

NAME: Solution

**ChBE 2130 Thermodynamics I**  
**Fall 2015**  
**Exam 1**

**Remember**

- Write down relevant relationships needed to solve each problem
- Provide details, intermediate steps, and units
- Note any assumptions
- Show your work
- Where indicated, place your final answer on the \_\_\_\_\_

Problem	Possible Points	Score
1	20	
2	28	
3	28	
4	24	
Total	100	

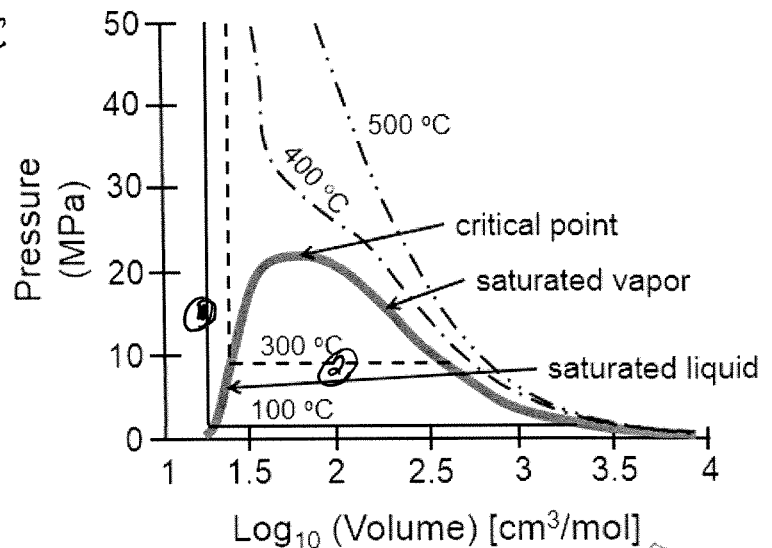
1. Concept Questions [20 pts: 5 points each, no partial credit]

- From diagram, what is the condition of water at 370 K and 15 MPa?

- ①
- a. Vapor
  - ☒ b. Liquid  $370\text{K} \approx 100^\circ\text{C}$
  - c. Mixed Phase
  - d. Supercritical

- ②
- From diagram, what is the approx. temperature in a 500 cm<sup>3</sup> vessel containing 5 mole of water at 9 MPa?

- a. 100° C
  - b. 200° C
  - ☒ c. 300° C
  - d. 400° C
- $500\text{ cm}^3 / 5\text{ mole} = 100\text{ cm}^3/\text{mol}$
- $\log_{10}(100) = 2$



- Water is in vapor-liquid (mixed) equilibrium in a fixed pressure container. Heat is added until the temperature increases by 5°C. How does the phase change?

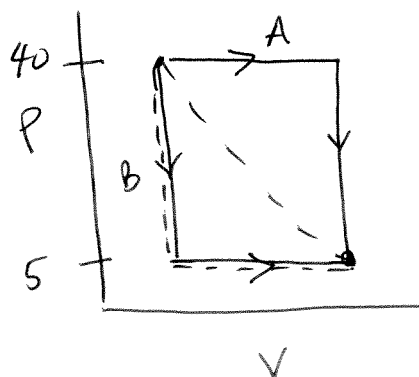
- a. Some vapor is condensed
- b. All vapor is condensed
- c. Some liquid evaporates
- ☒ d. All liquid evaporates

*All liquid will evaporate before temperature will start to rise*

- A gas undergoes reversible expansion from 40 bar and 500 K to 5 bar and 500 K by one of two pathways. Which process creates more work?

- ☒ a. A constant pressure process to the final volume and then constant volume process to 5 bar.
- b. A constant volume process to 5 bar and then constant pressure to the final volume.
- c. Same work for both

*Compare area under A versus area under B*



*--- isotherm 500 K*

2. [28 pts] Consider an isothermal, mechanically reversible compression of a fluid from  $V_1$  to  $V_2$ . Develop the equation for heat (in terms of  $V_1$  and  $V_2$ ) using the van der Waals equation of state:

$$P = \frac{RT}{V-b} - \frac{a}{V^2}$$

Assume that the coefficients,  $a$  and  $b$ , are constant and the internal energy is only a function of temperature.

Show intermediate steps for complete credit.

$$\text{Isothermal} \Rightarrow \Delta T = 0$$

$$U = f(T) = C_v dT = 0$$

Energy Balance

$$dU = dQ + dW = 0$$

← isothermal

$$dQ = -dW = P dV$$

← mech. rev

$$dQ = \left( \frac{RT}{V-b} - \frac{a}{V^2} \right) dV$$

← substitute vdW eq. of state

$$Q = \int_{V_1}^{V_2} \left( \frac{RT}{V-b} - \frac{a}{V^2} \right) dV$$

$R, T, a$  &  $b$  are constant

$$Q = \left[ RT \ln(V-b) + \frac{a}{V} \right] \bigg|_{V_1}^{V_2}$$

$$Q = RT \ln \left( \frac{V_2-b}{V_1-b} \right) + a \left( \frac{1}{V_2} - \frac{1}{V_1} \right)$$

3. An ideal gas undergoes the following cyclic process in a closed system:

- Initially at 30°C and 100 kPa (state 1)
- Adiabatically compressed to 500 kPa (state 2)
- Cooled at constant pressure to 30°C (state 3)
- Expanded isothermally to the original state

The process steps are mechanically reversible.  $C_p = (7/2) R$  and  $C_v = (5/2) R$

a. [12 pts] Complete the following table: Note Units

State	T (K)	P (kPa)
1	303	100
2	480	500
3	303	500

Adiabatic Step  $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{R/C_p} \Rightarrow T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{R/C_p}$

$$T_2 = 303 \left(\frac{500}{100}\right)^{2/7} = 479.9$$

b. [16 pts] Determine W for each step and the total process

Step	W (J/mol)
12	3679
23	1472
31	-4054
Total	1096

$$dW = dU - dQ$$

$W_{12}$  adiabatic,  $dQ = 0$

$W_{12} = \Delta U_{12} = C_v dT$  Ideal gas

$$W_{12} = \frac{5}{2} \left( 8.314 \frac{\text{J}}{\text{mol K}} \right) (480 - 303) \text{ K}$$

$$W_{12} = 3678.9 \text{ J/mol}$$

$W_{23} \Rightarrow$  constant pressure  $W_{23} = \int [RdT + \frac{RT}{P} dP] = -RAT$   
 $= -R(T_3 - T_2)$

$$W_{23} = -8.314 \frac{\text{J}}{\text{mol K}} (303 - 480) = 1471.6 \text{ J/mol}$$

$$W_{31} \Rightarrow \text{isothermal} \quad W_{31} = \int_0 \left[ -R \underbrace{dT}_0 + \frac{RT}{P} dP \right] = \frac{RT}{P} dP$$

$$W_{31} = RT_3 \ln\left(\frac{P_1}{P_3}\right) = \frac{8.314 \text{ J}}{\text{mol K}} (303 \text{ K}) \ln\left(\frac{100}{500}\right)$$

$$W_{31} = -4054.4 \text{ J/mol}$$

$$W_{TOT} = W_{12} + W_{23} + W_{31} = 3679 + 1472 - 4054$$

$$W_{TOT} = 1096 \text{ J/mol}$$

4. Five mol/s of water enter a boiler at 1 atm and 25°C and exit at 130°C and 1 atm. At 1 atm, the heat of fusion at 0°C is 6.02 kJ/mol and the heat of vaporization at 100°C is 40.6 kJ/mol.

a. [2 pts] What is the phase of the inlet stream?

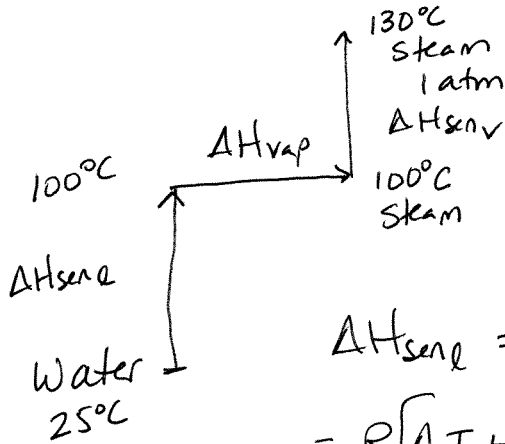
liquid

b. [2 pts] What is the phase of the outlet stream?

Vapor

c. [20 pts] How much heat is required in kJ/s to be added to the boiler?

236.5 kJ/s



$$\Delta H = \Delta H_{\text{sens}} + \Delta H_{\text{vap}} + \Delta H_{\text{sensv}}$$

$$\Delta H_{\text{sens}} = R \int \frac{C_p}{R} dT = R \int (A + BT + CT^2) dT$$

$$= R \left[ AT + \frac{B}{2} T^2 + \frac{C}{3} T^3 \right] \Big|_{25+273}^{373}$$

$$= R \left( 8.712 T + \frac{1.25 \times 10^{-3}}{2} T^2 + \frac{-0.18 \times 10^{-6}}{3} T^3 \right) \Big|_{298}^{373}$$

$$= 8.314 \frac{\text{J}}{\text{mol K}} (683.33 \text{ K}) = 5681.2 \text{ J/mol}$$

$$\Delta H_{\text{sensv}} = R \int (A + BT + DT^{-2}) dT = R \left[ AT + \frac{B}{2} T^2 - \frac{D}{T} \right] \Big|_{373}^{403}$$

$$= 8.314 \left( 3.47 T + \frac{1.45 \times 10^{-3}}{2} T^2 - \frac{0.121 \times 10^5}{T} \right) \Big|_{373}^{403}$$

$$= 8.314 \frac{\text{J}}{\text{mol K}} (123.39 \text{ K}) = 1025.9 \text{ J/mol}$$

$$\Delta H = 5 \frac{\text{mol}}{\text{s}} \left[ 5.6812 \frac{\text{kJ}}{\text{mol}} + 40.6 \frac{\text{kJ}}{\text{mol}} + \frac{1.0259 \text{ kJ}}{\text{mol}} \right]$$

$$\Delta H = 236.5 \text{ kJ/s}$$

**Table C.4: Standard Enthalpies and Gibbs Energies of Formation  
at 298.15 K<sup>†</sup>**

Joules per mole of the substance formed

Chemical species		State (Note 2)	$\Delta H_{f298}^{\circ}$ (Note 1)	$\Delta G_{f298}^{\circ}$ (Note 1)
Paraffins:				
Methane	CH <sub>4</sub>	(g)	-74,520	-50,460
Ethane	C <sub>2</sub> H <sub>6</sub>	(g)	-83,820	-31,855
Propane	C <sub>3</sub> H <sub>8</sub>	(g)	-104,680	-24,290
<i>n</i> -Butane	C <sub>4</sub> H <sub>10</sub>	(g)	-125,790	-16,570
<i>n</i> -Pentane	C <sub>5</sub> H <sub>12</sub>	(g)	-146,760	-8,650
<i>n</i> -Hexane	C <sub>6</sub> H <sub>14</sub>	(g)	-166,920	150
<i>n</i> -Heptane	C <sub>7</sub> H <sub>16</sub>	(g)	-187,780	8,260
<i>n</i> -Octane	C <sub>8</sub> H <sub>18</sub>	(g)	-208,750	16,260
1-Alkenes:				
Ethylene	C <sub>2</sub> H <sub>4</sub>	(g)	52,510	68,460
Propylene	C <sub>3</sub> H <sub>6</sub>	(g)	19,710	62,205
1-Butene	C <sub>4</sub> H <sub>8</sub>	(g)	-540	70,340
1-Pentene	C <sub>5</sub> H <sub>10</sub>	(g)	-21,280	78,410
1-Hexene	C <sub>6</sub> H <sub>12</sub>	(g)	-41,950	86,830
1-Heptene	C <sub>7</sub> H <sub>14</sub>	(g)	-62,760	
Miscellaneous organics:				
Acetaldehyde	C <sub>2</sub> H <sub>4</sub> O	(g)	-166,190	-128,860
Acetic acid	C <sub>2</sub> H <sub>4</sub> O <sub>2</sub>	(l)	-484,500	-389,900
Acetylene	C <sub>2</sub> H <sub>2</sub>	(g)	227,480	209,970
Benzene	C <sub>6</sub> H <sub>6</sub>	(g)	82,930	129,665
Benzene	C <sub>6</sub> H <sub>6</sub>	(l)	49,080	124,520
1,3-Butadiene	C <sub>4</sub> H <sub>6</sub>	(g)	109,240	149,795
Cyclohexane	C <sub>6</sub> H <sub>12</sub>	(g)	-123,140	31,920
Cyclohexane	C <sub>6</sub> H <sub>12</sub>	(l)	-156,230	26,850
1,2-Ethanediol	C <sub>2</sub> H <sub>6</sub> O <sub>2</sub>	(l)	-454,800	-323,080
Ethanol	C <sub>2</sub> H <sub>6</sub> O	(g)	-235,100	-168,490
Ethanol	C <sub>2</sub> H <sub>6</sub> O	(l)	-277,690	-174,780
Ethylbenzene	C <sub>8</sub> H <sub>10</sub>	(g)	29,920	130,890
Ethylene oxide	C <sub>2</sub> H <sub>4</sub> O	(g)	-52,630	-13,010
Formaldehyde	CH <sub>2</sub> O	(g)	-108,570	-102,530
Methanol	CH <sub>4</sub> O	(g)	-200,660	-161,960
Methanol	CH <sub>4</sub> O	(l)	-238,660	-166,270
Methylcyclohexane	C <sub>7</sub> H <sub>14</sub>	(g)	-154,770	27,480
Methylcyclohexane	C <sub>7</sub> H <sub>14</sub>	(l)	-190,160	20,560
Styrene	C <sub>8</sub> H <sub>8</sub>	(g)	147,360	213,900
Toluene	C <sub>7</sub> H <sub>8</sub>	(g)	50,170	122,050
Toluene	C <sub>7</sub> H <sub>8</sub>	(l)	12,180	113,630

Table C.4 (Continued)

✓/mole of substance formed

Chemical species		State (Note 2)	$\Delta H_{f298}^\circ$ (Note 1)	$\Delta G_{f298}^\circ$ (Note 1)
Miscellaneous inorganics:				
Ammonia	NH <sub>3</sub>	(g)	-46,110	-16,450
Ammonia	NH <sub>3</sub>	(aq)		-26,500
Calcium carbide	CaC <sub>2</sub>	(s)	-59,800	-64,900
Calcium carbonate	CaCO <sub>3</sub>	(s)	-1,206,920	-1,128,790
Calcium chloride	CaCl <sub>2</sub>	(s)	-795,800	-748,100
Calcium chloride	CaCl <sub>2</sub>	(aq)		-8,101,900
Calcium chloride	CaCl <sub>2</sub> ·6H <sub>2</sub> O	(s)	-2,607,900	
Calcium hydroxide	Ca(OH) <sub>2</sub>	(s)	-986,090	-898,490
Calcium hydroxide	Ca(OH) <sub>2</sub>	(aq)		-868,070
Calcium oxide	CaO	(s)	-635,090	-604,030
Carbon dioxide	CO <sub>2</sub>	(g)	-393,509	-394,359
Carbon monoxide	CO	(g)	-110,525	-137,169
Hydrochloric acid	HCl	(g)	-92,307	-95,299
Hydrogen cyanide	HCN	(g)	135,100	124,700
Hydrogen sulfide	H <sub>2</sub> S	(g)	-20,630	-33,560
Iron oxide	FeO	(s)	-272,000	
Iron oxide (hematite)	Fe <sub>2</sub> O <sub>3</sub>	(s)	-824,200	-742,200
Iron oxide (magnetite)	Fe <sub>3</sub> O <sub>4</sub>	(s)	-1,118,400	-1,015,400
Iron sulfide (pyrite)	FeS <sub>2</sub>	(s)	-178,200	-166,900
Lithium chloride	LiCl	(s)	-408,610	
Lithium chloride	LiCl·H <sub>2</sub> O	(s)	-712,580	
Lithium chloride	LiCl·2H <sub>2</sub> O	(s)	-1,012,650	
Lithium chloride	LiCl·3H <sub>2</sub> O	(s)	-1,311,300	
Nitric acid	HNO <sub>3</sub>	(l)	-174,100	-80,710
Nitric acid	HNO <sub>3</sub>	(aq)		-111,250
Nitrogen oxides	NO	(g)	90,250	86,550
	NO <sub>2</sub>	(g)	33,180	51,310
	N <sub>2</sub> O	(g)	82,050	104,200
	N <sub>2</sub> O <sub>4</sub>	(g)	9,160	97,540
Sodium carbonate	Na <sub>2</sub> CO <sub>3</sub>	(s)	-1,130,680	-1,044,440
Sodium carbonate	Na <sub>2</sub> CO <sub>3</sub> ·10H <sub>2</sub> O	(s)	-4,081,320	
Sodium chloride	NaCl	(s)	-411,153	-384,138
Sodium chloride	NaCl	(aq)		-393,133
Sodium hydroxide	NaOH	(s)	-425,609	-379,494
Sodium hydroxide	NaOH	(aq)		-419,150
Sulfur dioxide	SO <sub>2</sub>	(g)	-296,830	-300,194
Sulfur trioxide	SO <sub>3</sub>	(g)	-395,720	-371,060
Sulfur trioxide	SO <sub>3</sub>	(l)	-441,040	
Sulfuric acid	H <sub>2</sub> SO <sub>4</sub>	(l)	-813,989	-690,003
Sulfuric acid	H <sub>2</sub> SO <sub>4</sub>	(aq)		-744,530
Water	H <sub>2</sub> O	(g)	-241,818	-228,572
Water	H <sub>2</sub> O	(l)	-285,830	-237,129

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

#### Notes

1. The standard property changes of formation  $\Delta H_{f298}^\circ$  and  $\Delta G_{f298}^\circ$  are the changes occurring when 1 mol of the listed compound is formed from its elements with each substance in its standard state at 298.15 K (25°C).
2. Standard states: (a) Gases (g): pure ideal gas at 1 bar and 25°C. (b) Liquids (l) and solids (s): pure substance at 1 bar and 25°C. (c) Solutes in aqueous solution (aq): Hypothetical ideal 1-molal solution of solute in water at 1 bar and 25°C.