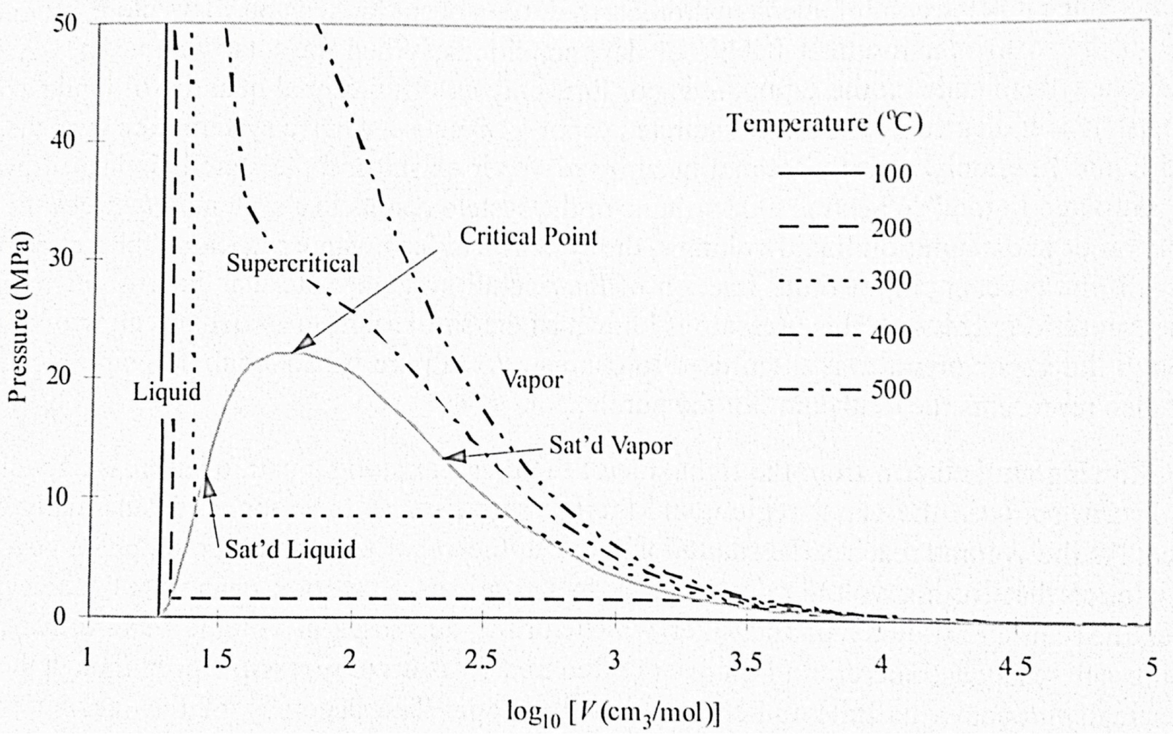
"Quality, q"

When a mixture of two phases (vapor/liquid) exist the **fraction vapor** is called the "**quality**". The intrinsic properties (M) such as V, U, H, S can be calculated for a two phase single component system using the "quality" and the values for the saturated liquid and vapor phases:

$M = (1\text{-}q)\ M^L + q\ M^V$

or

$M = M^L + q\ (\Delta M) = M^L + q\ (M^V\text{-}M^L)$



Phase Behavior for Single Component, C = 1
Water for example.

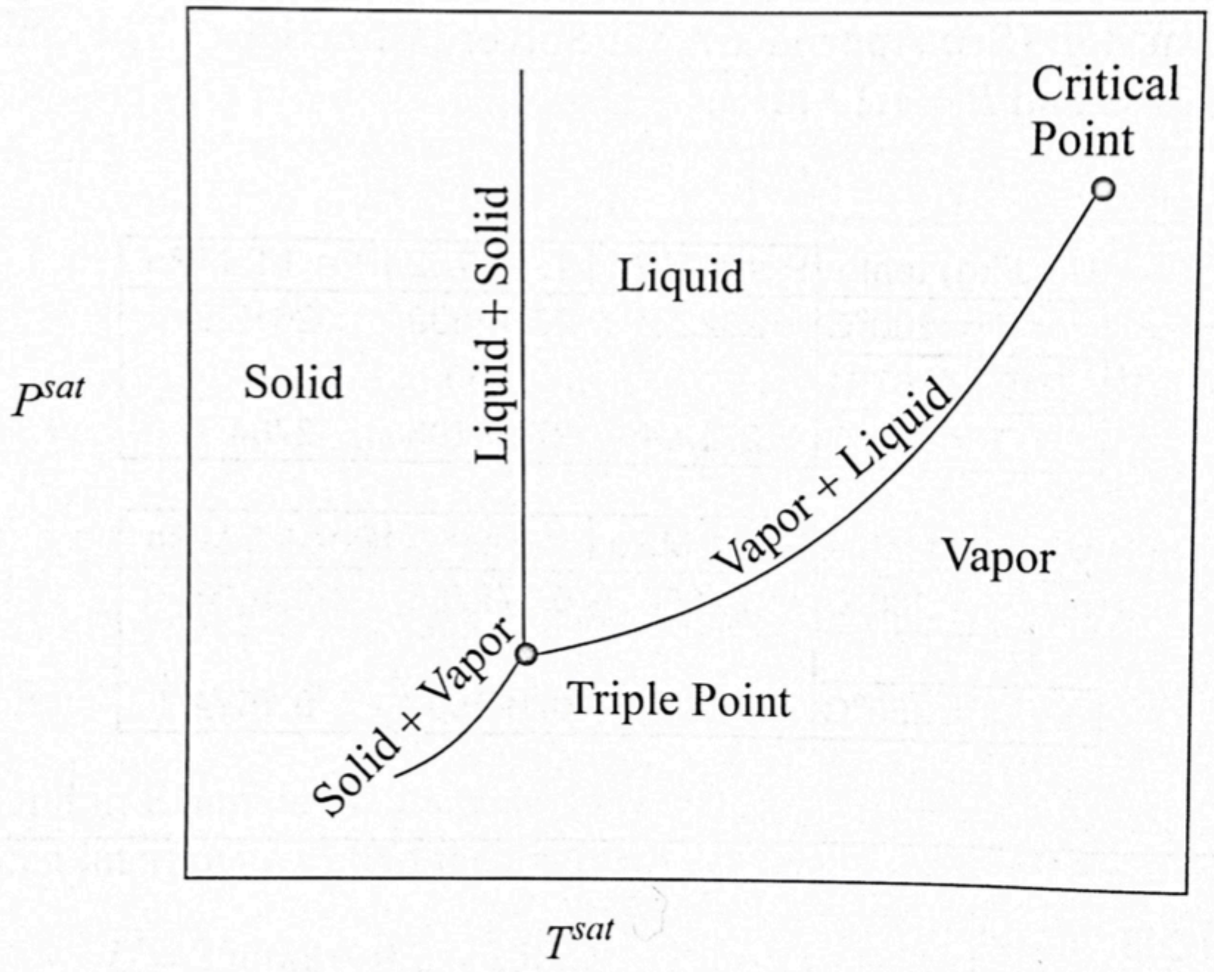


Figure 1.7 *P-T representation of real fluid behavior: Note that only vapor and liquid behavior is shown in Fig. 1.4 on page 23.*

$$F = C - P + 2$$

Gibbs Phase Rule

$$F = C - P + 2$$

F free parameters
C components
P phases

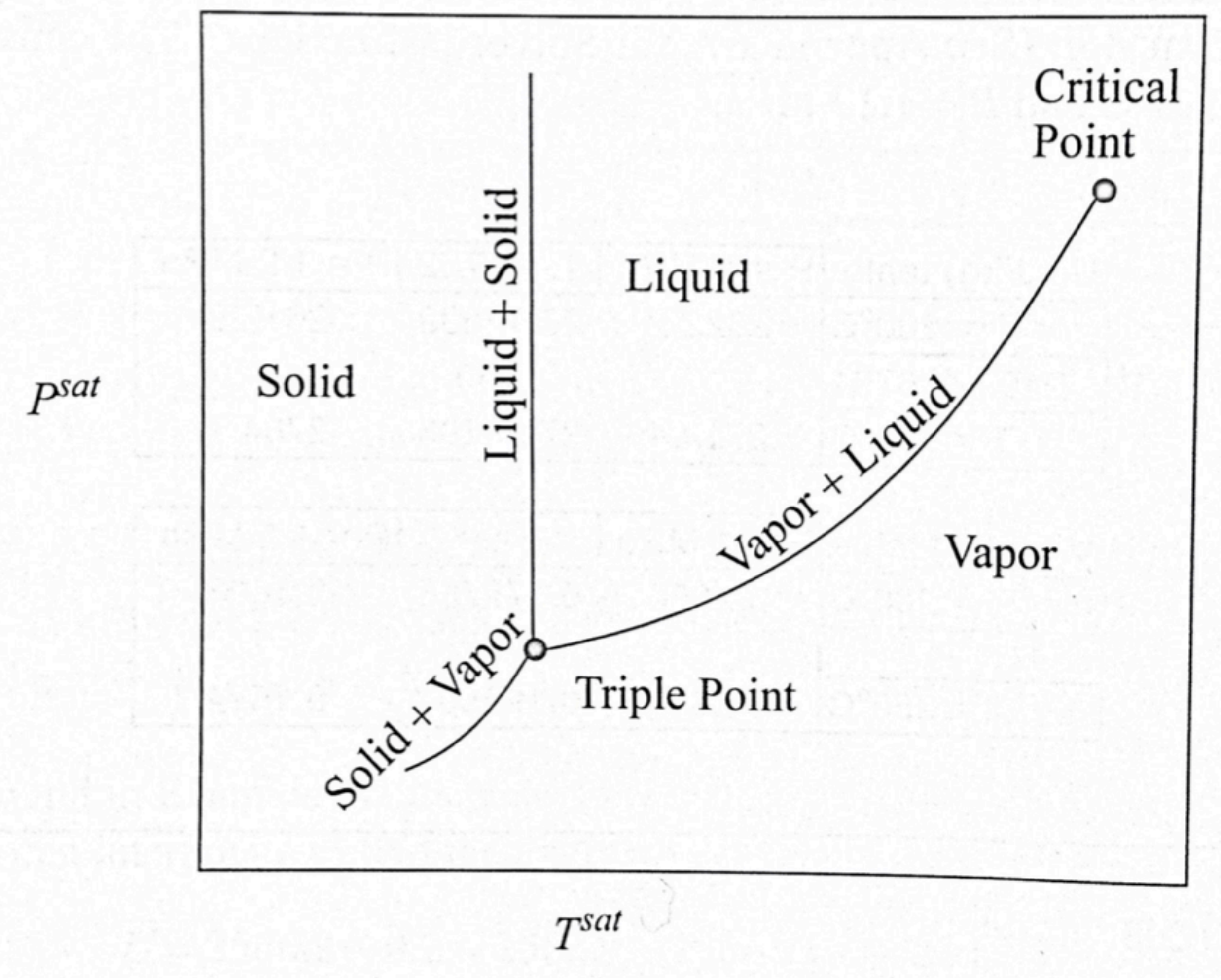
So for saturated water vapor we have one component, two phases and one free parameter. That is if T is known we know the vapor pressure. If we know the pressure we know the temperature.

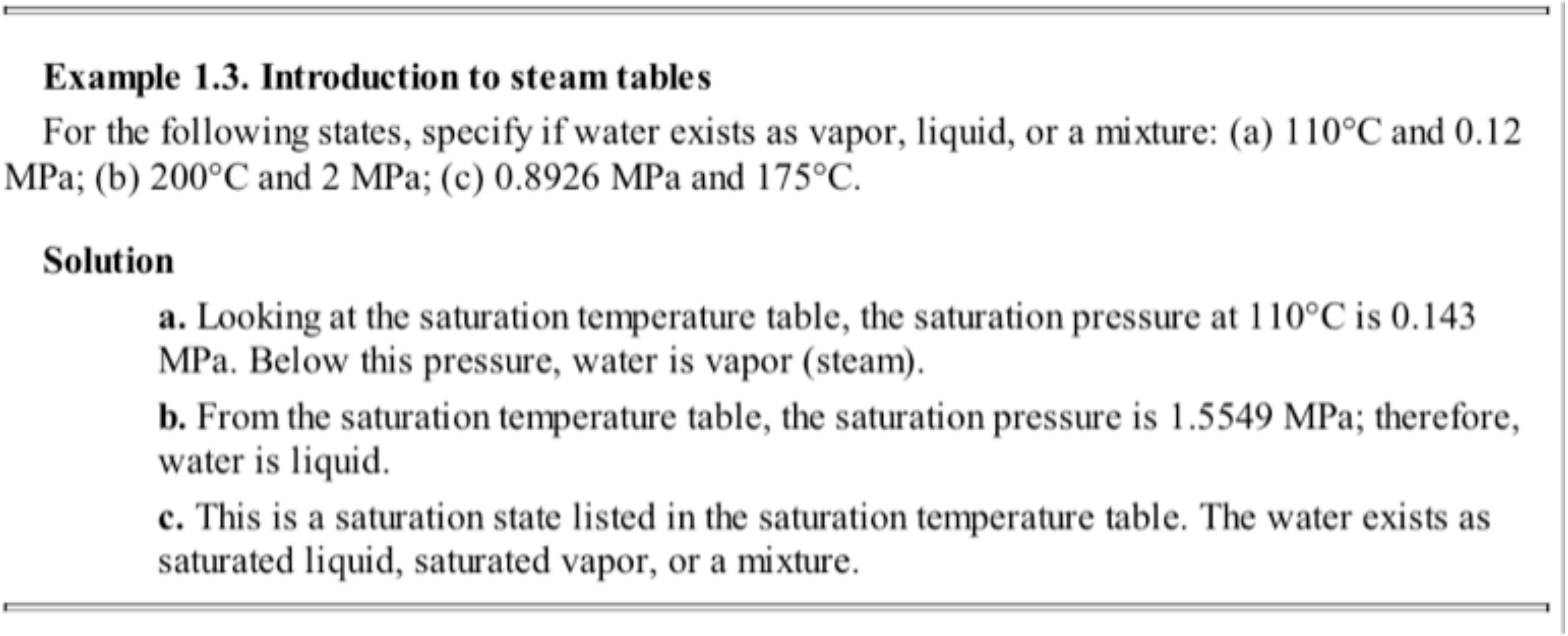
For supersaturated steam we have one component, one phase and we can vary P and T and these will determine the specific volume or density, internal energy, enthalpy, etc.

Gibbs Phase Rule

$F = C - P + 2$

F free parameters
C components
P phases





Example 1.3. Introduction to steam tables

For the following states, specify if water exists as vapor, liquid, or a mixture: (a) 110°C and 0.12 MPa; (b) 200°C and 2 MPa; (c) 0.8926 MPa and 175°C.

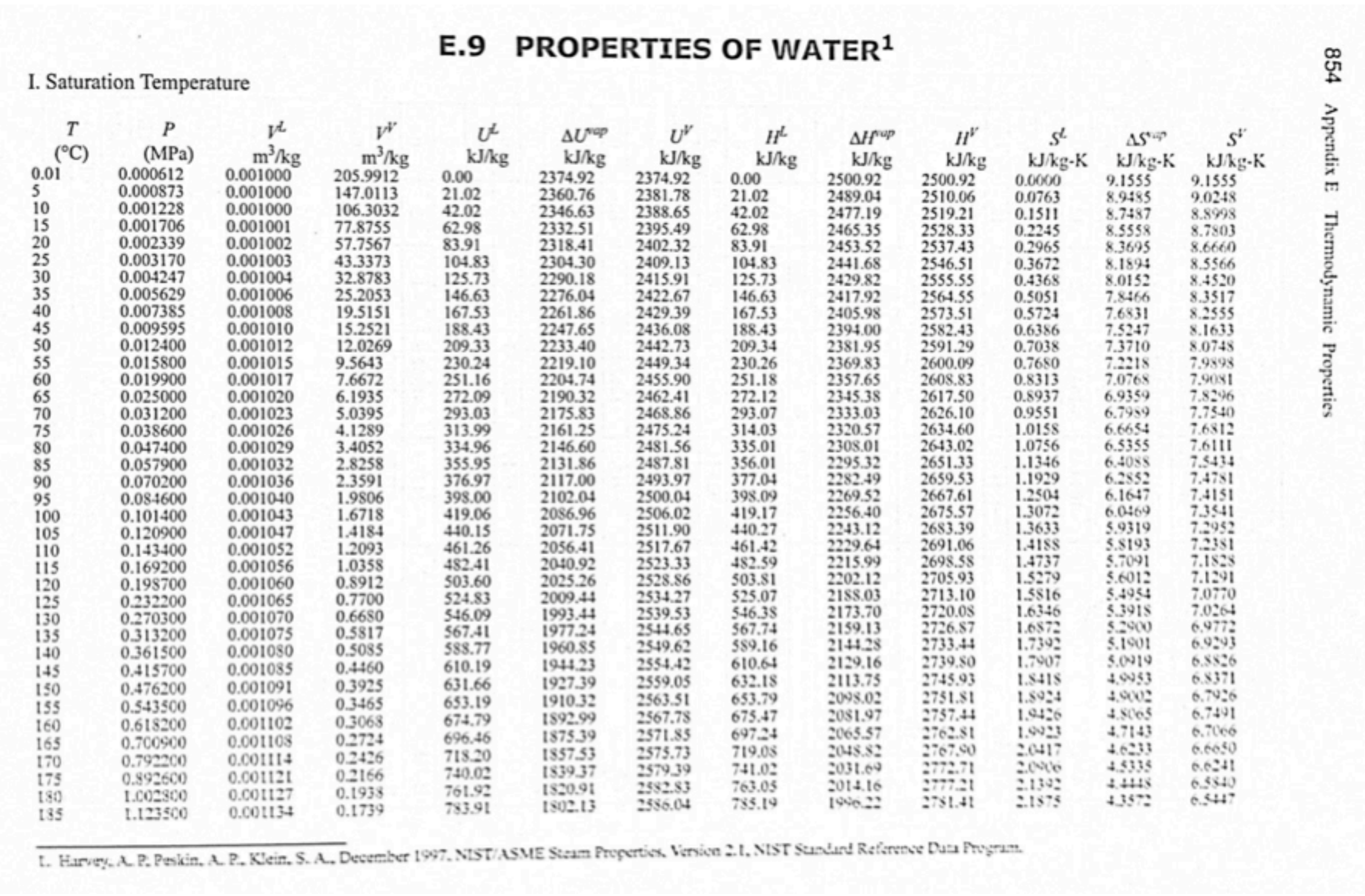
Solution

a. Looking at the saturation temperature table, the saturation pressure at 110°C is 0.143 MPa. Below this pressure, water is vapor (steam).

b. From the saturation temperature table, the saturation pressure is 1.5549 MPa; therefore, water is liquid.

c. This is a saturation state listed in the saturation temperature table. The water exists as saturated liquid, saturated vapor, or a mixture.

Steam Tables



E.9 PROPERTIES OF WATER[1]

I. Saturation Temperature

T (°C)	P (MPa)	V^L m³/kg	V^V m³/kg	U^L kJ/kg	ΔU^{vap} kJ/kg	U^V kJ/kg	H^L kJ/kg	ΔH^{vap} kJ/kg	H^V kJ/kg	S^L kJ/kg-K	ΔS^{vap} kJ/kg-K	S^V kJ/kg-K
0.01	0.000612	0.001000	205.9912	0.00	2374.92	2374.92	0.00	2500.92	2500.92	0.0000	9.1555	9.1555
5	0.000873	0.001000	147.0113	21.02	2360.76	2381.78	21.02	2489.04	2510.06	0.0763	8.9485	9.0248
10	0.001228	0.001000	106.3032	42.02	2346.63	2388.65	42.02	2477.19	2519.21	0.1511	8.7487	8.8998
15	0.001706	0.001001	77.8755	62.98	2332.51	2395.49	62.98	2465.35	2528.33	0.2245	8.5558	8.7803
20	0.002339	0.001002	57.7567	83.91	2318.41	2402.32	83.91	2453.52	2537.43	0.2965	8.3695	8.6660
25	0.003170	0.001003	43.3373	104.83	2304.30	2409.13	104.83	2441.68	2546.51	0.3672	8.1894	8.5566
30	0.004247	0.001004	32.8783	125.73	2290.18	2415.91	125.73	2429.82	2555.55	0.4368	8.0152	8.4520
35	0.005629	0.001006	25.2053	146.63	2276.04	2422.67	146.63	2417.92	2564.55	0.5051	7.8466	8.3517
40	0.007385	0.001008	19.5151	167.53	2261.86	2429.39	167.53	2405.98	2573.51	0.5724	7.6831	8.2555
45	0.009595	0.001010	15.2521	188.43	2247.65	2436.08	188.43	2394.00	2582.43	0.6386	7.5247	8.1633
50	0.012400	0.001012	12.0269	209.33	2233.40	2442.73	209.34	2381.95	2591.29	0.7038	7.3710	8.0748
55	0.015800	0.001015	9.5643	230.24	2219.10	2449.34	230.26	2369.83	2600.09	0.7680	7.2218	7.9898
60	0.019900	0.001017	7.6672	251.16	2204.74	2455.90	251.18	2357.65	2608.83	0.8313	7.0768	7.9081
65	0.025000	0.001020	6.1935	272.09	2190.32	2462.41	272.12	2345.38	2617.50	0.8937	6.9359	7.8296
70	0.031200	0.001023	5.0395	293.03	2175.83	2468.86	293.07	2333.03	2626.10	0.9551	6.7989	7.7540
75	0.038600	0.001026	4.1289	313.99	2161.25	2475.24	314.03	2320.57	2634.60	1.0158	6.6654	7.6812
80	0.047400	0.001029	3.4052	334.96	2146.60	2481.56	335.01	2308.01	2643.02	1.0756	6.5355	7.6111
85	0.057900	0.001032	2.8258	355.95	2131.86	2487.81	356.01	2295.32	2651.33	1.1346	6.4088	7.5434
90	0.070200	0.001036	2.3591	376.97	2117.00	2493.97	377.04	2282.49	2659.53	1.1929	6.2852	7.4781
95	0.084600	0.001040	1.9806	398.00	2102.04	2500.04	398.09	2269.52	2667.61	1.2504	6.1647	7.4151
100	0.101400	0.001043	1.6718	419.06	2086.96	2506.02	419.17	2256.40	2675.57	1.3072	6.0469	7.3541
105	0.120900	0.001047	1.4184	440.15	2071.75	2511.90	440.27	2243.12	2683.39	1.3633	5.9319	7.2952
110	0.143400	0.001052	1.2093	461.26	2056.41	2517.67	461.42	2229.64	2691.06	1.4188	5.8193	7.2381
115	0.169200	0.001056	1.0358	482.41	2040.92	2523.33	482.59	2215.99	2698.58	1.4737	5.7091	7.1828
120	0.198700	0.001060	0.8912	503.60	2025.26	2528.86	503.81	2202.12	2705.93	1.5279	5.6012	7.1291
125	0.232200	0.001065	0.7700	524.83	2009.44	2534.27	525.07	2188.03	2713.10	1.5816	5.4954	7.0770
130	0.270300	0.001070	0.6680	546.09	1993.44	2539.53	546.38	2173.70	2720.08	1.6346	5.3918	7.0264
135	0.313200	0.001075	0.5817	567.41	1977.24	2544.65	567.74	2159.13	2726.87	1.6872	5.2900	6.9772
140	0.361500	0.001080	0.5085	588.77	1960.85	2549.62	589.16	2144.28	2733.44	1.7392	5.1901	6.9293
145	0.415700	0.001085	0.4460	610.19	1944.23	2554.42	610.64	2129.16	2739.80	1.7907	5.0919	6.8826
150	0.476200	0.001091	0.3925	631.66	1927.39	2559.05	632.18	2113.75	2745.93	1.8418	4.9953	6.8371
155	0.543500	0.001096	0.3465	653.19	1910.32	2563.51	653.79	2098.02	2751.81	1.8924	4.9002	6.7926
160	0.618200	0.001102	0.3068	674.79	1892.99	2567.78	675.47	2081.97	2757.44	1.9426	4.8065	6.7491
165	0.700900	0.001108	0.2724	696.46	1875.39	2571.85	697.24	2065.57	2762.81	1.9923	4.7143	6.7066
170	0.792200	0.001114	0.2426	718.20	1857.53	2575.73	719.08	2048.82	2767.90	2.0417	4.6233	6.6650
175	0.892600	0.001121	0.2166	740.02	1839.37	2579.39	741.02	2031.69	2772.71	2.0906	4.5335	6.6241
180	1.002800	0.001127	0.1938	761.92	1820.91	2582.83	763.05	2014.16	2777.21	2.1392	4.4448	6.5840
185	1.123500	0.001134	0.1739	783.91	1802.13	2586.04	785.19	1996.22	2781.41	2.1875	4.3572	6.5447

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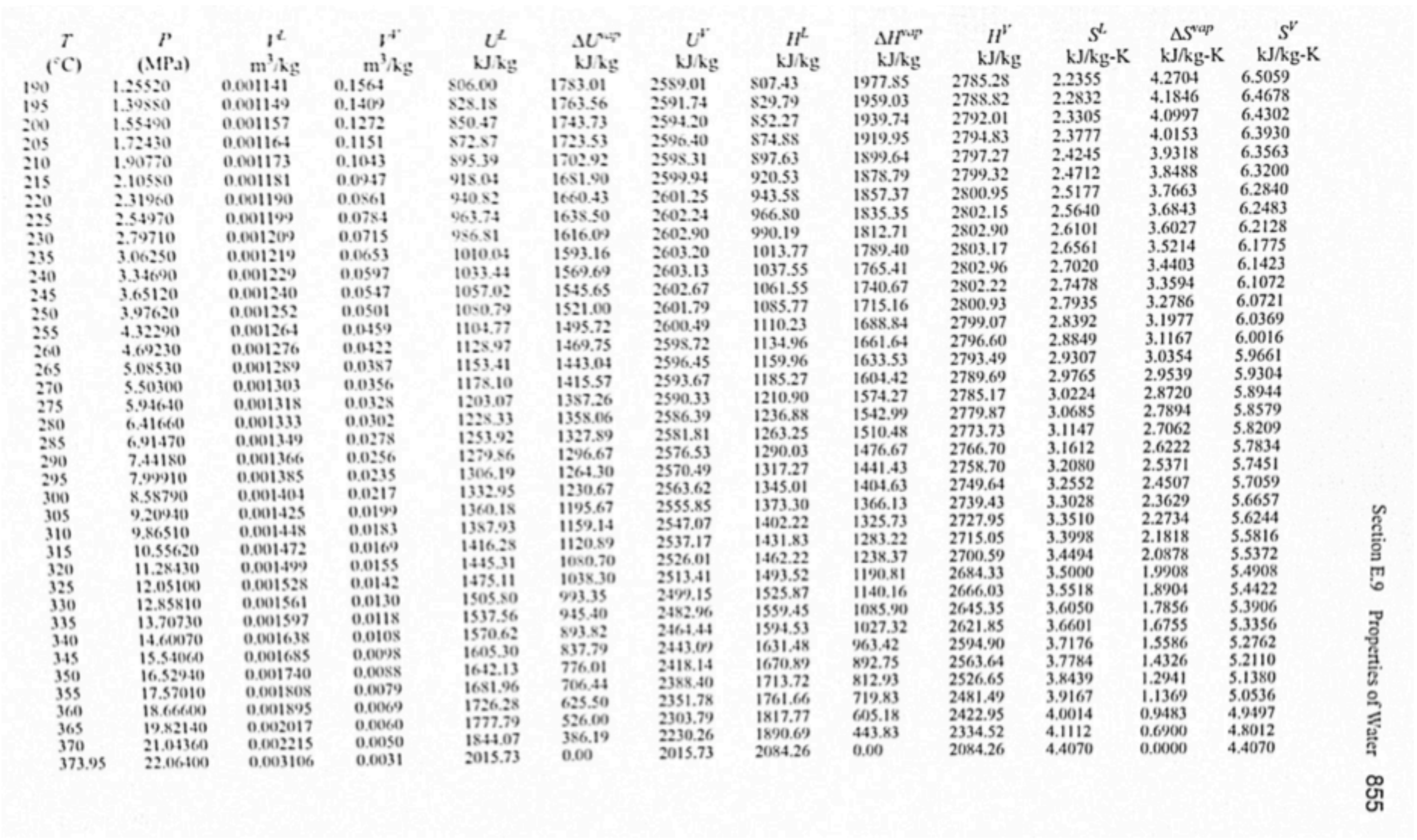
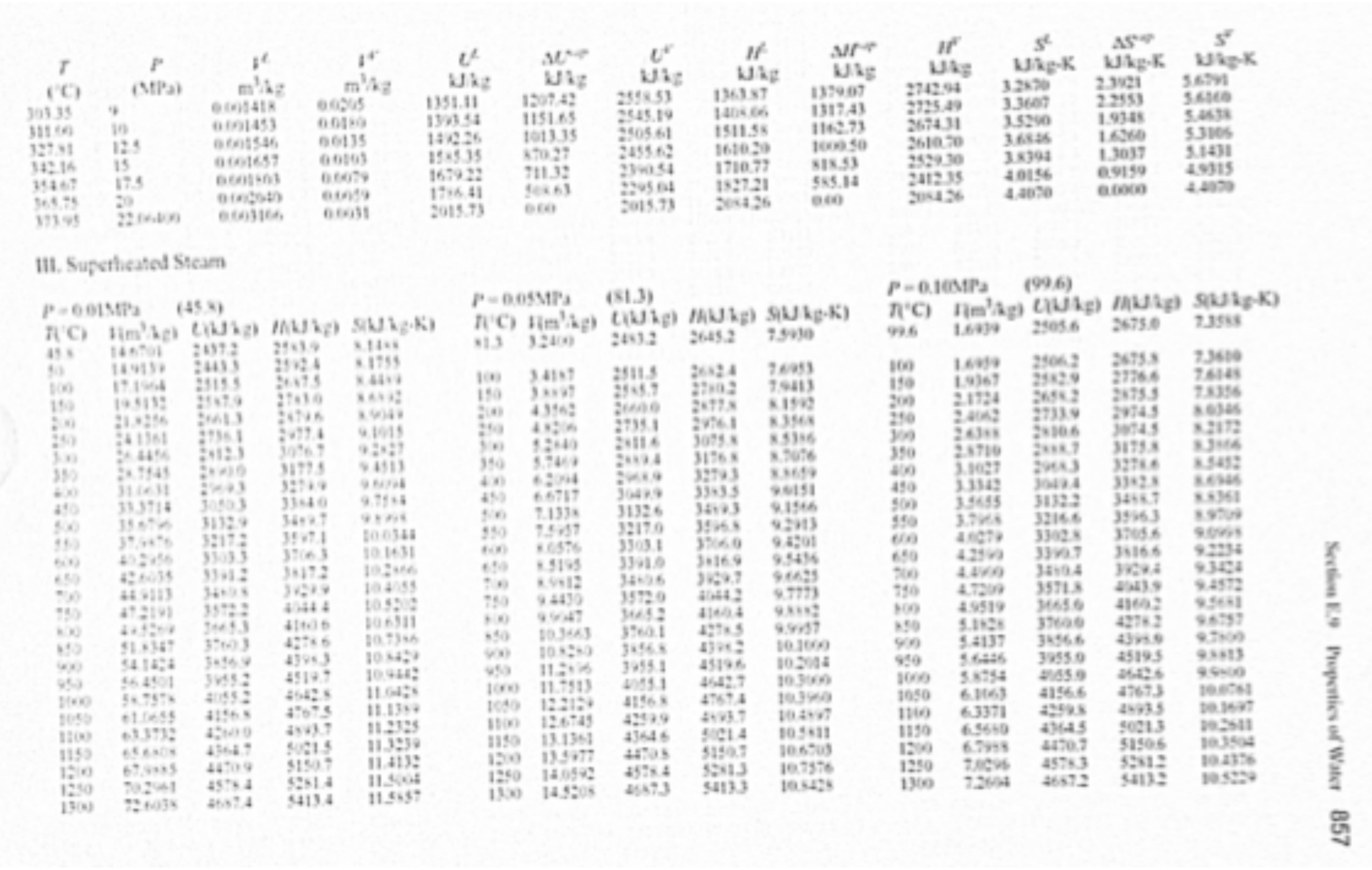
[1] Harvey, A. P., Peskin, A. P., Klein, S. A., December 1997. NIST/ASME Steam Properties, Version 2.1, NIST Standard Reference Data Program.



T (°C)	P (MPa)	V^L m^3/kg	V^V m^3/kg	U^L kJ/kg	ΔU^{vap} kJ/kg	U^V kJ/kg	H^L kJ/kg	ΔH^{vap} kJ/kg	H^V kJ/kg	S^L kJ/kg-K	ΔS^{vap} kJ/kg-K	S^V kJ/kg-K
190	1.25520	0.001141	0.1564	806.00	1783.01	2589.01	807.43	1977.85	2785.28	2.2355	4.2704	6.5059
195	1.39880	0.001149	0.1409	828.18	1763.56	2591.74	829.79	1959.03	2788.82	2.2832	4.1846	6.4678
200	1.55490	0.001157	0.1272	850.47	1743.73	2594.20	852.27	1939.74	2792.01	2.3305	4.0997	6.4302
205	1.72430	0.001164	0.1151	872.87	1723.53	2596.40	874.88	1919.95	2794.83	2.3777	4.0153	6.3930
210	1.90770	0.001173	0.1043	895.39	1702.92	2598.31	897.63	1899.64	2797.27	2.4245	3.9318	6.3563
215	2.10580	0.001181	0.0947	918.04	1681.90	2599.94	920.53	1878.79	2799.32	2.4712	3.8488	6.3200
220	2.31960	0.001190	0.0861	940.82	1660.43	2601.25	943.58	1857.37	2800.95	2.5177	3.7663	6.2840
225	2.54970	0.001199	0.0784	963.74	1638.50	2602.24	966.80	1835.35	2802.15	2.5640	3.6843	6.2483
230	2.79710	0.001209	0.0715	986.81	1616.09	2602.90	990.19	1812.71	2802.90	2.6101	3.6027	6.2128
235	3.06250	0.001219	0.0653	1010.04	1593.16	2603.20	1013.77	1789.40	2803.17	2.6561	3.5214	6.1775
240	3.34690	0.001229	0.0597	1033.44	1569.69	2603.13	1037.55	1765.41	2802.96	2.7020	3.4403	6.1423
245	3.65120	0.001240	0.0547	1057.02	1545.65	2602.67	1061.55	1740.67	2802.22	2.7478	3.3594	6.1072
250	3.97620	0.001252	0.0501	1080.79	1521.00	2601.79	1085.77	1715.16	2800.93	2.7935	3.2786	6.0721
255	4.32290	0.001264	0.0459	1104.77	1495.72	2600.49	1110.23	1688.84	2799.07	2.8392	3.1977	6.0369
260	4.69230	0.001276	0.0422	1128.97	1469.75	2598.72	1134.96	1661.64	2796.60	2.8849	3.1167	6.0016
265	5.08530	0.001289	0.0387	1153.41	1443.04	2596.45	1159.96	1633.53	2793.49	2.9307	3.0354	5.9661
270	5.50300	0.001303	0.0356	1178.10	1415.57	2593.67	1185.27	1604.42	2789.69	2.9765	2.9539	5.9304
275	5.94640	0.001318	0.0328	1203.07	1387.26	2590.33	1210.90	1574.27	2785.17	3.0224	2.8720	5.8944
280	6.41660	0.001333	0.0302	1228.33	1358.06	2586.39	1236.88	1542.99	2779.87	3.0685	2.7894	5.8579
285	6.91470	0.001349	0.0278	1253.92	1327.89	2581.81	1263.25	1510.48	2773.73	3.1147	2.7062	5.8209
290	7.44180	0.001366	0.0256	1279.86	1296.67	2576.53	1290.03	1476.67	2766.70	3.1612	2.6222	5.7834
295	7.99910	0.001385	0.0235	1306.19	1264.30	2570.49	1317.27	1441.43	2758.70	3.2080	2.5371	5.7451
300	8.58790	0.001404	0.0217	1332.95	1230.67	2563.62	1345.01	1404.63	2749.64	3.2552	2.4507	5.7059
305	9.20940	0.001425	0.0199	1360.18	1195.67	2555.85	1373.30	1366.13	2739.43	3.3028	2.3629	5.6657
310	9.86510	0.001448	0.0183	1387.93	1159.14	2547.07	1402.22	1325.73	2727.95	3.3510	2.2734	5.6244
315	10.55620	0.001472	0.0169	1416.28	1120.89	2537.17	1431.83	1283.22	2715.05	3.3998	2.1818	5.5816
320	11.28430	0.001499	0.0155	1445.31	1080.70	2526.01	1462.22	1238.37	2700.59	3.4494	2.0878	5.5372
325	12.05100	0.001528	0.0142	1475.11	1038.30	2513.41	1493.52	1190.81	2684.33	3.5000	1.9908	5.4908
330	12.85810	0.001561	0.0130	1505.80	993.35	2499.15	1525.87	1140.16	2666.03	3.5518	1.8904	5.4422
335	13.70730	0.001597	0.0118	1537.56	945.40	2482.96	1559.45	1085.90	2645.35	3.6050	1.7856	5.3906
340	14.60070	0.001638	0.0108	1570.62	893.82	2464.44	1594.53	1027.32	2621.85	3.6601	1.6755	5.3356
345	15.54060	0.001685	0.0098	1605.30	837.79	2443.09	1631.48	963.42	2594.90	3.7176	1.5586	5.2762
350	16.52940	0.001740	0.0088	1642.13	776.01	2418.14	1670.89	892.75	2563.64	3.7784	1.4326	5.2110
355	17.57010	0.001808	0.0079	1681.96	706.44	2388.40	1713.72	812.93	2526.65	3.8439	1.2941	5.1380
360	18.66600	0.001895	0.0069	1726.28	625.50	2351.78	1761.66	719.83	2481.49	3.9167	1.1369	5.0536
365	19.82140	0.002017	0.0060	1777.79	526.00	2303.79	1817.77	605.18	2422.95	4.0014	0.9483	4.9497
370	21.04360	0.002215	0.0050	1844.07	386.19	2230.26	1890.69	443.83	2334.52	4.1112	0.6900	4.8012
373.95	22.06400	0.003106	0.0031	2015.73	0.00	2015.73	2084.26	0.00	2084.26	4.4070	0.0000	4.4070

II. Saturation Pressure

T (°C)	P (MPa)	V^L m³/kg	V^V m³/kg	U^L kJ/kg	ΔU^{vap} kJ/kg	U^V kJ/kg	H^L kJ/kg	ΔH^{vap} kJ/kg	H^V kJ/kg	S^L kJ/kg-K	ΔS^{vap} kJ/kg-K	S^V kJ/kg-K
6.97	0.001	0.001000	129.1780	29.30	2355.19	2384.49	29.30	2484.37	2513.67	0.1059	8.8690	8.9749
17.50	0.002	0.001001	66.9869	73.43	2325.47	2398.90	73.43	2459.45	2532.88	0.2606	8.4620	8.7226
24.08	0.003	0.001003	45.6532	100.98	2306.90	2407.88	100.98	2443.86	2544.84	0.3543	8.2221	8.5764
28.96	0.004	0.001004	34.7911	121.38	2293.12	2414.50	121.39	2432.28	2553.67	0.4224	8.0510	8.4734
32.87	0.005	0.001005	28.1853	137.74	2282.06	2419.80	137.75	2422.98	2560.73	0.4762	7.9176	8.3938
36.16	0.006	0.001006	23.7334	151.47	2272.76	2424.23	151.48	2415.15	2566.63	0.5208	7.8082	8.3290
39.00	0.007	0.001008	20.5245	163.34	2264.71	2428.05	163.35	2408.37	2571.72	0.5590	7.7155	8.2745
41.51	0.008	0.001008	18.0989	173.83	2257.58	2431.41	173.84	2402.37	2576.21	0.5925	7.6348	8.2273
43.76	0.009	0.001009	16.1992	183.24	2251.19	2434.43	183.25	2396.97	2580.22	0.6223	7.5635	8.1858
45.81	0.01	0.001010	14.6701	191.80	2245.36	2437.16	191.81	2392.05	2583.86	0.6492	7.4996	8.1488
60.06	0.02	0.001017	7.6480	251.40	2204.58	2455.98	251.42	2357.52	2608.94	0.8320	7.0752	7.9072
69.10	0.03	0.001022	5.2284	289.24	2178.46	2467.70	289.27	2335.28	2624.55	0.9441	6.8234	7.7675
75.86	0.04	0.001026	3.9930	317.58	2158.75	2476.33	317.62	2318.43	2636.05	1.0261	6.6429	7.6690
81.32	0.05	0.001030	3.2400	340.49	2142.72	2483.21	340.54	2304.68	2645.22	1.0912	6.5018	7.5930
85.93	0.06	0.001033	2.7317	359.85	2129.10	2488.95	359.91	2292.95	2652.86	1.1455	6.3856	7.5311
89.93	0.07	0.001036	2.3648	376.68	2117.20	2493.88	376.75	2282.67	2659.42	1.1921	6.2869	7.4790
93.49	0.08	0.001039	2.0871	391.63	2106.58	2498.21	391.71	2273.47	2665.18	1.2330	6.2009	7.4339
96.69	0.09	0.001041	1.8694	405.10	2096.97	2502.07	405.20	2265.11	2670.31	1.2696	6.1247	7.3943
99.61	0.1	0.001043	1.6939	417.40	2088.15	2505.55	417.50	2257.45	2674.95	1.3028	6.0561	7.3589
120.21	0.2	0.001061	0.8857	504.49	2024.60	2529.09	504.70	2201.53	2706.23	1.5302	5.5967	7.1269
133.52	0.3	0.001073	0.6058	561.11	1982.04	2543.15	561.43	2163.45	2724.88	1.6717	5.3199	6.9916
143.61	0.4	0.001084	0.4624	604.22	1948.88	2553.10	604.66	2133.39	2738.05	1.7765	5.1190	6.8955
151.83	0.5	0.001093	0.3748	639.54	1921.17	2560.71	640.09	2108.02	2748.11	1.8604	4.9603	6.8207
158.83	0.6	0.001101	0.3156	669.72	1897.07	2566.79	670.38	2085.76	2756.14	1.9308	4.8285	6.7593
164.95	0.7	0.001108	0.2728	696.23	1875.58	2571.81	697.00	2065.75	2762.75	1.9918	4.7153	6.7071
170.41	0.8	0.001115	0.2403	719.97	1856.06	2576.03	720.86	2047.44	2768.30	2.0457	4.6159	6.6616
175.35	0.9	0.001121	0.2149	741.55	1838.09	2579.64	742.56	2030.47	2773.03	2.0941	4.5272	6.6213
179.88	1	0.001127	0.1944	761.39	1821.36	2582.75	762.52	2014.59	2777.11	2.1381	4.4469	6.5850
187.96	1.2	0.001139	0.1633	796.96	1790.87	2587.83	798.33	1985.41	2783.74	2.2159	4.3058	6.5217
195.04	1.4	0.001149	0.1408	828.36	1763.40	2591.76	829.97	1958.88	2788.85	2.2835	4.1840	6.4675
201.37	1.6	0.001159	0.1237	856.60	1738.23	2594.83	858.46	1934.36	2792.82	2.3435	4.0764	6.4199
207.11	1.8	0.001168	0.1104	882.37	1714.87	2597.24	884.47	1911.44	2795.91	2.3975	3.9800	6.3775
212.38	2	0.001177	0.0996	906.15	1692.97	2599.12	908.50	1889.79	2798.29	2.4468	3.8922	6.3390
223.95	2.5	0.001197	0.0799	958.91	1643.15	2602.06	961.91	1840.02	2801.93	2.5543	3.7015	6.2558
233.85	3	0.001217	0.0667	1004.69	1598.47	2603.16	1008.34	1794.81	2803.15	2.6456	3.5400	6.1856
242.56	3.5	0.001235	0.0571	1045.47	1557.47	2602.94	1049.80	1752.84	2802.64	2.7254	3.3989	6.1243
250.35	4	0.001253	0.0498	1082.48	1519.24	2601.72	1087.49	1713.33	2800.82	2.7968	3.2728	6.0696
257.44	4.5	0.001270	0.0441	1116.53	1483.15	2599.68	1122.25	1675.70	2797.95	2.8615	3.1582	6.0197
263.94	5	0.001286	0.0394	1148.21	1448.77	2596.98	1154.64	1639.57	2794.21	2.9210	3.0527	5.9737
275.59	6	0.001319	0.0324	1206.01	1383.89	2589.90	1213.92	1570.67	2784.59	3.0278	2.8623	5.8901
285.83	7	0.001352	0.0274	1258.20	1322.78	2580.98	1267.66	1504.97	2772.63	3.1224	2.6924	5.8148
295.01	8	0.001385	0.0235	1306.23	1264.25	2570.48	1317.31	1441.37	2758.68	3.2081	2.5369	5.7450



T (°C)	P (MPa)	V^L m³/kg	V^V m³/kg	U^L kJ/kg	ΔU^{vap} kJ/kg	U^V kJ/kg	H^L kJ/kg	ΔH^{vap} kJ/kg	H^V kJ/kg	S^L kJ/kg-K	ΔS^{vap} kJ/kg-K	S^V kJ/kg-K
303.35	9	0.001418	0.0205	1351.11	1207.42	2558.53	1363.87	1379.07	2742.94	3.2870	2.3921	5.6791
311.00	10	0.001453	0.0180	1393.54	1151.65	2545.19	1408.06	1317.43	2725.49	3.3607	2.2553	5.6160
327.81	12.5	0.001546	0.0135	1492.26	1013.35	2505.61	1511.58	1162.73	2674.31	3.5290	1.9348	5.4638
342.16	15	0.001657	0.0103	1585.35	870.27	2455.62	1610.20	1000.50	2610.70	3.6846	1.6260	5.3106
354.67	17.5	0.001803	0.0079	1679.22	711.32	2390.54	1710.77	818.53	2529.30	3.8394	1.3037	5.1431
365.75	20	0.002040	0.0059	1786.41	508.63	2295.04	1827.21	585.14	2412.35	4.0156	0.9159	4.9315
373.95	22.06400	0.003106	0.0031	2015.73	0.00	2015.73	2084.26	0.00	2084.26	4.4070	0.0000	4.4070

III. Superheated Steam

P = 0.01MPa (45.8)

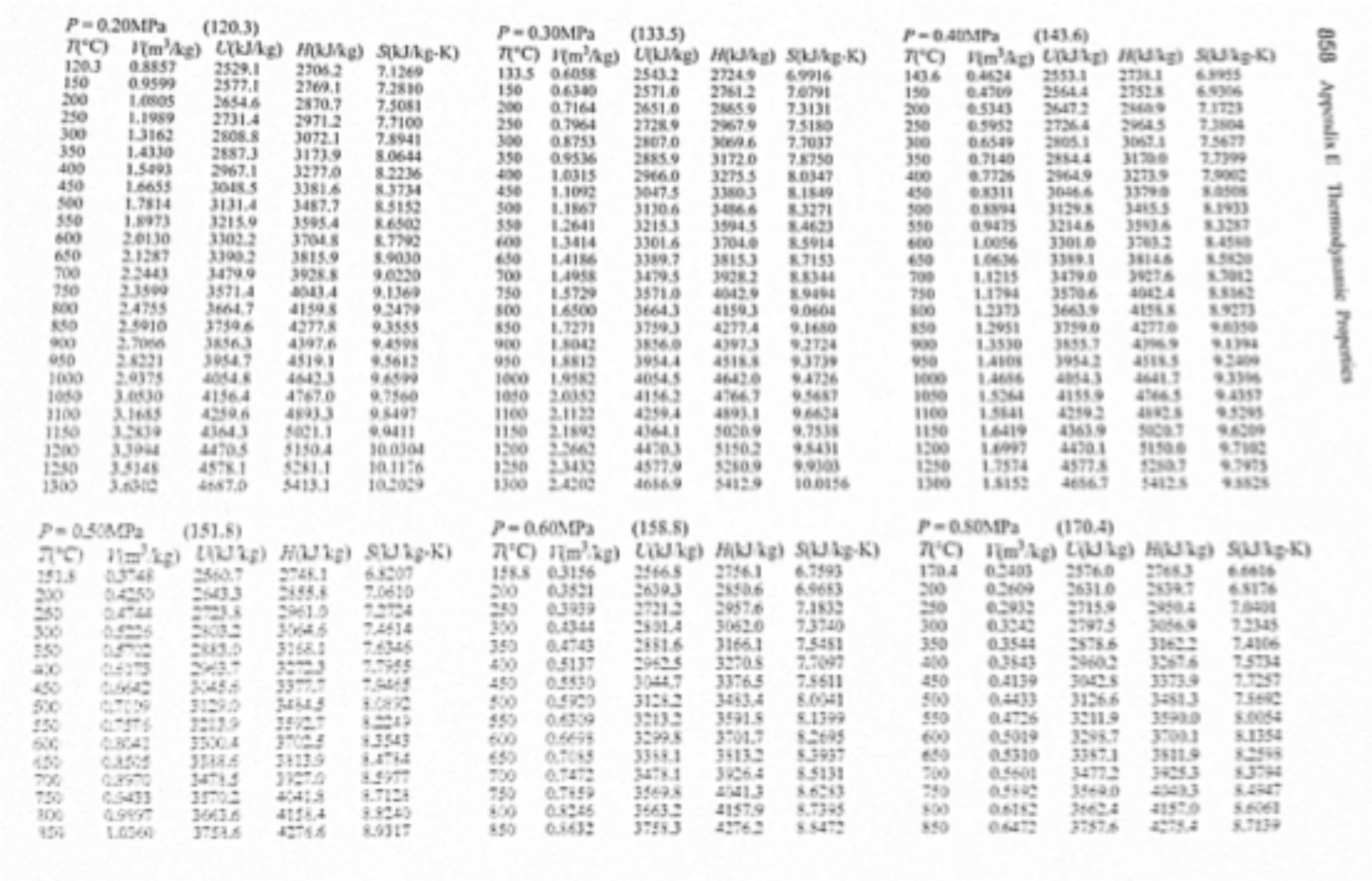
T(°C)	V(m³/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
45.8	14.6701	2437.2	2583.9	8.1488
50	14.9139	2443.3	2592.4	8.1755
100	17.1964	2515.5	2687.5	8.4489
150	19.5132	2587.9	2783.0	8.6892
200	21.8256	2661.3	2879.6	8.9049
250	24.1361	2736.1	2977.4	9.1015
300	26.4456	2812.3	3076.7	9.2827
350	28.7545	2890.0	3177.5	9.4513
400	31.0631	2969.3	3279.9	9.6094
450	33.3714	3050.3	3384.0	9.7584
500	35.6796	3132.9	3489.7	9.8998
550	37.9876	3217.2	3597.1	10.0344
600	40.2956	3303.3	3706.3	10.1631
650	42.6035	3391.2	3817.2	10.2866
700	44.9113	3480.8	3929.9	10.4055
750	47.2191	3572.2	4044.4	10.5202
800	49.5269	3665.3	4160.6	10.6311
850	51.8347	3760.3	4278.6	10.7386
900	54.1424	3856.9	4398.3	10.8429
950	56.4501	3955.2	4519.7	10.9442
1000	58.7578	4055.2	4642.8	11.0428
1050	61.0655	4156.8	4767.5	11.1389
1100	63.3732	4260.0	4893.7	11.2325
1150	65.6808	4364.7	5021.5	11.3239
1200	67.9885	4470.9	5150.7	11.4132
1250	70.2961	4578.4	5281.4	11.5004
1300	72.6038	4687.4	5413.4	11.5857

P = 0.05MPa (81.3)

T(°C)	V(m³/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
81.3	3.2400	2483.2	2645.2	7.5930
100	3.4187	2511.5	2682.4	7.6953
150	3.8897	2585.7	2780.2	7.9413
200	4.3562	2660.0	2877.8	8.1592
250	4.8206	2735.1	2976.1	8.3568
300	5.2840	2811.6	3075.8	8.5386
350	5.7469	2889.4	3176.8	8.7076
400	6.2094	2968.9	3279.3	8.8659
450	6.6717	3049.9	3383.5	9.0151
500	7.1338	3132.6	3489.3	9.1566
550	7.5957	3217.0	3596.8	9.2913
600	8.0576	3303.1	3706.0	9.4201
650	8.5195	3391.0	3816.9	9.5436
700	8.9812	3480.6	3929.7	9.6625
750	9.4430	3572.0	4044.2	9.7773
800	9.9047	3665.2	4160.4	9.8882
850	10.3663	3760.1	4278.5	9.9957
900	10.8280	3856.8	4398.2	10.1000
950	11.2896	3955.1	4519.6	10.2014
1000	11.7513	4055.1	4642.7	10.3000
1050	12.2129	4156.8	4767.4	10.3960
1100	12.6745	4259.9	4893.7	10.4897
1150	13.1361	4364.6	5021.4	10.5811
1200	13.5977	4470.5	5150.7	10.6703
1250	14.0592	4578.4	5281.3	10.7576
1300	14.5208	4687.3	5413.3	10.8428

P = 0.10MPa (99.6)

T(°C)	V(m³/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
99.6	1.6939	2505.6	2675.0	7.3588
100	1.6959	2506.2	2675.8	7.3610
150	1.9367	2582.9	2776.6	7.6148
200	2.1724	2658.2	2875.5	7.8356
250	2.4062	2733.9	2974.5	8.0346
300	2.6388	2810.6	3074.5	8.2172
350	2.8710	2888.7	3175.8	8.3866
400	3.1027	2968.3	3278.6	8.5452
450	3.3342	3049.4	3382.8	8.6946
500	3.5655	3132.2	3488.7	8.8361
550	3.7968	3216.6	3596.3	8.9709
600	4.0279	3302.8	3705.6	9.0998
650	4.2590	3390.7	3816.6	9.2234
700	4.4900	3480.4	3929.4	9.3424
750	4.7209	3571.8	4043.9	9.4572
800	4.9519	3665.0	4160.2	9.5681
850	5.1828	3760.0	4278.2	9.6757
900	5.4137	3856.6	4398.0	9.7800
950	5.6446	3955.0	4519.5	9.8813
1000	5.8754	4055.0	4642.6	9.9800
1050	6.1063	4156.6	4767.3	10.0761
1100	6.3371	4259.8	4893.5	10.1697
1150	6.5680	4364.5	5021.3	10.2611
1200	6.7988	4470.7	5150.6	10.3504
1250	7.0296	4578.3	5281.2	10.4376
1300	7.2604	4687.2	5413.2	10.5229



$P = 0.20$MPa (120.3)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
120.3	0.8857	2529.1	2706.2	7.1269
150	0.9599	2577.1	2769.1	7.2810
200	1.0805	2654.6	2870.7	7.5081
250	1.1989	2731.4	2971.2	7.7100
300	1.3162	2808.8	3072.1	7.8941
350	1.4330	2887.3	3173.9	8.0644
400	1.5493	2967.1	3277.0	8.2236
450	1.6655	3048.5	3381.6	8.3734
500	1.7814	3131.4	3487.7	8.5152
550	1.8973	3215.9	3595.4	8.6502
600	2.0130	3302.2	3704.8	8.7792
650	2.1287	3390.2	3815.9	8.9030
700	2.2443	3479.9	3928.8	9.0220
750	2.3599	3571.4	4043.4	9.1369
800	2.4755	3664.7	4159.8	9.2479
850	2.5910	3759.6	4277.8	9.3555
900	2.7066	3856.3	4397.6	9.4598
950	2.8221	3954.7	4519.1	9.5612
1000	2.9375	4054.8	4642.3	9.6599
1050	3.0530	4156.4	4767.0	9.7560
1100	3.1685	4259.6	4893.3	9.8497
1150	3.2839	4364.3	5021.1	9.9411
1200	3.3994	4470.5	5150.4	10.0304
1250	3.5148	4578.1	5281.1	10.1176
1300	3.6302	4687.0	5413.1	10.2029

$P = 0.30$MPa (133.5)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
133.5	0.6058	2543.2	2724.9	6.9916
150	0.6340	2571.0	2761.2	7.0791
200	0.7164	2651.0	2865.9	7.3131
250	0.7964	2728.9	2967.9	7.5180
300	0.8753	2807.0	3069.6	7.7037
350	0.9536	2885.9	3172.0	7.8750
400	1.0315	2966.0	3275.5	8.0347
450	1.1092	3047.5	3380.3	8.1849
500	1.1867	3130.6	3486.6	8.3271
550	1.2641	3215.3	3594.5	8.4623
600	1.3414	3301.6	3704.0	8.5914
650	1.4186	3389.7	3815.3	8.7153
700	1.4958	3479.5	3928.2	8.8344
750	1.5729	3571.0	4042.9	8.9494
800	1.6500	3664.3	4159.3	9.0604
850	1.7271	3759.3	4277.4	9.1680
900	1.8042	3856.0	4397.3	9.2724
950	1.8812	3954.4	4518.8	9.3739
1000	1.9582	4054.5	4642.0	9.4726
1050	2.0352	4156.2	4766.7	9.5687
1100	2.1122	4259.4	4893.1	9.6624
1150	2.1892	4364.1	5020.9	9.7538
1200	2.2662	4470.3	5150.2	9.8431
1250	2.3432	4577.9	5280.9	9.9303
1300	2.4202	4686.9	5412.9	10.0156

$P = 0.40$MPa (143.6)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
143.6	0.4624	2553.1	2738.1	6.8955
150	0.4709	2564.4	2752.8	6.9306
200	0.5343	2647.2	2860.9	7.1723
250	0.5952	2726.4	2964.5	7.3804
300	0.6549	2805.1	3067.1	7.5677
350	0.7140	2884.4	3170.0	7.7399
400	0.7726	2964.9	3273.9	7.9002
450	0.8311	3046.6	3379.0	8.0508
500	0.8894	3129.8	3485.5	8.1933
550	0.9475	3214.6	3593.6	8.3287
600	1.0056	3301.0	3703.2	8.4580
650	1.0636	3389.1	3814.6	8.5820
700	1.1215	3479.0	3927.6	8.7012
750	1.1794	3570.6	4042.4	8.8162
800	1.2373	3663.9	4158.8	8.9273
850	1.2951	3759.0	4277.0	9.0350
900	1.3530	3855.7	4396.9	9.1394
950	1.4108	3954.2	4518.5	9.2409
1000	1.4686	4054.3	4641.7	9.3396
1050	1.5264	4155.9	4766.5	9.4357
1100	1.5841	4259.2	4892.8	9.5295
1150	1.6419	4363.9	5020.7	9.6209
1200	1.6997	4470.1	5150.0	9.7102
1250	1.7574	4577.8	5280.7	9.7975
1300	1.8152	4686.7	5412.8	9.8828

$P = 0.50$MPa (151.8)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
151.8	0.3748	2560.7	2748.1	6.8207
200	0.4250	2643.3	2855.8	7.0610
250	0.4744	2723.8	2961.0	7.2724
300	0.5226	2803.2	3064.6	7.4614
350	0.5702	2883.0	3168.1	7.6346
400	0.6173	2963.7	3272.3	7.7955
450	0.6642	3045.6	3377.7	7.9465
500	0.7109	3129.0	3484.5	8.0892
550	0.7576	3213.9	3592.7	8.2249
600	0.8041	3300.4	3702.5	8.3543
650	0.8505	3388.6	3813.9	8.4784
700	0.8970	3478.5	3927.0	8.5977
750	0.9433	3570.2	4041.8	8.7128
800	0.9897	3663.6	4158.4	8.8240
850	1.0360	3758.6	4276.6	8.9317

$P = 0.60$MPa (158.8)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
158.8	0.3156	2566.8	2756.1	6.7593
200	0.3521	2639.3	2850.6	6.9683
250	0.3939	2721.2	2957.6	7.1832
300	0.4344	2801.4	3062.0	7.3740
350	0.4743	2881.6	3166.1	7.5481
400	0.5137	2962.5	3270.8	7.7097
450	0.5530	3044.7	3376.5	7.8611
500	0.5920	3128.2	3483.4	8.0041
550	0.6309	3213.2	3591.8	8.1399
600	0.6698	3299.8	3701.7	8.2695
650	0.7085	3388.1	3813.2	8.3937
700	0.7472	3478.1	3926.4	8.5131
750	0.7859	3569.8	4041.3	8.6283
800	0.8246	3663.2	4157.9	8.7395
850	0.8632	3758.3	4276.2	8.8472

$P = 0.80$MPa (170.4)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
170.4	0.2403	2576.0	2768.3	6.6616
200	0.2609	2631.0	2839.7	6.8176
250	0.2932	2715.9	2950.4	7.0401
300	0.3242	2797.5	3056.9	7.2345
350	0.3544	2878.6	3162.2	7.4106
400	0.3843	2960.2	3267.6	7.5734
450	0.4139	3042.8	3373.9	7.7257
500	0.4433	3126.6	3481.3	7.8692
550	0.4726	3211.9	3590.0	8.0054
600	0.5019	3298.7	3700.1	8.1354
650	0.5310	3387.1	3811.9	8.2598
700	0.5601	3477.2	3925.3	8.3794
750	0.5892	3569.0	4040.3	8.4947
800	0.6182	3662.4	4157.0	8.6061
850	0.6472	3757.6	4275.4	8.7139

900	1.0821	3855.1	4396.6	9.0367
950	1.1285	3953.9	4518.2	9.1377
1000	1.1748	4054.0	4641.4	9.2361
1050	1.2210	4155.7	4766.2	9.3326
1100	1.2674	4259.0	4892.6	9.4263
1150	1.3135	4363.7	5020.5	9.5178
1200	1.3597	4470.0	5149.8	9.6071
1250	1.4059	4577.6	5280.5	9.6944
1300	1.4521	4686.6	5412.6	9.7797

$P = 1.00$MPa (179.9)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
179.9	0.1944	2582.8	2777.1	6.5850
200	0.2060	2622.2	2828.3	6.6955
250	0.2327	2710.4	2943.1	6.9265
300	0.2580	2793.6	3051.6	7.1246
350	0.2825	2875.7	3158.2	7.3029
400	0.3066	2957.9	3264.5	7.4669
450	0.3304	3040.9	3371.3	7.6200
500	0.3541	3125.0	3479.1	7.7641
550	0.3777	3210.5	3588.1	7.9008
600	0.4011	3297.5	3698.6	8.0310
650	0.4245	3386.0	3810.5	8.1557
700	0.4478	3476.2	3924.1	8.2755
750	0.4711	3568.1	4039.3	8.3909
800	0.4944	3661.7	4156.1	8.5024
850	0.5176	3757.0	4274.6	8.6103
900	0.5408	3853.9	4394.8	8.7150
950	0.5640	3952.5	4516.5	8.8166
1000	0.5872	4052.7	4639.9	8.9155
1050	0.6104	4154.5	4764.9	9.0118
1100	0.6335	4257.9	4891.4	9.1056
1150	0.6567	4362.7	5019.4	9.1972
1200	0.6798	4469.0	5148.9	9.2866
1250	0.7030	4576.7	5279.7	9.3739
1300	0.7261	4685.8	5411.9	9.4593

$P = 1.60$MPa (201.4)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
201.4	0.1237	2594.8	2792.8	6.4199
250	0.1419	2692.9	2919.9	6.6753
300	0.1587	2781.6	3035.4	6.8863
350	0.1746	2866.6	3146.0	7.0713
400	0.1901	2950.7	3254.9	7.2394
450	0.2053	3035.0	3363.5	7.3950
500	0.2203	3120.1	3472.6	7.5409
550	0.2352	3206.3	3582.6	7.6788

900	0.9018	3855.1	4396.2	8.9518
950	0.9404	3953.6	4517.6	9.0533
1000	0.9789	4053.7	4641.1	9.1521
1050	1.0175	4155.5	4766.0	9.2487
1100	1.0560	4258.7	4892.4	9.3420
1150	1.0946	4363.5	5020.3	9.4335
1200	1.1331	4469.8	5149.6	9.5228
1250	1.1716	4577.4	5280.4	9.6101
1300	1.2101	4686.4	5412.5	9.6954

$P = 1.20$MPa (188.0)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
188.0	0.1633	2587.8	2783.7	6.5217
200	0.1693	2612.9	2816.1	6.5909
250	0.1924	2704.7	2935.6	6.8313
300	0.2139	2789.7	3046.3	7.0335
350	0.2346	2872.7	3154.2	7.2139
400	0.2548	2955.5	3261.3	7.3793
450	0.2748	3038.9	3368.7	7.5332
500	0.2946	3123.4	3476.9	7.6779
550	0.3143	3209.1	3586.3	7.8150
600	0.3339	3296.3	3697.0	7.9455
650	0.3535	3385.0	3809.2	8.0701
700	0.3730	3475.3	3922.9	8.1904
750	0.3924	3567.3	4038.2	8.3064
800	0.4118	3661.0	4155.2	8.4176
850	0.4312	3756.3	4273.8	8.5256
900	0.4506	3853.3	4394.0	8.6303
950	0.4699	3952.0	4515.9	8.7320
1000	0.4893	4052.2	4639.4	8.8310
1050	0.5086	4154.1	4764.4	8.9273
1100	0.5279	4257.5	4891.0	9.0212
1150	0.5472	4362.3	5019.0	9.1128
1200	0.5665	4468.7	5148.5	9.2022
1250	0.5858	4576.4	5279.3	9.2895
1300	0.6051	4685.4	5411.5	9.3749

$P = 1.80$MPa (207.1)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
207.1	0.1104	2597.2	2795.9	6.3775
250	0.1250	2686.7	2911.7	6.6087
300	0.1402	2777.4	3029.9	6.8246
350	0.1546	2863.6	3141.8	7.0120
400	0.1685	2948.3	3251.6	7.1814
450	0.1821	3033.1	3360.9	7.3380
500	0.1955	3118.5	3470.4	7.4845
550	0.2088	3205.0	3580.8	7.6228

900	0.6762	3854.5	4395.5	8.8191
950	0.7052	3953.3	4517.2	8.9205
1000	0.7341	4053.2	4640.5	9.0193
1050	0.7630	4155.0	4765.4	9.1153
1100	0.7920	4258.3	4891.9	9.2093
1150	0.8209	4363.1	5019.8	9.3008
1200	0.8498	4469.4	5149.2	9.3902
1250	0.8787	4577.0	5280.0	9.4775
1300	0.9076	4686.1	5412.2	9.5625

$P = 1.40$MPa (195.0)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
195.0	0.1408	2591.8	2788.9	6.4675
200	0.1430	2602.7	2803.0	6.4975
250	0.1636	2698.9	2927.9	6.7488
300	0.1823	2785.7	3040.9	6.9552
350	0.2003	2869.7	3150.1	7.1379
400	0.2178	2953.1	3258.1	7.3046
450	0.2351	3037.0	3366.1	7.4598
500	0.2522	3121.8	3474.8	7.6047
550	0.2691	3207.7	3584.5	7.7422
600	0.2860	3295.1	3695.4	7.8730
650	0.3028	3384.0	3807.8	7.9982
700	0.3195	3474.4	3921.7	8.1183
750	0.3362	3566.5	4037.2	8.2340
800	0.3529	3660.2	4154.3	8.3457
850	0.3695	3755.6	4273.0	8.4538
900	0.3861	3852.7	4393.3	8.5567
950	0.4027	3951.4	4515.2	8.6604
1000	0.4193	4051.7	4638.8	8.7594
1050	0.4359	4153.6	4763.9	8.8558
1100	0.4525	4257.0	4890.5	8.9497
1150	0.4690	4361.9	5018.6	9.0413
1200	0.4856	4468.3	5148.1	9.1308
1250	0.5021	4576.0	5279.0	9.2182
1300	0.5187	4685.1	5411.2	9.3036

$P = 2.00$MPa (212.4)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
212.4	0.0996	2599.1	2798.3	6.3390
250	0.1115	2680.2	2903.2	6.5475
300	0.1255	2773.2	3024.2	6.7684
350	0.1386	2860.5	3137.7	6.9583
400	0.1512	2945.9	3248.3	7.1292
450	0.1635	3031.1	3358.2	7.2866
500	0.1757	3116.9	3468.2	7.4337
550	0.1877	3203.6	3579.0	7.5725

600	0.2500	3293.9	3693.9	7.8100
650	0.2647	3382.9	3806.5	7.9354
700	0.2794	3473.5	3920.5	8.0557
750	0.2940	3565.7	4036.1	8.1716
800	0.3087	3659.5	4153.3	8.2834
850	0.3232	3755.0	4272.2	8.3916
900	0.3378	3852.1	4392.6	8.4965
950	0.3523	3950.9	4514.6	8.5984
1000	0.3669	4051.2	4638.2	8.6974
1050	0.3814	4153.1	4763.4	8.7938
1100	0.3959	4256.6	4890.0	8.8878
1150	0.4104	4361.5	5018.2	8.9794
1200	0.4249	4467.9	5147.7	9.0689
1250	0.4394	4575.7	5278.7	9.1563
1300	0.4538	4684.8	5410.9	9.2417

P = 2.50MPa (224.0)

T(°C)	*V*(m³/kg)	*U*(kJ/kg)	*H*(kJ/kg)	*S*(kJ/kg-K)
224.0	0.0799	2602.1	2801.9	6.2558
250	0.0871	2663.3	2880.9	6.4107
300	0.0989	2762.2	3009.6	6.6459
350	0.1098	2852.5	3127.0	6.8424
400	0.1201	2939.8	3240.1	7.0170
450	0.1302	3026.2	3351.6	7.1767
500	0.1400	3112.8	3462.7	7.3254
550	0.1497	3200.1	3574.3	7.4653
600	0.1593	3288.5	3686.8	7.5979
650	0.1689	3378.2	3800.4	7.7243
700	0.1783	3469.3	3915.2	7.8455
750	0.1878	3562.0	4031.5	7.9620
800	0.1972	3656.2	4149.2	8.0743
850	0.2066	3752.0	4268.5	8.1830
900	0.2160	3849.4	4389.3	8.2882
950	0.2253	3948.4	4511.7	8.3904
1000	0.2347	4048.9	4635.6	8.4896
1050	0.2440	4151.0	4761.0	8.5863
1100	0.2533	4254.7	4887.9	8.6804
1150	0.2626	4359.7	5016.2	8.7722
1200	0.2719	4466.2	5146.0	8.8618
1250	0.2812	4574.1	5277.1	8.9493
1300	0.2905	4683.3	5409.5	9.0349

600	0.2220	3292.7	3692.3	7.7543
650	0.2351	3381.9	3805.1	7.8799
700	0.2482	3472.6	3919.4	8.0004
750	0.2613	3564.9	4035.1	8.1164
800	0.2743	3658.8	4152.4	8.2284
850	0.2872	3754.3	4271.3	8.3367
900	0.3002	3851.5	4391.9	8.4416
950	0.3131	3950.3	4514.0	8.5435
1000	0.3261	4050.7	4637.6	8.6426
1050	0.3390	4152.7	4762.8	8.7391
1100	0.3519	4256.2	4889.5	8.8331
1150	0.3648	4361.1	5017.7	8.9248
1200	0.3777	4467.5	5147.3	9.0143
1250	0.3905	4575.3	5278.3	9.1017
1300	0.4034	4684.5	5410.6	9.1872

P = 3.00MPa (233.9)

T(°C)	*V*(m³/kg)	*U*(kJ/kg)	*H*(kJ/kg)	*S*(kJ/kg-K)
233.9	0.0667	2603.2	2803.2	6.1856
250	0.0706	2644.7	2856.5	6.2893
300	0.0812	2750.8	2994.3	6.5412
350	0.0906	2844.4	3116.1	6.7449
400	0.0994	2933.5	3231.7	6.9234
450	0.1079	3021.2	3344.8	7.0856
500	0.1162	3108.6	3457.2	7.2359
550	0.1244	3196.6	3569.7	7.3768
600	0.1324	3285.5	3682.8	7.5103
650	0.1405	3375.6	3796.9	7.6373
700	0.1484	3467.0	3912.2	7.7590
750	0.1563	3559.9	4028.9	7.8758
800	0.1642	3654.3	4146.9	7.9885
850	0.1720	3750.3	4266.5	8.0973
900	0.1799	3847.9	4387.5	8.2028
950	0.1877	3947.0	4510.1	8.3051
1000	0.1955	4047.7	4634.1	8.4045
1050	0.2033	4149.9	4759.7	8.5012
1100	0.2111	4253.6	4886.7	8.5955
1150	0.2188	4358.7	5015.2	8.6874
1200	0.2266	4465.3	5145.0	8.7770
1250	0.2343	4573.3	5276.2	8.8646
1300	0.2421	4682.5	5408.8	8.9502

600	0.1996	3291.5	3690.7	7.7043
650	0.2115	3380.8	3803.8	7.8302
700	0.2233	3471.6	3918.2	7.9509
750	0.2350	3564.0	4034.1	8.0670
800	0.2467	3658.0	4151.5	8.1790
850	0.2584	3753.6	4270.5	8.2874
900	0.2701	3850.9	4391.1	8.3925
950	0.2818	3949.8	4513.3	8.4945
1000	0.2934	4050.2	4637.0	8.5936
1050	0.3051	4152.2	4762.3	8.6901
1100	0.3167	4255.7	4889.1	8.7842
1150	0.3283	4360.7	5017.3	8.8759
1200	0.3399	4467.2	5147.0	8.9654
1250	0.3515	4575.0	5278.0	9.0529
1300	0.3631	4684.1	5410.3	9.1384

P = 3.50MPa (242.6)

T(°C)	*V*(m³/kg)	*U*(kJ/kg)	*H*(kJ/kg)	*S*(kJ/kg-K)
242.6	0.0571	2602.9	2802.6	6.1243
250	0.0588	2624.0	2829.7	6.1764
300	0.0685	2738.8	2978.4	6.4484
350	0.0768	2836.0	3104.8	6.6601
400	0.0846	2927.2	3223.2	6.8427
450	0.0920	3016.1	3338.0	7.0074
500	0.0992	3104.5	3451.6	7.1593
550	0.1063	3193.1	3565.0	7.3014
600	0.1133	3282.5	3678.9	7.4356
650	0.1202	3372.9	3793.5	7.5633
700	0.1270	3464.7	3909.3	7.6854
750	0.1338	3557.8	4026.3	7.8027
800	0.1406	3652.5	4144.6	7.9156
850	0.1474	3748.6	4264.4	8.0247
900	0.1541	3846.4	4385.7	8.1303
950	0.1608	3945.6	4508.4	8.2328
1000	0.1675	4046.4	4632.7	8.3324
1050	0.1742	4148.7	4758.4	8.4292
1100	0.1809	4252.5	4885.6	8.5235
1150	0.1875	4357.7	5014.1	8.6155
1200	0.1942	4464.4	5144.1	8.7053
1250	0.2009	4572.4	5275.4	8.7929
1300	0.2075	4681.7	5408.0	8.8785

P = 4.00MPa (250.4)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
250.4	0.0498	2601.7	2800.8	6.0696
300	0.0588	2725.2	2961.7	6.3630
350	0.0665	2827.4	3093.3	6.5843
400	0.0734	2920.7	3214.5	6.7714
450	0.0800	3011.0	3331.2	6.9386
500	0.0864	3100.3	3446.0	7.0922
550	0.0927	3189.5	3560.3	7.2355
600	0.0989	3279.4	3674.9	7.3705
650	0.1049	3370.3	3790.1	7.4988
700	0.1110	3462.4	3906.3	7.6214
750	0.1170	3555.8	4023.6	7.7390
800	0.1229	3650.6	4142.3	7.8523
850	0.1289	3747.0	4262.4	7.9616
900	0.1348	3844.8	4383.9	8.0674
950	0.1406	3944.2	4506.8	8.1701
1000	0.1465	4045.1	4631.2	8.2697
1050	0.1524	4147.5	4757.1	8.3667
1100	0.1582	4251.4	4884.4	8.4611
1150	0.1641	4356.7	5013.1	8.5532
1200	0.1699	4463.5	5143.1	8.6430
1250	0.1757	4571.5	5274.5	8.7307
1300	0.1816	4680.9	5407.2	8.8164

P = 4.50MPa (257.4)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
257.4	0.0441	2599.7	2798.0	6.0197
300	0.0514	2713.0	2944.2	6.2854
350	0.0584	2818.6	3081.5	6.5153
400	0.0648	2914.2	3205.6	6.7070
450	0.0708	3005.8	3324.2	6.8770
500	0.0765	3096.0	3440.4	7.0323
550	0.0821	3186.0	3555.6	7.1767
600	0.0877	3276.4	3670.9	7.3127
650	0.0931	3367.7	3786.6	7.4416
700	0.0985	3460.0	3903.3	7.5646
750	0.1038	3553.7	4021.0	7.6826
800	0.1092	3648.8	4140.0	7.7962
850	0.1145	3745.3	4260.3	7.9057
900	0.1197	3843.3	4382.1	8.0118
950	0.1250	3942.8	4505.2	8.1146
1000	0.1302	4043.9	4629.8	8.2144
1050	0.1354	4146.4	4755.8	8.3115
1100	0.1406	4250.4	4883.2	8.4060
1150	0.1458	4355.8	5012.0	8.4981
1200	0.1510	4462.5	5142.2	8.5880
1250	0.1562	4570.7	5273.7	8.6758
1300	0.1614	4680.1	5406.4	8.7615

P = 5.00MPa (263.9)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
263.9	0.0394	2597.0	2794.2	5.9737
300	0.0453	2699.0	2925.7	6.2110
350	0.0520	2809.5	3069.3	6.4516
400	0.0578	2907.5	3196.7	6.6483
450	0.0633	3000.6	3317.2	6.8210
500	0.0686	3091.7	3434.7	6.9781
550	0.0737	3182.4	3550.9	7.1237
600	0.0787	3273.3	3666.8	7.2605
650	0.0836	3365.0	3783.2	7.3901
700	0.0885	3457.7	3900.3	7.5136
750	0.0934	3551.6	4018.4	7.6320
800	0.0982	3646.9	4137.7	7.7458
850	0.1029	3743.6	4258.3	7.8556
900	0.1077	3841.8	4380.2	7.9618
950	0.1124	3941.5	4503.6	8.0648
1000	0.1171	4042.6	4628.3	8.1648
1050	0.1219	4145.2	4754.5	8.2620
1100	0.1266	4249.3	4882.0	8.3566
1150	0.1312	4354.8	5011.0	8.4488
1200	0.1359	4461.6	5141.2	8.5388
1250	0.1406	4569.8	5272.8	8.6266
1300	0.1453	4679.3	5405.7	8.7124

P = 6.00MPa (275.6)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
275.6	0.0324	2589.9	2784.6	5.8901
300	0.0362	2668.4	2885.5	6.0703
350	0.0423	2790.4	3043.9	6.3357
400	0.0474	2893.7	3178.2	6.5432
450	0.0522	2989.9	3302.9	6.7219
500	0.0567	3083.1	3423.1	6.8826
550	0.0610	3175.2	3541.3	7.0307
600	0.0653	3267.2	3658.7	7.1693
650	0.0694	3359.6	3776.2	7.3001
700	0.0735	3453.0	3894.3	7.4246
750	0.0776	3547.5	4013.2	7.5438
800	0.0816	3643.2	4133.1	7.6582
850	0.0857	3740.3	4254.2	7.7685
900	0.0896	3838.8	4376.6	7.8751
950	0.0936	3938.7	4500.3	7.9784
1000	0.0976	4040.1	4625.4	8.0786
1050	0.1015	4142.9	4751.9	8.1760
1100	0.1054	4247.1	4879.7	8.2709
1150	0.1093	4352.8	5008.9	8.3632
1200	0.1133	4459.8	5139.3	8.4534
1250	0.1172	4568.1	5271.3	8.5413
1300	0.1211	4677.7	5404.1	8.6272

P = 7.00MPa (285.8)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
285.8	0.0274	2581.0	2772.6	5.8148
300	0.0295	2633.5	2839.9	5.9337
350	0.0353	2770.1	3016.9	6.2304
400	0.0400	2879.5	3159.2	6.4502
450	0.0442	2979.0	3288.3	6.6353
500	0.0482	3074.3	3411.4	6.8000
550	0.0520	3167.9	3531.6	6.9506
600	0.0557	3260.9	3650.6	7.0910
650	0.0593	3354.3	3769.3	7.2231
700	0.0629	3448.3	3888.2	7.3486
750	0.0664	3543.3	4007.9	7.4685
800	0.0699	3639.5	4128.4	7.5836
850	0.0733	3736.9	4250.1	7.6944
900	0.0768	3835.7	4373.0	7.8014
950	0.0802	3935.9	4497.1	7.9050
1000	0.0836	4037.5	4622.5	8.0055
1050	0.0870	4140.5	4749.3	8.1031
1100	0.0903	4245.0	4877.3	8.1983
1150	0.0937	4350.8	5006.7	8.2907
1200	0.0971	4457.9	5137.4	8.3810
1250	0.1004	4566.4	5269.4	8.4690
1300	0.1038	4676.1	5402.6	8.5551

P = 8.00MPa (295.0)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
295.0	0.0235	2570.5	2758.7	5.7450
300	0.0243	2592.3	2786.5	5.7937
350	0.0300	2748.3	2988.1	6.1321
400	0.0343	2864.6	3139.4	6.3658
450	0.0382	2967.8	3273.3	6.5579
500	0.0418	3065.4	3399.5	6.7266
550	0.0452	3160.5	3521.8	6.8799
600	0.0485	3254.7	3642.4	7.0221
650	0.0517	3348.9	3762.3	7.1556
700	0.0548	3443.6	3882.2	7.2821
750	0.0579	3539.1	4002.6	7.4028
800	0.0610	3635.7	4123.8	7.5184
850	0.0641	3733.5	4246.0	7.6297
900	0.0671	3832.6	4369.3	7.7371
950	0.0701	3933.1	4493.8	7.8411
1000	0.0731	4035.0	4619.6	7.9419
1050	0.0761	4138.2	4746.7	8.0397
1100	0.0790	4242.8	4875.0	8.1350
1150	0.0820	4348.8	5004.6	8.2277
1200	0.0849	4456.1	5135.5	8.3181
1250	0.0879	4564.6	5267.7	8.4063
1300	0.0908	4674.5	5401.0	8.4924

$P = 9.00$ MPa (303.4)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
303.4	0.0205	2558.5	2742.9	5.6791
350	0.0258	2724.9	2957.3	6.0380
400	0.0300	2849.2	3118.8	6.2876
450	0.0335	2956.3	3258.0	6.4872
500	0.0368	3056.3	3387.4	6.6603
550	0.0399	3153.0	3512.0	6.8164
600	0.0429	3248.4	3634.1	6.9605
650	0.0458	3343.4	3755.2	7.0953
700	0.0486	3438.8	3876.1	7.2229
750	0.0514	3534.9	3997.3	7.3443
800	0.0541	3632.0	4119.1	7.4606
850	0.0569	3730.2	4241.9	7.5724
900	0.0596	3829.6	4365.7	7.6802
950	0.0622	3930.3	4490.6	7.7844
1000	0.0649	4032.4	4616.7	7.8855
1050	0.0676	4135.9	4744.0	7.9836
1100	0.0702	4240.6	4872.7	8.0790
1150	0.0729	4346.8	5002.5	8.1719
1200	0.0755	4454.2	5133.6	8.2625
1250	0.0781	4562.9	5266.0	8.3508
1300	0.0807	4672.9	5399.5	8.4370

$P = 10.00$ MPa (311.0)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
311.0	0.0180	2545.2	2725.5	5.6160
350	0.0224	2699.6	2924.0	5.9459
400	0.0264	2833.1	3097.4	6.2141
450	0.0298	2944.5	3242.3	6.4219
500	0.0328	3047.0	3375.1	6.5995
550	0.0357	3145.4	3502.0	6.7585
600	0.0384	3242.0	3625.8	6.9045
650	0.0410	3337.9	3748.1	7.0408
700	0.0436	3434.0	3870.0	7.1693
750	0.0461	3530.7	3992.0	7.2916
800	0.0486	3628.2	4114.5	7.4085
850	0.0511	3726.8	4237.8	7.5207
900	0.0535	3826.5	4362.0	7.6290
950	0.0560	3927.5	4487.3	7.7335
1000	0.0584	4029.9	4613.8	7.8349
1050	0.0608	4133.5	4741.4	7.9332
1100	0.0632	4238.5	4870.3	8.0288
1150	0.0656	4344.8	5000.4	8.1219
1200	0.0679	4452.3	5131.7	8.2126
1250	0.0703	4561.2	5264.2	8.3010
1300	0.0727	4671.3	5397.9	8.3874

$P = 12.50$ MPa (327.8)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
327.8	0.0135	2505.61	2674.31	5.4628
350	0.0161	2624.8	2826.6	5.7130
400	0.0200	2789.6	3040.0	6.0433
450	0.0230	2913.7	3201.4	6.2749
500	0.0256	3023.2	3343.6	6.4659
550	0.0280	3126.1	3476.5	6.6317
600	0.0303	3225.8	3604.6	6.7828
650	0.0325	3324.1	3730.2	6.9227
700	0.0346	3422.0	3854.6	7.0539
750	0.0367	3520.1	3978.6	7.1782
800	0.0387	3618.7	4102.8	7.2967
850	0.0407	3718.3	4227.5	7.4102
900	0.0427	3818.9	4352.9	7.5194
950	0.0447	3920.6	4479.2	7.6249
1000	0.0466	4023.5	4606.5	7.7269
1050	0.0486	4127.7	4734.9	7.8258
1100	0.0505	4233.1	4864.5	7.9219
1150	0.0524	4339.8	4995.1	8.0154
1200	0.0543	4447.7	5127.0	8.1065
1250	0.0562	4556.9	5260.0	8.1952
1300	0.0581	4667.3	5394.1	8.2819

$P = 15.00$ MPa (342.2)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
342.2	0.0103	2455.6	2610.7	5.3106
350	0.0115	2520.9	2693.1	5.4437
400	0.0157	2740.6	2975.7	5.8819
450	0.0185	2880.7	3157.9	6.1434
500	0.0208	2998.4	3310.8	6.3480
550	0.0229	3106.2	3450.4	6.5230
600	0.0249	3209.3	3583.1	6.6796
650	0.0268	3310.1	3712.1	6.8233
700	0.0286	3409.8	3839.1	6.9572
750	0.0304	3509.4	3965.2	7.0836
800	0.0321	3609.2	4091.1	7.2037
850	0.0338	3709.8	4217.1	7.3185
900	0.0355	3811.2	4343.7	7.4288
950	0.0372	3913.6	4471.0	7.5350
1000	0.0388	4017.1	4599.2	7.6378
1050	0.0404	4121.8	4728.4	7.7373
1100	0.0421	4227.7	4858.6	7.8339
1150	0.0437	4334.8	4989.9	7.9278
1200	0.0453	4443.1	5122.1	8.0192
1250	0.0469	4552.6	5255.7	8.1081
1300	0.0485	4663.2	5390.3	8.1952

$P = 17.50$ MPa (354.7)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
354.7	0.0079	2390.5	2529.3	5.1431
400	0.0125	2684.3	2902.4	5.7211
450	0.0152	2845.4	3111.4	6.0212
500	0.0174	2972.4	3276.7	6.2424
550	0.0193	3085.8	3423.6	6.4266
600	0.0211	3192.5	3561.3	6.5890
650	0.0227	3295.8	3693.8	6.7366
700	0.0243	3397.5	3823.5	6.8734
750	0.0259	3498.6	3951.7	7.0019
800	0.0274	3599.7	4079.3	7.1236
850	0.0289	3701.2	4206.8	7.2398
900	0.0303	3803.4	4334.5	7.3511
950	0.0318	3906.6	4462.9	7.4582
1000	0.0332	4010.7	4592.0	7.5616
1050	0.0346	4115.9	4721.9	7.6617
1100	0.0360	4222.3	4852.8	7.7588
1150	0.0374	4329.8	4984.6	7.8531
1200	0.0388	4438.4	5117.5	7.9449
1250	0.0402	4548.3	5251.5	8.0343
1300	0.0416	4659.2	5386.4	8.1215

$P = 20.00$ MPa (365.8)

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
365.8	0.0059	2295.0	2412.4	4.9315
400	0.0100	2617.9	2816.9	5.5525
450	0.0127	2807.2	3061.7	5.9043
500	0.0148	2945.3	3241.2	6.1446
550	0.0166	3064.7	3396.1	6.3389
600	0.0182	3175.3	3539.0	6.5075
650	0.0197	3281.4	3675.3	6.6593
700	0.0211	3385.1	3807.8	6.7990
750	0.0225	3487.7	3938.1	6.9297
800	0.0239	3590.1	4067.5	7.0531
850	0.0252	3692.6	4196.4	7.1705
900	0.0265	3795.7	4325.4	7.2829
950	0.0278	3899.5	4454.7	7.3909
1000	0.0290	4004.3	4584.7	7.4950
1050	0.0303	4110.0	4715.4	7.5957
1100	0.0315	4216.9	4846.9	7.6933
1150	0.0327	4324.8	4979.4	7.7880
1200	0.0340	4433.8	5112.8	7.8802
1250	0.0352	4544.0	5247.2	7.9699
1300	0.0364	4655.2	5382.6	8.0574

$P = 25.00$MPa

T(°C)	$V(\mathrm{m}^3/\mathrm{kg})$	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
400	0.0060	2428.5	2578.7	5.1400
450	0.0092	2721.2	2950.6	5.6759
500	0.0111	2887.3	3165.9	5.9642
550	0.0127	3020.8	3339.2	6.1816
600	0.0141	3140.0	3493.5	6.3637
650	0.0154	3251.9	3637.7	6.5242
700	0.0166	3359.9	3776.0	6.6702
750	0.0178	3465.8	3910.9	6.8054
800	0.0189	3570.7	4043.8	6.9322
850	0.0200	3675.4	4175.6	7.0523
900	0.0211	3780.2	4307.1	7.1668
950	0.0221	3885.5	4438.5	7.2765
1000	0.0232	3991.5	4570.2	7.3820
1050	0.0242	4098.3	4702.5	7.4839
1100	0.0252	4206.0	4835.4	7.5825
1150	0.0262	4314.8	4969.0	7.6781
1200	0.0272	4424.6	5103.5	7.7710
1250	0.0281	4535.4	5238.8	7.8613
1300	0.0291	4647.2	5375.1	7.9493

$P = 30.00$MPa

T(°C)	$V(\mathrm{m}^3/\mathrm{kg})$	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
400	0.0028	2071.9	2156.2	4.4808
450	0.0067	2618.9	2821.0	5.4421
500	0.0087	2824.0	3084.7	5.7956
550	0.0102	2974.5	3279.7	6.0402
600	0.0114	3103.4	3446.7	6.2373
650	0.0126	3221.7	3599.4	6.4074
700	0.0137	3334.3	3743.9	6.5598
750	0.0147	3443.6	3883.4	6.6997
800	0.0156	3551.2	4020.0	6.8300
850	0.0166	3658.0	4154.9	6.9529
900	0.0175	3764.6	4288.8	7.0695
950	0.0184	3871.4	4422.3	7.1810
1000	0.0192	3978.6	4555.8	7.2880
1050	0.0201	4086.5	4689.6	7.3910
1100	0.0210	4195.2	4823.8	7.4906
1150	0.0218	4304.8	4958.7	7.5871
1200	0.0226	4415.3	5094.2	7.6807
1250	0.0235	4526.8	5230.5	7.7716
1300	0.0243	4639.2	5367.6	7.8602

$P = 35.00$MPa

T(°C)	$V(\mathrm{m}^3/\mathrm{kg})$	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
400	0.0021	1914.8	1988.5	4.2142
450	0.0050	2497.5	2671.0	5.1945
500	0.0069	2755.3	2997.9	5.6331
550	0.0083	2925.8	3218.0	5.9092
600	0.0095	3065.6	3398.9	6.1228
650	0.0106	3190.9	3560.7	6.3030
700	0.0115	3308.3	3711.6	6.4622
750	0.0124	3421.2	3855.9	6.6069
800	0.0133	3531.5	3996.3	6.7409
850	0.0141	3640.5	4134.2	6.8665
900	0.0149	3748.9	4270.6	6.9853
950	0.0157	3857.2	4406.2	7.0985
1000	0.0165	3965.8	4541.5	7.2069
1050	0.0172	4074.8	4676.8	7.3112
1100	0.0179	4184.4	4812.4	7.4118
1150	0.0187	4294.8	4948.4	7.5091
1200	0.0194	4406.1	5085.0	7.6034
1250	0.0201	4518.2	5222.2	7.6950
1300	0.0208	4631.2	5360.1	7.7841

$P = 40.00$MPa

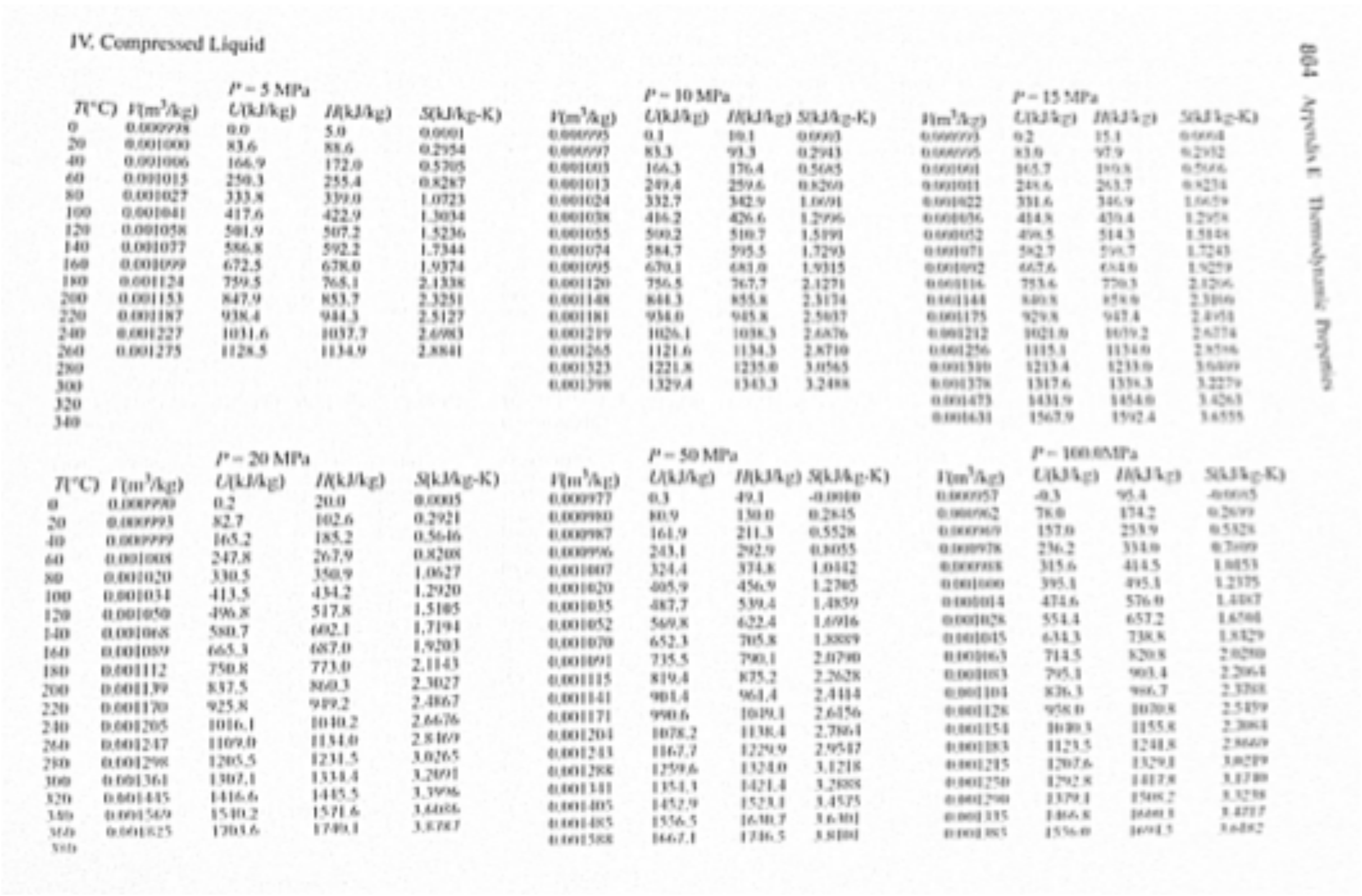
T(°C)	$V(\mathrm{m}^3/\mathrm{kg})$	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
400	0.0019	1854.9	1931.4	4.1145
450	0.0037	2364.2	2511.8	4.9449
500	0.0056	2681.6	2906.5	5.4744
550	0.0070	2875.0	3154.4	5.7857
600	0.0081	3026.8	3350.4	6.0170
650	0.0091	3159.5	3521.6	6.2078
700	0.0099	3282.0	3679.1	6.3740
750	0.0107	3398.6	3828.4	6.5236
800	0.0115	3511.8	3972.6	6.6612
850	0.0123	3623.1	4113.6	6.7896
900	0.0130	3733.3	4252.5	6.9106
950	0.0137	3843.1	4390.2	7.0256
1000	0.0144	3952.9	4527.3	7.1355
1050	0.0150	4063.0	4664.2	7.2409
1100	0.0157	4173.7	4801.1	7.3425
1150	0.0163	4284.9	4938.3	7.4406
1200	0.0170	4396.9	5075.9	7.5357
1250	0.0176	4509.7	5214.1	7.6279
1300	0.0182	4623.3	5352.8	7.7175

$P = 50.00$MPa

T(°C)	$V(\mathrm{m}^3/\mathrm{kg})$	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
400	0.0017	1787.8	1874.4	4.0029
450	0.0025	2160.3	2284.7	4.5896
500	0.0039	2528.1	2722.6	5.1762
550	0.0051	2769.5	3025.3	5.5563
600	0.0061	2947.1	3252.5	5.8245
650	0.0070	3095.6	3443.4	6.0373
700	0.0077	3228.7	3614.6	6.2178
750	0.0084	3353.1	3773.9	6.3775
800	0.0091	3472.2	3925.8	6.5225
850	0.0097	3588.0	4072.9	6.6565
900	0.0103	3702.0	4216.8	6.7819
950	0.0109	3814.9	4358.7	6.9004
1000	0.0114	3927.3	4499.4	7.0131
1050	0.0120	4039.7	4639.3	7.1209
1100	0.0125	4152.2	4778.9	7.2244
1150	0.0131	4265.1	4918.4	7.3242
1200	0.0136	4378.6	5058.1	7.4207
1250	0.0141	4492.7	5198.1	7.5141
1300	0.0146	4607.4	5338.4	7.6048

$P = 60.00$MPa

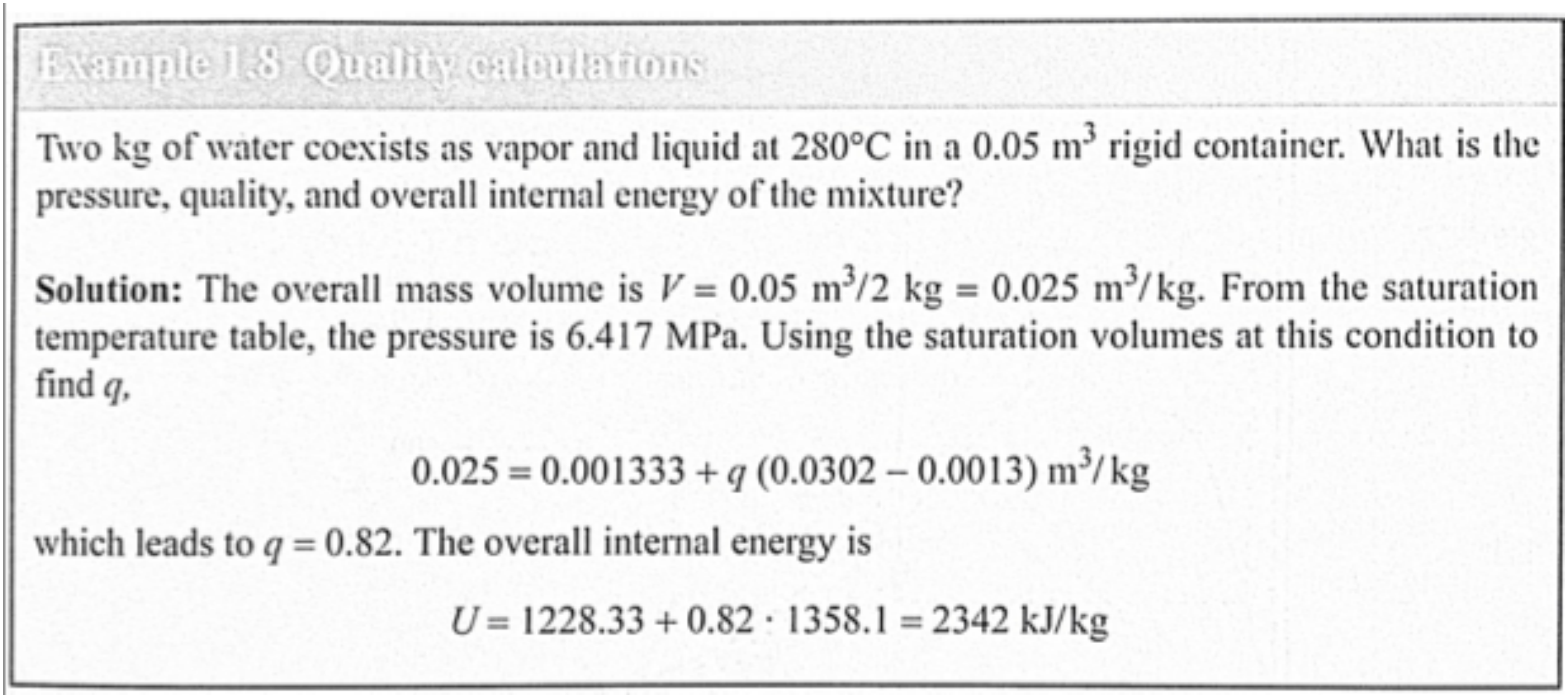
T(°C)	$V(\mathrm{m}^3/\mathrm{kg})$	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
400	0.0016	1745.2	1843.2	3.9317
450	0.0021	2055.1	2180.2	4.4140
500	0.0030	2393.2	2570.3	4.9356
550	0.0040	2645.5	2901.9	5.3517
600	0.0048	2866.8	3156.8	5.6527
650	0.0056	3031.3	3366.7	5.8867
700	0.0063	3175.4	3551.3	6.0814
750	0.0069	3307.6	3720.5	6.2510
800	0.0075	3432.6	3880.0	6.4033
850	0.0080	3553.2	4033.1	6.5428
900	0.0085	3670.9	4182.0	6.6725
950	0.0090	3786.9	4328.1	6.7944
1000	0.0095	3901.9	4472.2	6.9099
1050	0.0100	4016.5	4615.1	7.0200
1100	0.0104	4130.9	4757.3	7.1255
1150	0.0109	4245.5	4899.1	7.2269
1200	0.0113	4360.4	5040.8	7.3248
1250	0.0118	4475.8	5182.5	7.4194
1300	0.0122	4591.8	5324.5	7.5111



IV. Compressed Liquid

	P = 5 MPa				P = 10 MPa				P = 15 MPa			
T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
0	0.000998	0.0	5.0	0.0001	0.000995	0.1	10.1	0.0003	0.000993	0.2	15.1	0.0004
20	0.001000	83.6	88.6	0.2954	0.000997	83.3	93.3	0.2943	0.000995	83.0	97.9	0.2932
40	0.001006	166.9	172.0	0.5705	0.001003	166.3	176.4	0.5685	0.001001	165.7	180.8	0.5666
60	0.001015	250.3	255.4	0.8287	0.001013	249.4	259.6	0.8260	0.001011	248.6	263.7	0.8234
80	0.001027	333.8	339.0	1.0723	0.001024	332.7	342.9	1.0691	0.001022	331.6	346.9	1.0659
100	0.001041	417.6	422.9	1.3034	0.001038	416.2	426.6	1.2996	0.001036	414.8	430.4	1.2958
120	0.001058	501.9	507.2	1.5236	0.001055	500.2	510.7	1.5191	0.001052	498.5	514.3	1.5148
140	0.001077	586.8	592.2	1.7344	0.001074	584.7	595.5	1.7293	0.001071	582.7	598.7	1.7243
160	0.001099	672.5	678.0	1.9374	0.001095	670.1	681.0	1.9315	0.001092	667.6	684.0	1.9259
180	0.001124	759.5	765.1	2.1338	0.001120	756.5	767.7	2.1271	0.001116	753.6	770.3	2.1206
200	0.001153	847.9	853.7	2.3251	0.001148	844.3	855.8	2.3174	0.001144	840.8	858.0	2.3100
220	0.001187	938.4	944.3	2.5127	0.001181	934.0	945.8	2.5037	0.001175	929.8	947.4	2.4951
240	0.001227	1031.6	1037.7	2.6983	0.001219	1026.1	1038.3	2.6876	0.001212	1021.0	1039.2	2.6774
260	0.001275	1128.5	1134.9	2.8841	0.001265	1121.6	1134.3	2.8710	0.001256	1115.1	1134.0	2.8586
280					0.001323	1221.8	1235.0	3.0565	0.001310	1213.4	1233.0	3.0410
300					0.001398	1329.4	1343.3	3.2488	0.001378	1317.6	1338.3	3.2279
320									0.001473	1431.9	1454.0	3.4263
340									0.001631	1567.9	1592.4	3.6555

	P = 20 MPa				P = 50 MPa				P = 100.0MPa			
T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
0	0.000990	0.2	20.0	0.0005	0.000977	0.3	49.1	-0.0010	0.000957	-0.3	95.4	-0.0005
20	0.000993	82.7	102.6	0.2921	0.000980	80.9	130.0	0.2845	0.000962	78.0	174.2	0.2699
40	0.000999	165.2	185.2	0.5646	0.000987	161.9	211.3	0.5528	0.000969	157.0	253.9	0.5328
60	0.001008	247.8	267.9	0.8208	0.000996	243.1	292.9	0.8055	0.000978	236.2	334.0	0.7699
80	0.001020	330.5	350.9	1.0627	0.001007	324.4	374.8	1.0442	0.000988	315.6	414.5	1.0053
100	0.001034	413.5	434.2	1.2920	0.001020	405.9	456.9	1.2705	0.001000	395.1	495.1	1.2375
120	0.001050	496.8	517.8	1.5105	0.001035	487.7	539.4	1.4859	0.001014	474.6	576.0	1.4467
140	0.001068	580.7	602.1	1.7194	0.001052	569.8	622.4	1.6916	0.001028	554.4	657.2	1.6508
160	0.001089	665.3	687.0	1.9203	0.001070	652.3	705.8	1.8889	0.001045	634.3	738.8	1.8529
180	0.001112	750.8	773.0	2.1143	0.001091	735.5	790.1	2.0790	0.001063	714.5	820.8	2.0298
200	0.001139	837.5	860.3	2.3027	0.001115	819.4	875.2	2.2628	0.001083	795.1	903.4	2.2064
220	0.001170	925.8	949.2	2.4867	0.001141	904.4	961.4	2.4414	0.001104	876.3	986.7	2.3768
240	0.001205	1016.1	1040.2	2.6676	0.001171	990.6	1049.1	2.6156	0.001126	958.0	1070.8	2.5459
260	0.001247	1109.0	1134.0	2.8469	0.001204	1078.2	1138.4	2.7864	0.001154	1040.3	1155.8	2.7064
280	0.001298	1205.5	1231.5	3.0265	0.001243	1167.7	1229.9	2.9547	0.001183	1123.5	1241.8	2.8669
300	0.001361	1307.1	1334.4	3.2091	0.001288	1259.6	1324.0	3.1218	0.001215	1207.6	1329.1	3.0259
320	0.001445	1416.6	1445.5	3.3996	0.001341	1354.3	1421.4	3.2888	0.001250	1292.8	1417.8	3.1780
340	0.001569	1540.2	1571.6	3.6086	0.001405	1452.9	1523.1	3.4575	0.001290	1379.1	1508.2	3.3258
360	0.001825	1703.6	1740.1	3.8787	0.001485	1556.5	1630.7	3.6301	0.001335	1466.8	1600.1	3.4717
380					0.001588	1667.1	1746.5	3.8101	0.001385	1556.0	1694.5	3.6182



Example 1.8 Quality calculations

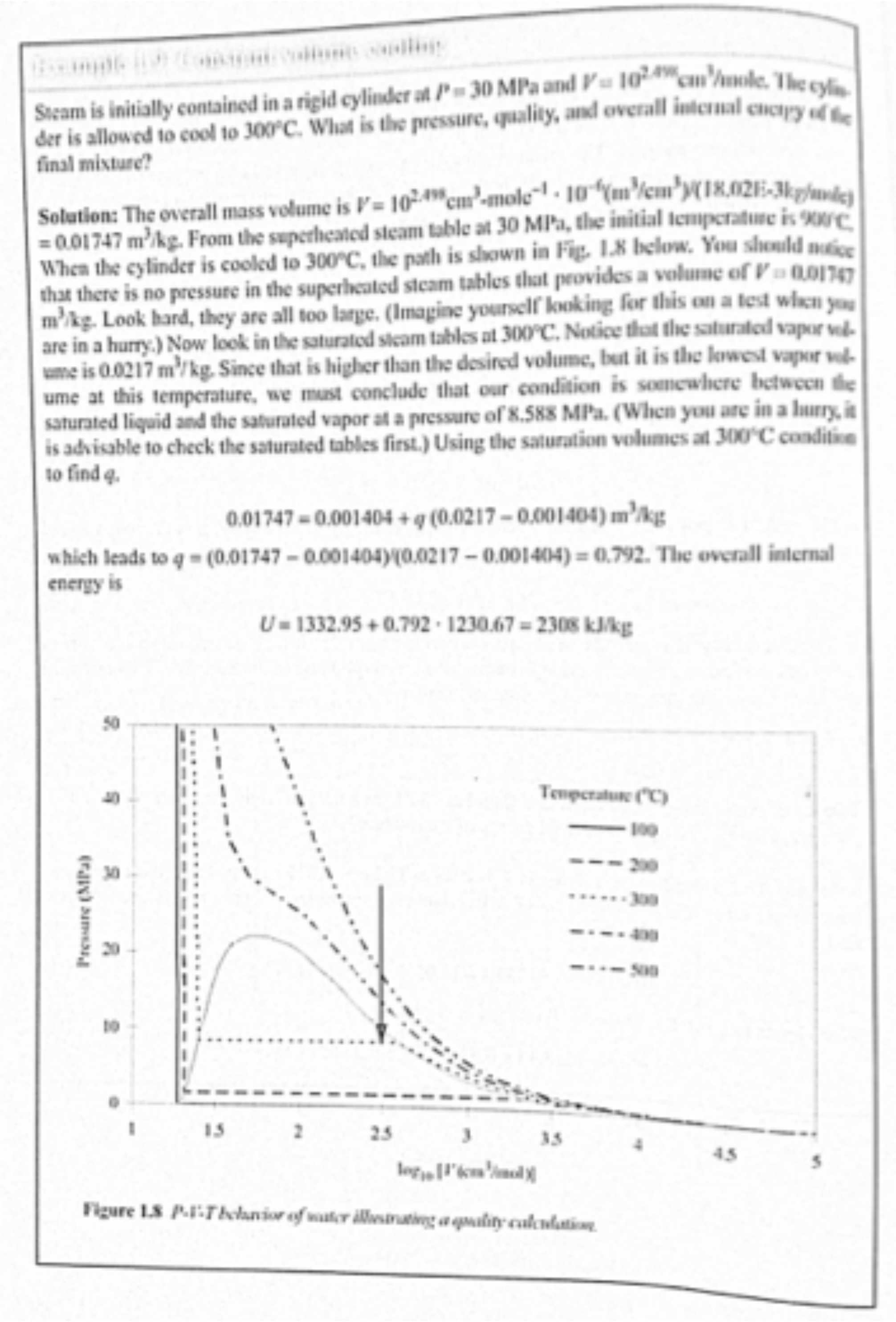
Two kg of water coexists as vapor and liquid at 280°C in a 0.05 m^3 rigid container. What is the pressure, quality, and overall internal energy of the mixture?

Solution: The overall mass volume is $V = 0.05\ m^3/2\ kg = 0.025\ m^3/kg$. From the saturation temperature table, the pressure is 6.417 MPa. Using the saturation volumes at this condition to find q,

$$0.025 = 0.001333 + q\,(0.0302 - 0.0013)\ m^3/kg$$

which leads to $q = 0.82$. The overall internal energy is

$$U = 1228.33 + 0.82 \cdot 1358.1 = 2342\ kJ/kg$$



Example 1.9 Constant volume cooling

Steam is initially contained in a rigid cylinder at $P = 30$ MPa and $V = 10^{2.498}$ cm^3/mole. The cylinder is allowed to cool to 300°C. What is the pressure, quality, and overall internal energy of the final mixture?

Solution: The overall mass volume is $V = 10^{2.498}\text{cm}^3\text{-mole}^{-1} \cdot 10^{-6}(\text{m}^3/\text{cm}^3)/(18.02\text{E-3kg/mole}) = 0.01747\ \text{m}^3/\text{kg}$. From the superheated steam table at 30 MPa, the initial temperature is 900°C. When the cylinder is cooled to 300°C, the path is shown in Fig. 1.8 below. You should notice that there is no pressure in the superheated steam tables that provides a volume of $V = 0.01747$ m^3/kg. Look hard, they are all too large. (Imagine yourself looking for this on a test when you are in a hurry.) Now look in the saturated steam tables at 300°C. Notice that the saturated vapor volume is 0.0217 m^3/kg. Since that is higher than the desired volume, but it is the lowest vapor volume at this temperature, we must conclude that our condition is somewhere between the saturated liquid and the saturated vapor at a pressure of 8.588 MPa. (When you are in a hurry, it is advisable to check the saturated tables first.) Using the saturation volumes at 300°C condition to find q.

$$0.01747 = 0.001404 + q\,(0.0217 - 0.001404)\ \text{m}^3/\text{kg}$$

which leads to $q = (0.01747 - 0.001404)/(0.0217 - 0.001404) = 0.792$. The overall internal energy is

$$U = 1332.95 + 0.792 \cdot 1230.67 = 2308\ \text{kJ/kg}$$

Figure 1.8 *P-V-T behavior of water illustrating a quality calculation.*

boil, but real fluids can. This interplay between kinetic energy, temperature, and potential energy pervades many discussions throughout the text.

Finally, we can write a generic equation that symbolizes the procedure for interpolation:

$$M = M_1 + \frac{x - x_1}{x_2 - x_1}(M_2 - M_1) \tag{1.30}$$

A similar equation is used for quality calculations which can be viewed as an interpolation between saturated liquid and saturated vapor. Throughout Unit I, we refer extensively to the steam tables and interpolation to account for deviations from the ideal gas law.

Test Yourself

1. Draw a sketch of the force model implied by the square-well potential, indicating the position(s) where the force between two atoms is zero and the positions where it is nonzero.
2. Explain in words how the pressure of a fluid against the walls of its container is related to the velocity of the molecules.
3. What is it about molecules that requires us to add heat to convert liquids to gases?
4. If the kinetic energy of pure liquid and vapor molecules at phase equilibrium must be the same, and the internal energy of a system is the sum of the kinetic and potential energies, what does this say about the intensive internal energy of a liquid phase compared with the intensive internal energy of the gas phase?
5. Explain the terms "energy," "potential energy," "kinetic energy," and "internal energy."
6. How is the internal energy of a substance related to the intermolecular pair potentials of the molecules?
7. Are T and P intensive properties? Name two intensive properties and two extensive properties.
8. How many degrees of freedom exist when a pure substance coexists as a liquid and gas?
9. Can an ideal gas condense? Can real fluids that follow the ideal gas law condense?
10. Give examples of bubble, dew, saturation, and superheated conditions. Explain what is meant when wet steam has a quality of 25%.
11. Create and solve a problem that requires double interpolation.

1.7 PRACTICE PROBLEMS

P1.1 Estimate the average speed (mph) of hydrogen molecules at 200 K and 3 bars. (ANS. 3532)

P1.2 Estimate the entropy (J/g-K) of steam at 27.5MPa and 425C. (ANS. 5.1847)

Test Yourself

1. Draw a sketch of the force model implied by the square-well potential, indicating the position(s) where the force between two atoms is zero and the positions where it is nonzero.

2. Explain in words how the pressure of a fluid against the walls of its container is related to the velocity of the molecules.

3. What is it about molecules that requires us to add heat to convert liquids to gases?

4. If the kinetic energy of pure liquid and vapor molecules at phase equilibrium must be the same, and the internal energy of a system is the sum of the kinetic and potential energies, what does this say about the intensive internal energy of a liquid phase compared with the intensive internal energy of the gas phase?

5. Explain the terms “energy,” “potential energy,” “kinetic energy,” and “internal energy.”

6. How is the internal energy of a substance related to the intermolecular pair potentials of the molecules?

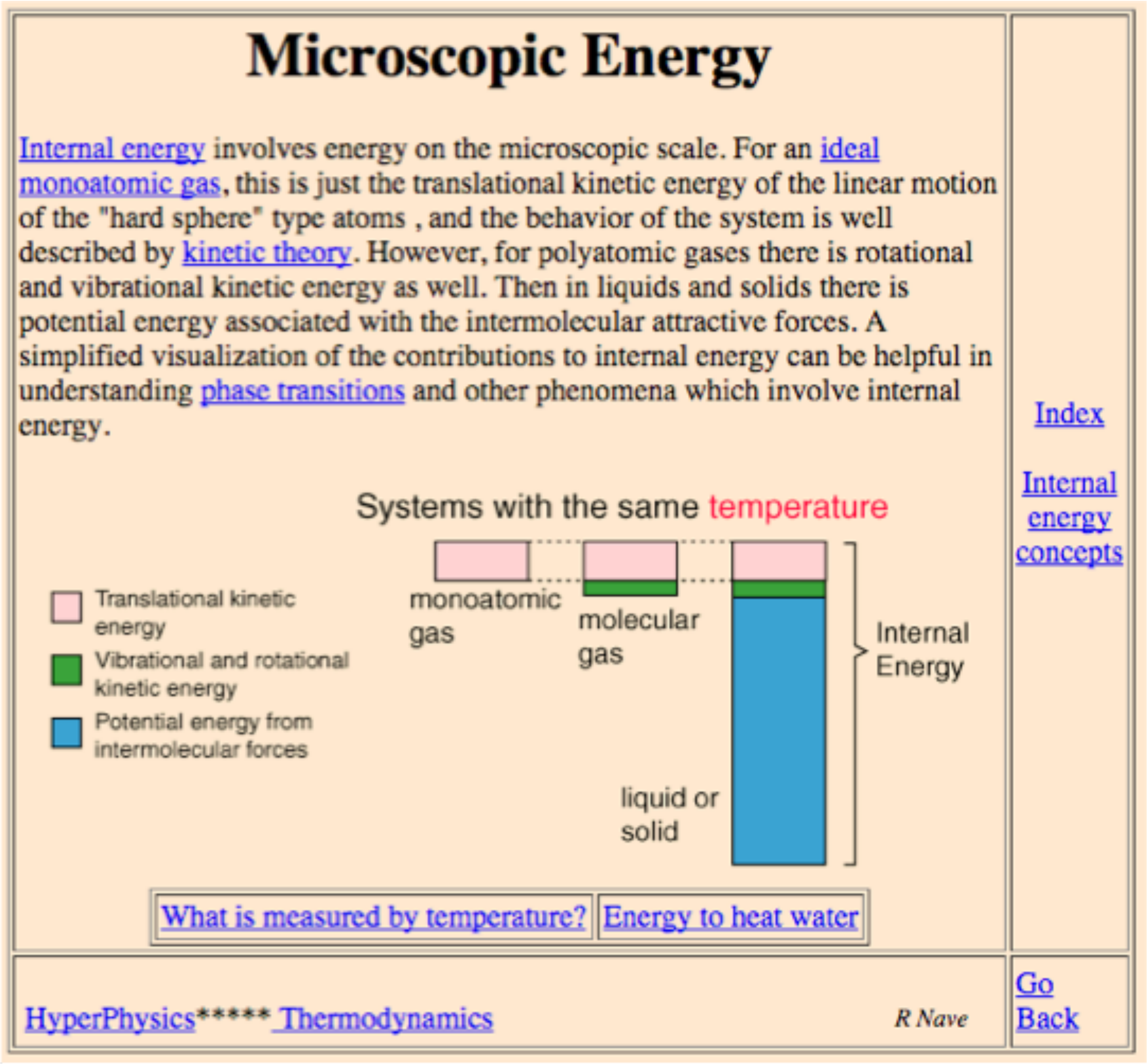
7. Are T and P intensive properties? Name two intensive properties and two extensive properties.

8. How many degrees of freedom exist when a pure substance coexists as a liquid and gas?

9. Can an ideal gas condense? Can real fluids that follow the ideal gas law condense?

10. Give examples of bubble, dew, saturation, and superheated conditions. Explain what is meant when wet steam has a quality of 25%.

Question 4



Microscopic Energy

Internal energy involves energy on the microscopic scale. For an ideal monoatomic gas, this is just the translational kinetic energy of the linear motion of the "hard sphere" type atoms , and the behavior of the system is well described by kinetic theory. However, for polyatomic gases there is rotational and vibrational kinetic energy as well. Then in liquids and solids there is potential energy associated with the intermolecular attractive forces. A simplified visualization of the contributions to internal energy can be helpful in understanding phase transitions and other phenomena which involve internal energy.

What is measured by temperature? | Energy to heat water

HyperPhysics***** Thermodynamics

R Nave

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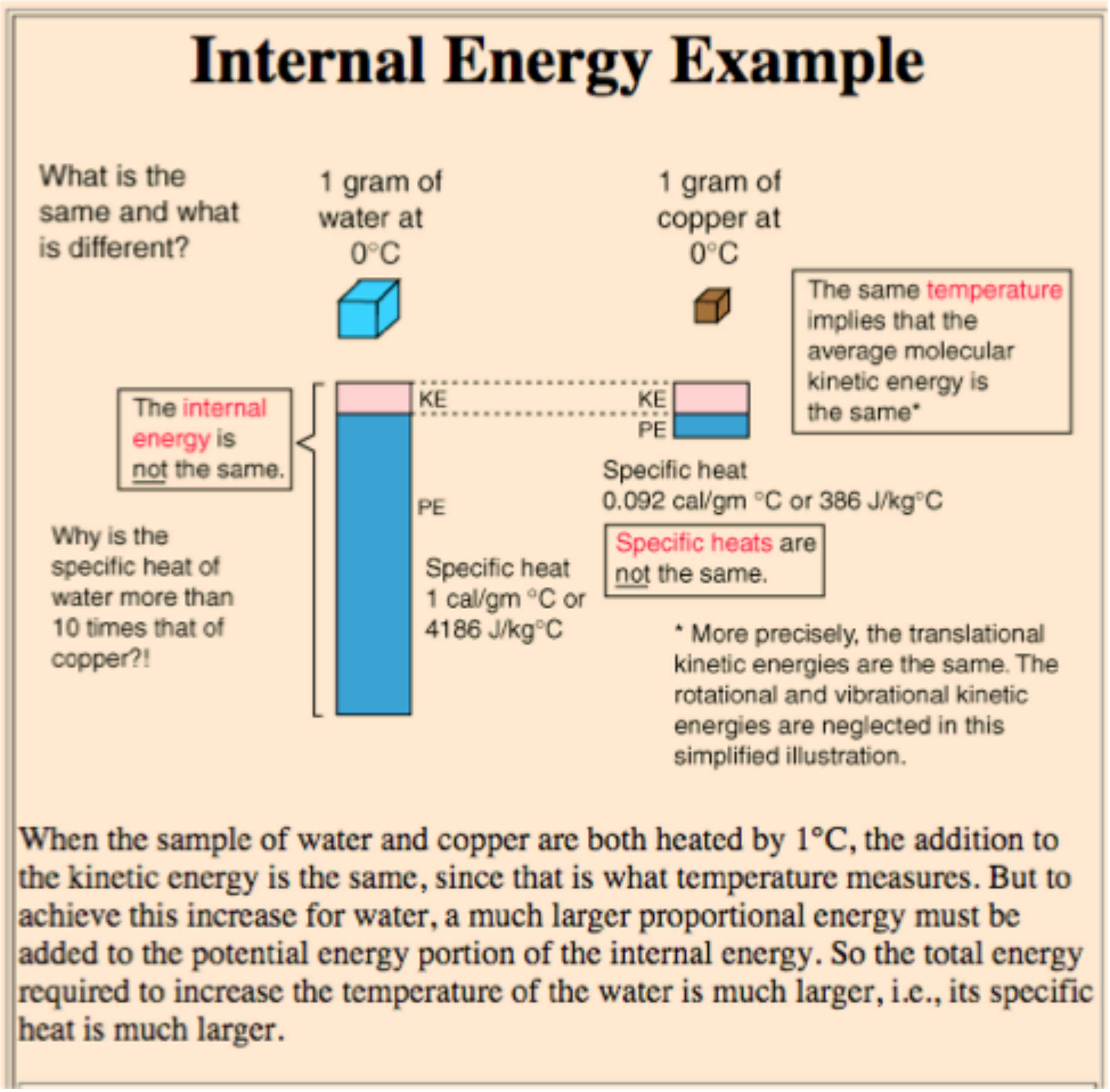


Internal Energy Example

What is the same and what is different?

1 gram of water at 0°C

1 gram of copper at 0°C

The same **temperature** implies that the average molecular kinetic energy is the same*

The **internal energy** is <u>not</u> the same.

Specific heat 0.092 cal/gm °C or 386 J/kg°C

Specific heats are <u>not</u> the same.

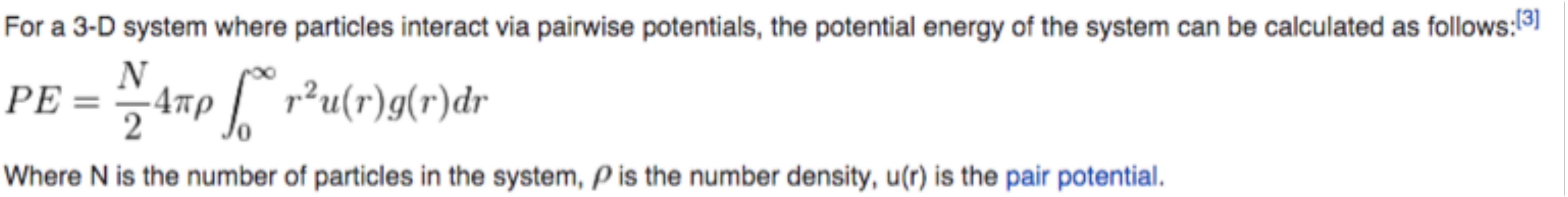
Why is the specific heat of water more than 10 times that of copper?!

Specific heat 1 cal/gm °C or 4186 J/kg°C

* More precisely, the translational kinetic energies are the same. The rotational and vibrational kinetic energies are neglected in this simplified illustration.

When the sample of water and copper are both heated by 1°C, the addition to the kinetic energy is the same, since that is what temperature measures. But to achieve this increase for water, a much larger proportional energy must be added to the potential energy portion of the internal energy. So the total energy required to increase the temperature of the water is much larger, i.e., its specific heat is much larger.

Question 6

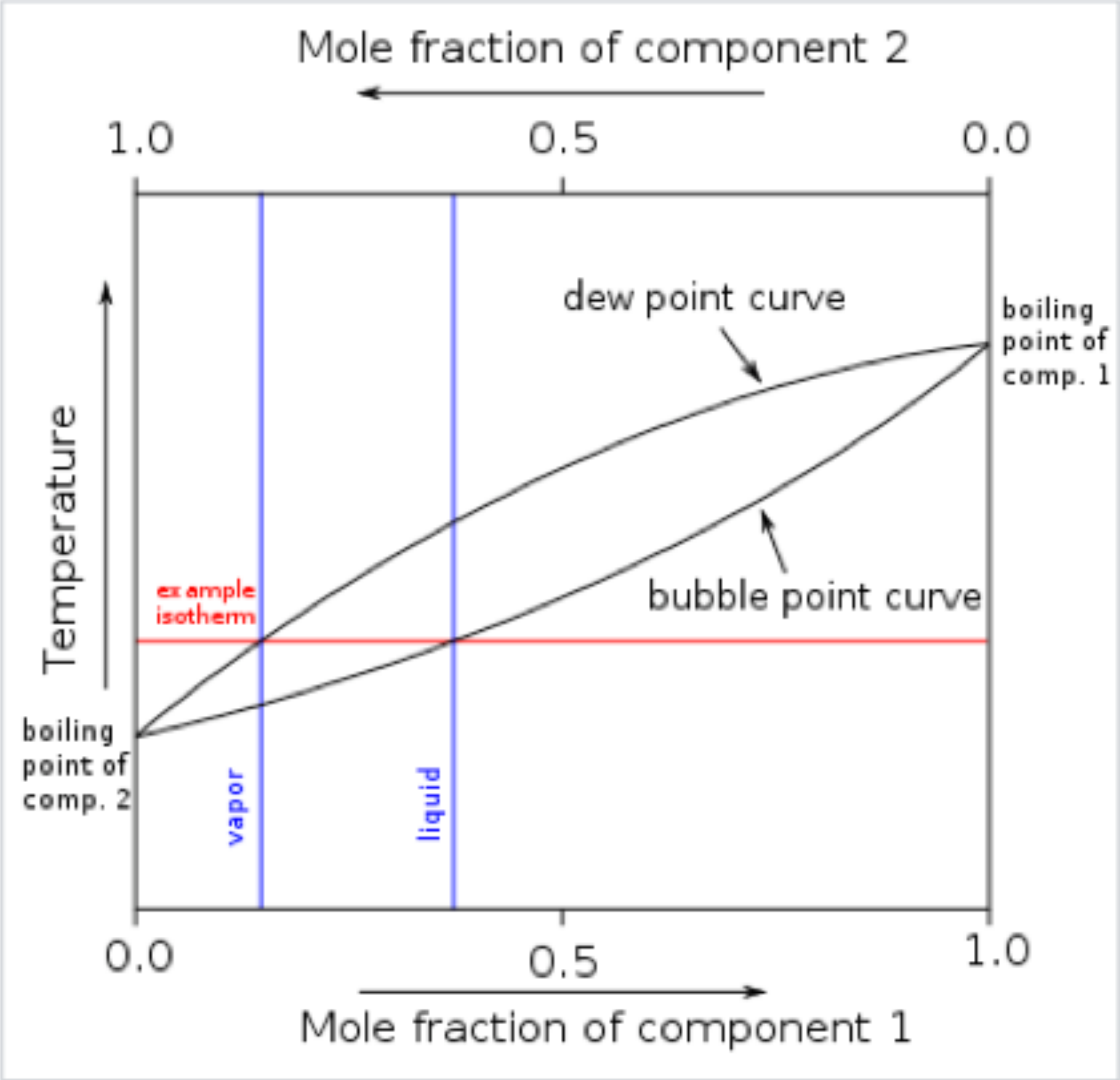


For a 3-D system where particles interact via pairwise potentials, the potential energy of the system can be calculated as follows:[3]

$$PE = \frac{N}{2} 4\pi\rho \int_0^\infty r^2 u(r) g(r) dr$$

Where N is the number of particles in the system, ρ is the number density, u(r) is the pair potential.

Question 10



Mole fraction vs. temperature diagram for a two-component system, showing the bubble point and dew point curves.

1.8 HOMEWORK PROBLEMS

Note: *Some of the steam table homework problems involve enthalpy, H, which is defined for convenience using properties discussed in this chapter, $H \equiv U + PV$. The enthalpy calculations can be performed by reading the tabulated enthalpy values from the tables in an analogous manner used for internal energy. We expect that students will be introduced to this property in course lectures in parallel with the homework problems that utilize H.*

1.1 In each of the following, sketch your estimates of the intermolecular potentials between the given molecules and their mixture on the same pair of axes.

(a) Chloroform is about 20% larger than acetone and about 10% stickier, but chloroform and acetone stick to one another much more strongly than they stick to themselves.

(b) You have probably heard that "oil and water don't mix." What does that mean in molecular terms? Let's assume that oil can be characterized as benzene and that benzene is four times larger than water, but water is 10% stickier than benzene. If the ε_{12} parameter is practically zero, that would represent that the benzene and water stick to themselves more strongly than to one another. Sketch this.

1.2 For each of the states below, calculate the number of moles of ideal gas held in a three liter container.

(a) $T = 673$ K, $P = 2$ MPa
(b) $T = 500$ K, $P = 0.7$ MPa
(c) $T = 450$ K, $P = 1.5$ MPa

1.3 A 5 m^3 outdoor gas storage tank warms from 10°C to 40°C on a sunny day. If the initial pressure was 0.12 MPa at 10°C, what is the pressure at 40°C, and how many moles of gas are in the tank? Use the ideal gas law.

1.4 An automobile tire has a pressure of 255 kPa (gauge) in the summer when the tire temperature after driving is 50°C. What is the wintertime pressure of the same tire at 0°C if the volume of the tire is considered the same and there are no leaks in the tire?

1.5 A 5 m^3 gas storage tank contains methane. The initial temperature and pressure are $P = 1$ bar, $T = 18$°C. Using the ideal gas law, calculate the P following each of the successive steps.

(a) 1 m^3 (at standard conditions) is withdrawn isothermally.
(b) The sun warms the tank to 40°C.
(c) 1.2 m^3 (at standard conditions) is added to the tank and the final temperature is 35°C.
(d) The tank cools overnight to 18°C.

1.6 Calculate the mass density of the following gases at 298 K and 1 bar.

(a) Nitrogen
(b) Oxygen
(c) Air (use average molecular weight)
(d) CO_2
(e) Argon

1.7 Calculate the mass of air (in kg) that is contained in a classroom that is 12m x 7m x 3m at 293 K and 0.1 MPa.

1.8 Five grams of the specified pure solvent is placed in a variable volume piston. What is the volume of the pure system when 50% and 75% have been evaporated at: (*i*) 30°C, (*ii*) 50°C? Use the Antoine equation (Appendix E) to relate the saturation temperature and saturation pressure. Use the ideal gas law to model the vapor phase. Show that the volume of the system occupied by liquid is negligible compared to the volume occupied by vapor.

(a) Hexane ($\rho^L = 0.66$ g/cm^3)
(b) Benzene ($\rho^L = 0.88$ g/cm^3)
(c) Ethanol ($\rho^L = 0.79$ g/cm^3)
(d) Water without using the steam tables ($\rho^L = 1$ g/cm^3)
(e) Water using the steam tables

1.9 A gasoline spill is approximately 4 liters of liquid. What volume of vapor is created at 1 bar and 293 K when the liquid evaporates? The density of regular gasoline can be estimated by treating it as pure isooctane (2,2,4-trimethylpentane $\rho^L = 0.692$ g/cm^3) at 298 K and 1 bar.

1.10 The gross lifting force of a balloon is given by $(\rho_{air} - \rho_{gas})\underline{V}_{balloon}$. What is the gross lifting force (in kg) of a hot air balloon of volume 1.5E6 L, if the balloon contains gas at 100°C and 1 atm? The hot gas is assumed to have an average molecular weight of 32 due to carbon dioxide from combustion. The surrounding air has an average molecular weight of 29 and is at 25°C and 1 atm.

1.11 LPG is a useful fuel in rural locations without natural gas pipelines. A leak during the filling of a tank can be extremely dangerous because the vapor is denser than air and drifts to low elevations before dispersing, creating an explosion hazard. What volume of vapor is created by a leak of 40L of LPG? Model the liquid before leaking as propane with $\rho^L = 0.24$ g/cm^3. What is the mass density of pure vapor propane after depressurization to 293 K and 1 bar? Compare with the mass density of air at the same conditions.

1.12 The gas phase reaction $A \rightarrow 2R$ is conducted in a 0.1 m^3 spherical tank. The initial temperature and pressure in the tank are 0.05 MPa and 400 K. After species A is 50% reacted, the temperature has fallen to 350 K. What is the pressure in the vessel?

1.13 A gas stream entering an absorber is 20 mol% CO_2 and 80 mol% air. The flowrate is 1 m^3/min at 1 bar and 360 K. When the gas stream exits the absorber, 98% of the incoming CO_2 has been absorbed into a flowing liquid amine stream.

(a) What are the gas stream mass flowrates on the inlet and outlets in g/min?
(b) What is the volumetric flowrate on the gas outlet of the absorber if the stream is at 320 K and 1 bar?

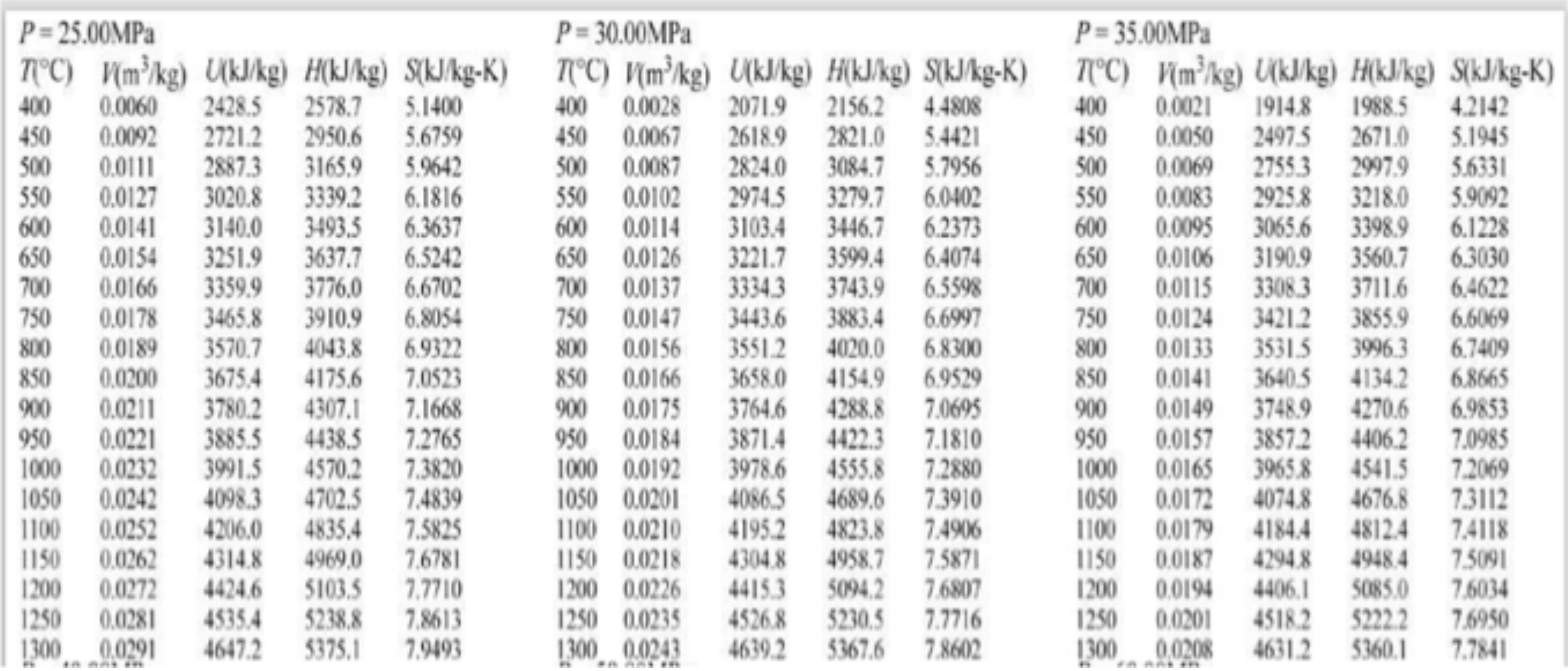
1.14 A permeation membrane separates an inlet air stream, *F*, (79 mol% N_2, 21 mol% O_2), into a permeate stream, *M*, and a reject stream, *J*. The inlet stream conditions are 293 K, 0.5 MPa, and 2 mol/min; the conditions for both outlet streams are 293 K and 0.1 MPa. If the permeate stream is 50 mol% O_2, and the reject stream is 13 mol% O_2, what are the volumetric flowrates (L/min) of the two outlet streams?

1.7. Practice Problems

P1.1. Estimate the average speed (mph) of hydrogen molecules at 200 K and 3 bars. (ANS. 3532)

P1.2. Estimate the entropy (J/g-K) of steam at 27.5MPa and 425C. (ANS. 5.1847)

$$T = \frac{M_w}{3R}\langle v^2\rangle \text{ (for 3D)} \qquad T_{2D} = \frac{M_w}{2R}\langle v^2\rangle \text{ (for 2D) monatomic fluid.} \qquad 1.1$$



$P = 25.00$MPa

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
400	0.0060	2428.5	2578.7	5.1400
450	0.0092	2721.2	2950.6	5.6759
500	0.0111	2887.3	3165.9	5.9642
550	0.0127	3020.8	3339.2	6.1816
600	0.0141	3140.0	3493.5	6.3637
650	0.0154	3251.9	3637.7	6.5242
700	0.0166	3359.9	3776.0	6.6702
750	0.0178	3465.8	3910.9	6.8054
800	0.0189	3570.7	4043.8	6.9322
850	0.0200	3675.4	4175.6	7.0523
900	0.0211	3780.2	4307.1	7.1668
950	0.0221	3885.5	4438.5	7.2765
1000	0.0232	3991.5	4570.2	7.3820
1050	0.0242	4098.3	4702.5	7.4839
1100	0.0252	4206.0	4835.4	7.5825
1150	0.0262	4314.8	4969.0	7.6781
1200	0.0272	4424.6	5103.5	7.7710
1250	0.0281	4535.4	5238.8	7.8613
1300	0.0291	4647.2	5375.1	7.9493

$P = 30.00$MPa

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
400	0.0028	2071.9	2156.2	4.4808
450	0.0067	2618.9	2821.0	5.4421
500	0.0087	2824.0	3084.7	5.7956
550	0.0102	2974.5	3279.7	6.0402
600	0.0114	3103.4	3446.7	6.2373
650	0.0126	3221.7	3599.4	6.4074
700	0.0137	3334.3	3743.9	6.5598
750	0.0147	3443.6	3883.4	6.6997
800	0.0156	3551.2	4020.0	6.8300
850	0.0166	3658.0	4154.9	6.9529
900	0.0175	3764.6	4288.8	7.0695
950	0.0184	3871.4	4422.3	7.1810
1000	0.0192	3978.6	4555.8	7.2880
1050	0.0201	4086.5	4689.6	7.3910
1100	0.0210	4195.2	4823.8	7.4906
1150	0.0218	4304.8	4958.7	7.5871
1200	0.0226	4415.3	5094.2	7.6807
1250	0.0235	4526.8	5230.5	7.7716
1300	0.0243	4639.2	5367.6	7.8602

$P = 35.00$MPa

T(°C)	V(m^3/kg)	U(kJ/kg)	H(kJ/kg)	S(kJ/kg-K)
400	0.0021	1914.8	1988.5	4.2142
450	0.0050	2497.5	2671.0	5.1945
500	0.0069	2755.3	2997.9	5.6331
550	0.0083	2925.8	3218.0	5.9092
600	0.0095	3065.6	3398.9	6.1228
650	0.0106	3190.9	3560.7	6.3030
700	0.0115	3308.3	3711.6	6.4622
750	0.0124	3421.2	3855.9	6.6069
800	0.0133	3531.5	3996.3	6.7409
850	0.0141	3640.5	4134.2	6.8665
900	0.0149	3748.9	4270.6	6.9853
950	0.0157	3857.2	4406.2	7.0985
1000	0.0165	3965.8	4541.5	7.2069
1050	0.0172	4074.8	4676.8	7.3112
1100	0.0179	4184.4	4812.4	7.4118
1150	0.0187	4294.8	4948.4	7.5091
1200	0.0194	4406.1	5085.0	7.6034
1250	0.0201	4518.2	5222.2	7.6950
1300	0.0208	4631.2	5360.1	7.7841

1.3. A 5 m^3 outdoor gas storage tank warms from 10°C to 40°C on a sunny day. If the initial pressure was 0.12 MPa at 10°C, what is the pressure at 40°C, and how many moles of gas are in the tank? Use the ideal gas law.

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- **a.** 1 m^3 (at standard conditions) is withdrawn isothermally.
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- **d.** The tank cools overnight to 18°C.

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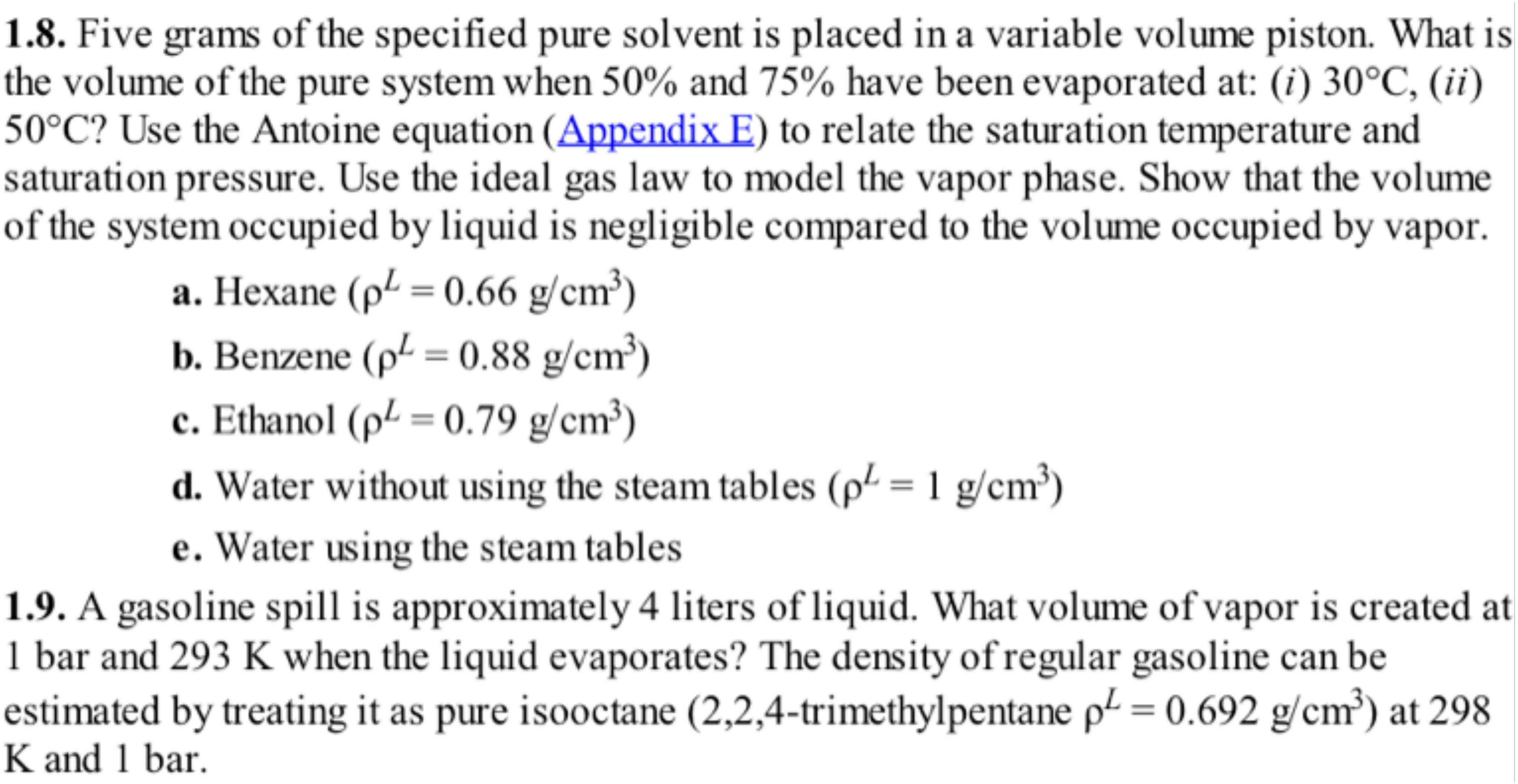
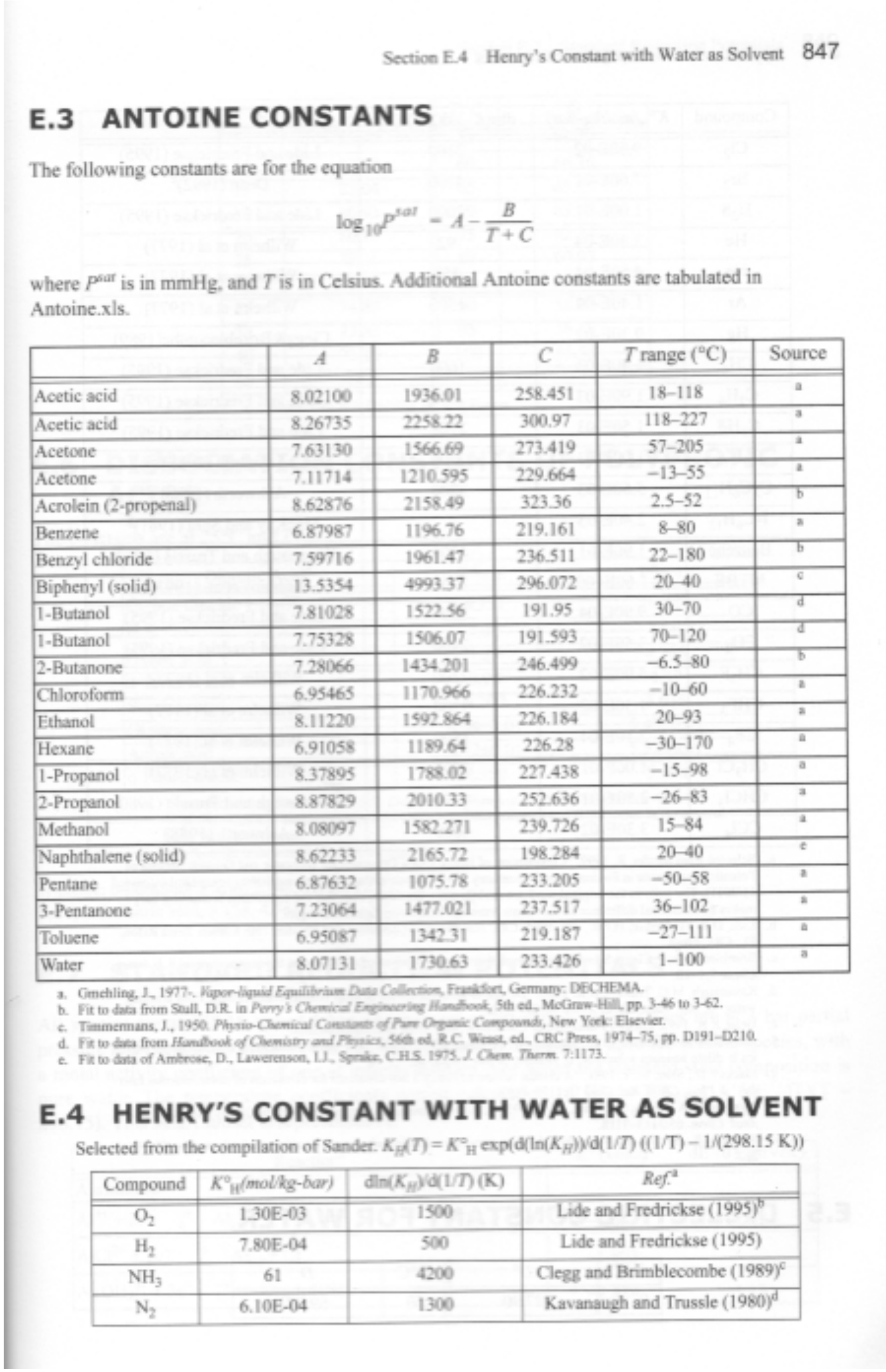
- **a.** Nitrogen
- **b.** Oxygen
- **c.** Air (use average molecular weight)
- **d.** CO_2
- **e.** Argon



1.8. Five grams of the specified pure solvent is placed in a variable volume piston. What is the volume of the pure system when 50% and 75% have been evaporated at: (*i*) 30°C, (*ii*) 50°C? Use the Antoine equation (Appendix E) to relate the saturation temperature and saturation pressure. Use the ideal gas law to model the vapor phase. Show that the volume of the system occupied by liquid is negligible compared to the volume occupied by vapor.

- **a.** Hexane ($\rho^L = 0.66$ g/cm^3)
- **b.** Benzene ($\rho^L = 0.88$ g/cm^3)
- **c.** Ethanol ($\rho^L = 0.79$ g/cm^3)
- **d.** Water without using the steam tables ($\rho^L = 1$ g/cm^3)
- **e.** Water using the steam tables

1.9. A gasoline spill is approximately 4 liters of liquid. What volume of vapor is created at 1 bar and 293 K when the liquid evaporates? The density of regular gasoline can be estimated by treating it as pure isooctane (2,2,4-trimethylpentane $\rho^L = 0.692$ g/cm^3) at 298 K and 1 bar.



E.3 ANTOINE CONSTANTS

The following constants are for the equation

$$\log_{10} P^{sat} = A - \frac{B}{T+C}$$

where P^{sat} is in mmHg, and T is in Celsius. Additional Antoine constants are tabulated in Antoine.xls.

	A	*B*	*C*	*T* range (°C)	Source
Acetic acid	8.02100	1936.01	258.451	18–118	a
Acetic acid	8.26735	2258.22	300.97	118–227	a
Acetone	7.63130	1566.69	273.419	57–205	a
Acetone	7.11714	1210.595	229.664	–13–55	a
Acrolein (2-propenal)	8.62876	2158.49	323.36	2.5–52	b
Benzene	6.87987	1196.76	219.161	8–80	a
Benzyl chloride	7.59716	1961.47	236.511	22–180	b
Biphenyl (solid)	13.5354	4993.37	296.072	20–40	c
1-Butanol	7.81028	1522.56	191.95	30–70	d
1-Butanol	7.75328	1506.07	191.593	70–120	d
2-Butanone	7.28066	1434.201	246.499	–6.5–80	b
Chloroform	6.95465	1170.966	226.232	–10–60	a
Ethanol	8.11220	1592.864	226.184	20–93	a
Hexane	6.91058	1189.64	226.28	–30–170	a
1-Propanol	8.37895	1788.02	227.438	–15–98	a
2-Propanol	8.87829	2010.33	252.636	–26–83	a
Methanol	8.08097	1582.271	239.726	15–84	a
Naphthalene (solid)	8.62233	2165.72	198.284	20–40	e
Pentane	6.87632	1075.78	233.205	–50–58	a
3-Pentanone	7.23064	1477.021	237.517	36–102	a
Toluene	6.95087	1342.31	219.187	–27–111	a
Water	8.07131	1730.63	233.426	1–100	a

a. Gmehling, J., 1977-. *Vapor-liquid Equilibrium Data Collection*, Frankfort, Germany: DECHEMA.
b. Fit to data from Stull, D.R. in *Perry's Chemical Engineering Handbook*, 5th ed., McGraw-Hill, pp. 3-46 to 3-62.
c. Timmermans, J., 1950. *Physio-Chemical Constants of Pure Organic Compounds*, New York: Elsevier.
d. Fit to data from *Handbook of Chemistry and Physics*, 56th ed, R.C. Weast, ed., CRC Press, 1974–75, pp. D191–D210.
e. Fit to data of Ambrose, D., Lawerenson, I.J., Sprake, C.H.S. 1975. *J. Chem. Therm.* 7:1173.

E.4 HENRY'S CONSTANT WITH WATER AS SOLVENT

Selected from the compilation of Sander. $K_H(T) = K°_H \exp(d(\ln(K_H))/d(1/T)\ ((1/T) - 1/(298.15\ K))$

Compound	$K°_H$(mol/kg-bar)	$d\ln(K_H)/d(1/T)$ (K)	*Ref.*[a]
O_2	1.30E-03	1500	Lide and Fredrickse (1995)[b]
H_2	7.80E-04	500	Lide and Fredrickse (1995)
NH_3	61	4200	Clegg and Brimblecombe (1989)[c]
N_2	6.10E-04	1300	Kavanaugh and Trussle (1980)[d]

1.11. LPG is a useful fuel in rural locations without natural gas pipelines. A leak during the filling of a tank can be extremely dangerous because the vapor is denser than air and drifts to low elevations before dispersing, creating an explosion hazard. What volume of vapor is created by a leak of 40L of LPG? Model the liquid before leaking as propane with $\rho^L = 0.24$ g/cm^3. What is the mass density of pure vapor propane after depressurization to 293 K and 1 bar? Compare with the mass density of air at the same conditions.

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1.13. A gas stream entering an absorber is 20 mol% CO_2 and 80 mol% air. The flowrate is 1 m^3/min at 1 bar and 360 K. When the gas stream exits the absorber, 98% of the incoming CO_2 has been absorbed into a flowing liquid amine stream.

a. What are the gas stream mass flowrates on the inlet and outlets in g/min?

b. What is the volumetric flowrate on the gas outlet of the absorber if the stream is at 320 K and 1 bar?

1.14. A permeation membrane separates an inlet air stream, *F*, (79 mol% N_2, 21 mol% O_2), into a permeate stream, *M*, and a reject stream, *J*. The inlet stream conditions are 293 K, 0.5 MPa, and 2 mol/min; the conditions for both outlet streams are 293 K and 0.1 MPa. If the permeate stream is 50 mol% O_2, and the reject stream is 13 mol% O_2, what are the volumetric flowrates (L/min) of the two outlet streams?

1.15.

a. What size vessel holds 2 kg water at 80°C such that 70% is vapor? What are the pressure and internal energy?

b. A 1.6 m^3 vessel holds 2 kg water at 0.2 MPa. What are the quality, temperature, and internal energy?

1.16. For water at each of the following states, determine the internal energy and enthalpy using the steam tables.

	T(°C)	P(MPa)
(a)	100	0.01
(b)	550	6.25
(c)	475	7.5
(d)	180	0.7

1.17. Determine the temperature, volume, and quality for one kg water under the following conditions:

a. $U = 3000$ kJ/kg, $P = 0.3$ MPa

b. $U = 2900$ kJ/kg, $P = 1.7$ MPa

c. $U = 2500$ kJ/kg, $P = 0.3$ MPa

d. $U = 350$ kJ/kg, $P = 0.03$ MPa

1.18. Two kg of water exist initially as a vapor and liquid at 90°C in a rigid container of volume 2.42 m^3.

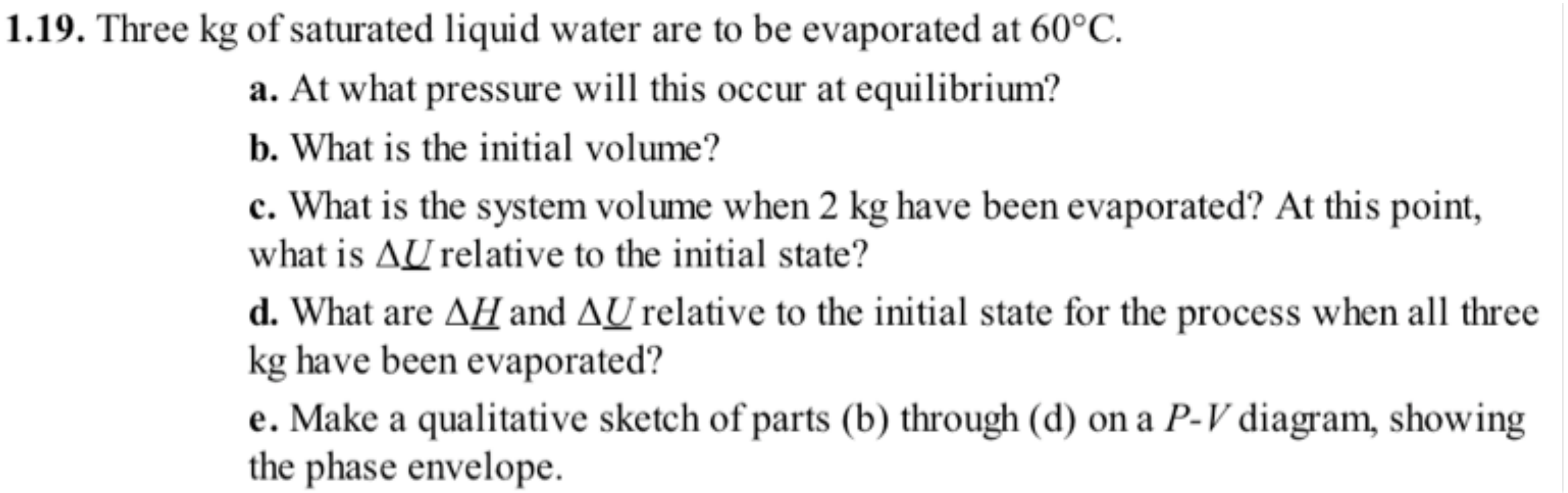
a. At what pressure is the system?

b. What is the quality of the system?

c. The temperature of the container is raised to 100°C. What is the quality of the system, and what is the pressure? What are $\Delta \underline{H}$ and $\Delta \underline{U}$ at this point relative to the initial state?

d. As the temperature is increased, at what temperature and pressure does the container contain only saturated vapor? What is $\Delta \underline{H}$ and $\Delta \underline{U}$ at this point relative to the initial state?

e. Make a qualitative sketch of parts (a) through (d) on a P-V diagram, showing the phase envelope.



1.19. Three kg of saturated liquid water are to be evaporated at 60°C.

a. At what pressure will this occur at equilibrium?

b. What is the initial volume?

c. What is the system volume when 2 kg have been evaporated? At this point, what is $\Delta \underline{U}$ relative to the initial state?

d. What are $\Delta \underline{H}$ and $\Delta \underline{U}$ relative to the initial state for the process when all three kg have been evaporated?

e. Make a qualitative sketch of parts (b) through (d) on a *P*-*V* diagram, showing the phase envelope.

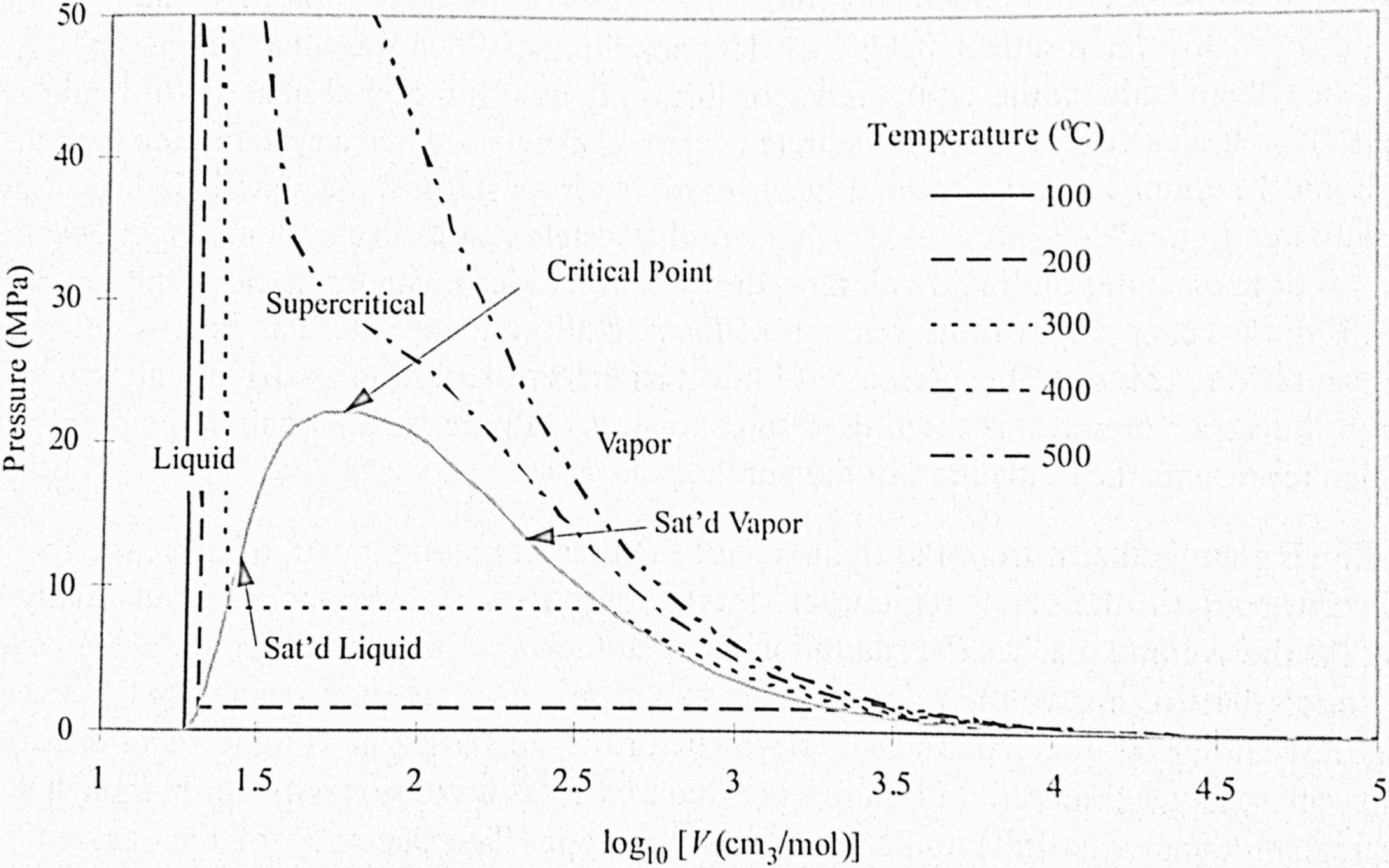
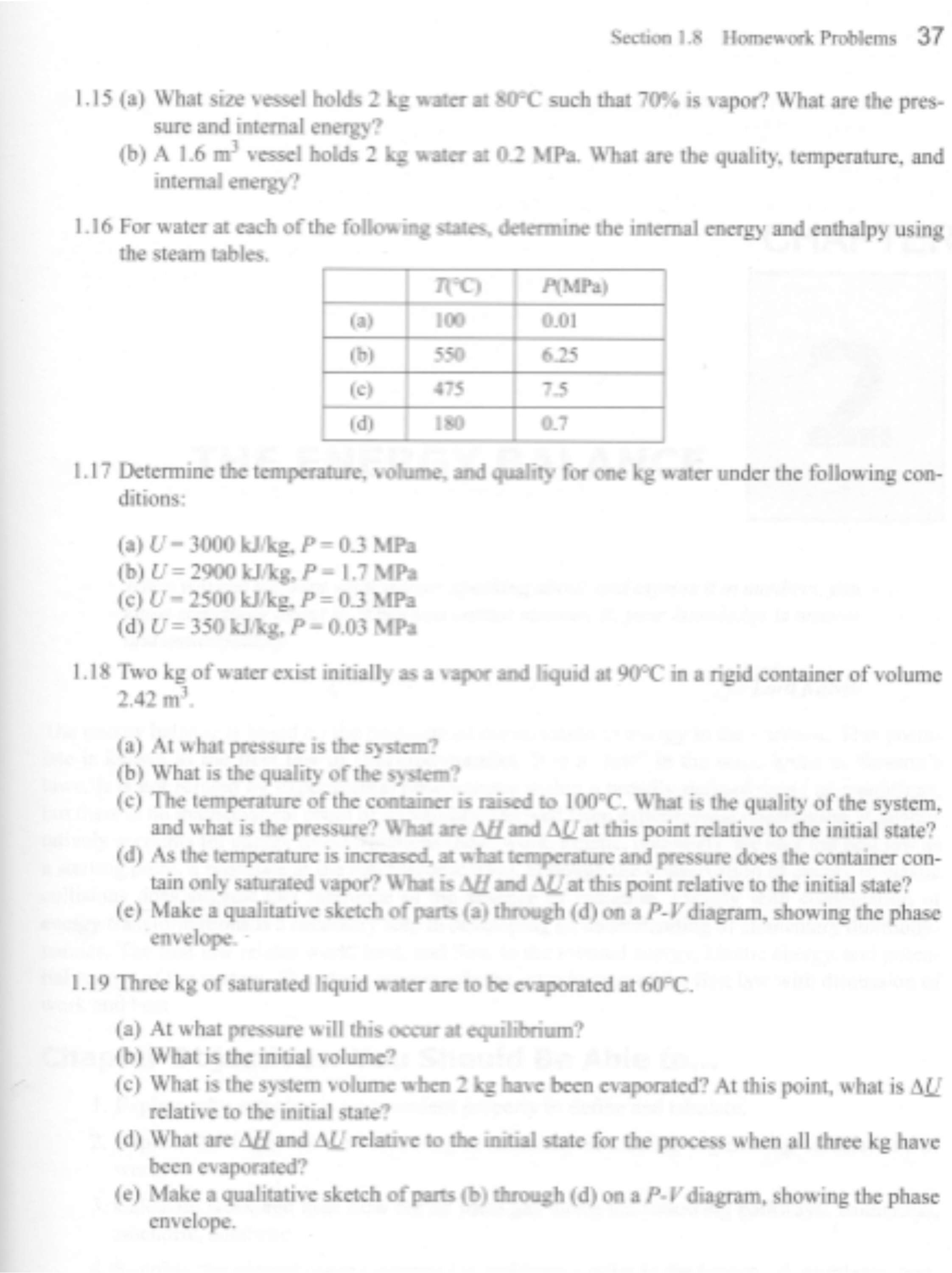


Figure 1.4 *P-V-T behavior of water at the same temperatures used in Fig. 1.3. The plot is prepared from the steam tables in Appendix E.*



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(b) What is the initial volume?
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(d) What are $\Delta \underline{H}$ and $\Delta \underline{U}$ relative to the initial state for the process when all three kg have been evaporated?
(e) Make a qualitative sketch of parts (b) through (d) on a P-V diagram, showing the phase envelope.