Name: ANSWER KEY **Last 4 Digits of Student I.D.#:** ______

CBE 140 Midterm – Spring Semester 2014 – Closed-Book Section – 40 Points (out of 150 Total)

(Circle the letter of the correct answer on multiple-choice questions)

1. (2 pts.) The SI unit for power is the watt. What is the watt equivalent in SI Units?

   Power = Energy / Time = Force × Distance / Time = (SI Units): N-m / s

   a. N-m
   b. N/m-s
   (c.) N-m/s
   d. N/m^2-s

2. (2 pts.) Part 1: For the function: $y = a\,(e^{-b/x})^{½}$, which will yield a linear plot?

   Take log of both sides:

   $\ln y = \ln a + \left(-\frac{b}{2}\right)\left(\frac{1}{x}\right)$

   a. ln y vs. $1/x^{½}$
   (b.) ln y vs. 1/x
   c. y vs. ln $(1/x^2)$
   d. y^2 vs. ln (1/x)

   (2 pts.) Part 2: When plotted correctly, how can **a** & **b** be determined from the slope & intercept of the resulting line?

   Slope = – b/2
   Intercept = ln a

3. (2 pt.) Suppose that we wanted to use a unit within the SI system called a kg_f (kilogram of force), such that a mass of 1 kg would have a weight of 1 kg_f under standard Earth gravity. What would be the appropriate conversion factor?

   → F = m × g

   a. F = m × a, so the conversion factor is 1 kg-s^2/m-kg_f
   (b.) F = m x g, so the conversion factor is 9.8 kg-m / s^2-kg_f
   c. F = m x g, so the conversion factor is 9.8 kg_f-m / kg-s^2
   d. Conversion factor is just 1 kg_f / kg – a kilogram weighs a kilogram!

$F = m \times g / g_c \rightarrow 1\,kg_f = 1\,kg \times 9.8\,\frac{m}{s^2} / g_c$

Mult. by g_c & Divide by kg_f → $g_c = 9.8\,kg\text{-}m / kg_f\text{-}s^2$

4. (2 pts.) You perform the following calculation on your calculator:

$$1.0236 - 0.97268$$

The calculator displays: 0.050920000 What number should you report?

a. 0.051
(b.) 0.0509
c. 0.05092
d. 0.050920

The trailing "2" cannot be significant in a <u>subtraction</u> operation, so it should not be reported. Another signif. digit is "lost" because the two numbers are very close to equal.

5 Sig. Figs → 3 Sig. Figs

5. (2 pts.) A catalyst used in an automotive catalytic converter has a platinum (Pt) mass fraction of 0.005, with the balance being alumina (Al_2O_3). What is the mole fraction of Pt? (Molecular weights: Al =27, O =16, Pt = 195)

a. 0.005
(b.) Less than 0.005
c. Greater than 0.005
d. Impossible to tell from the information provided

$$MW(Al_2O_3) = (2\times27) + (3\times16) = 54 + 48 = 102$$

$$102 < 195$$

On a relative basis, there will be fewer moles of Pt per mole of Al_2O_3 than grams, so the mole fraction of Pt must be < 0.005.

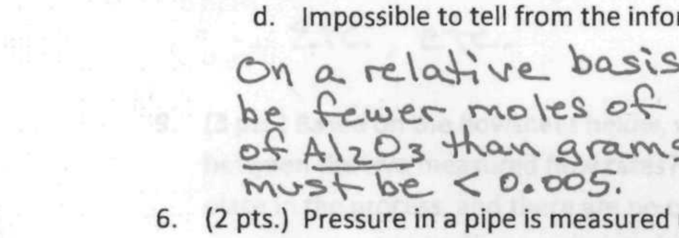
6. (2 pts.) Pressure in a pipe is measured using an open-end mercury manometer. The barometric pressure in the plant happens to be exactly 760 mmHg. The level in the arm connected to the pipe is 10 mm higher than the level in the open arm. What is the gauge pressure in the pipe?

a. 10 mmHg
(b.) -10 mmHg
c. 750 mmHg
d. 770 mmHg
e. Impossible to tell from the information provided

$$P_g = P_a - P_b$$

(P_g: gauge; P_a: absolute; P_b: barometric)

$$= -10 \text{ mmHg}$$



Pressure in Pipe (P_a) is 10 mm higher than in open arm, so $P_a - P_b = -10$ mmHg

7. (2 pts.) Before the development of chemical engineering as a separate profession, what were the professions of those who usually carried out "chemical engineering work?"

2 pts { Industrial Chemist
" " + Mech. Engr.

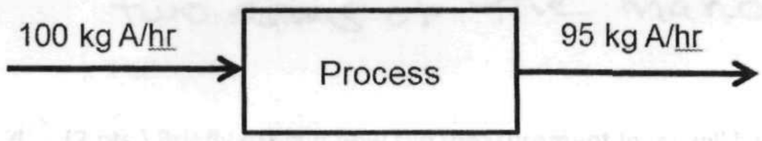
1 pt. { Chemist
Mech Engr.
Chemist + (Mech) Engr.

8. (4 pts.) Name one major event of the past two centuries that had a significant effect on the development of the "chemical process industries" (i.e., the industries that produce fuels and chemicals on a large scale), and briefly describe how the event caused the effect.

Many advancements in Chemistry & Physics could qualify.
WWI, WWII, The "Cold War"
Development of Digital Computers
Environmental Movement
Etc., etc.

• 1-2 pts. for a valid event
• 2-3 pts. for the explanation
• 4 pts max.

9. (3 pts.) Based on the flowsheet below, which of the following could **not** explain the discrepancy between the two measured flow rates? (circle all that apply) <u>Note:</u> No chemical reactions take place in the process, and there are no components other than "A" in either stream.



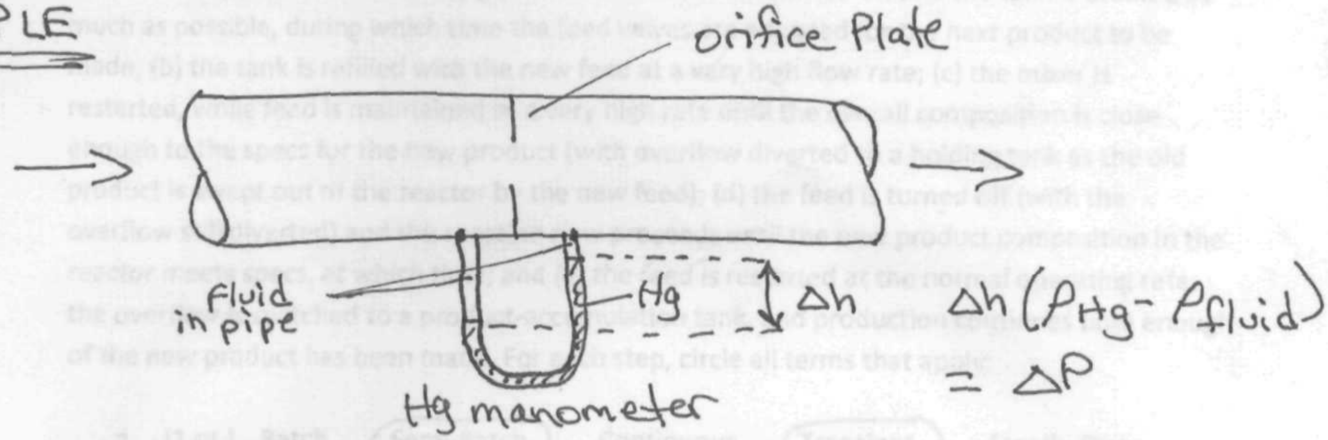
a. Accumulation of A within the process ✓
b. Faulty measurement of one or both flow rates ✓
c. A leak within the process ✓
(d.) Temperature decrease causing A to become more dense X
e. None of the above

Change in density would not affect an accurate measurement of mass flow rate

10. (7 pts.) Describe a device to measure flow of liquid in a metal pipe 300 cm in diameter. You may use any flowmeter discussed in class or in the book, one you've read about somewhere else, or one of your own invention. The flowmeter must give a continuous reading, so its operation cannot be based on periodic accumulation of fluid, and it must not disrupt the flow of the fluid to a significant extent (very small disruptions are OK).

a. (2 pts.) Draw a picture of the device

EXAMPLE



b. (2 pts.) Briefly explain the physical principle of its operation

The orifice plate creates a slight loss of pressure in the direction of flow, and the pressure loss will increase as the flow increases, and vice-versa

c. (1 pts.) Describe the actual measurement / observation that will be made

Difference in heights of Hg in the two arms of the manometer.

d. (2 pts.) Briefly explain how the measurement in (c) will be related to the flow rate

Either:

① via fundamental modeling using the principles of fluid dynamics,

OR:

② by conducting a series of tests using some variant of "bucket & stopwatch" and using the data to create a calibration curve

11. (5 pts.) An old type of liquid-phase reactor is the so-called "overflow reactor." This kind of reactor is fed slowly through a pipe at the bottom, and once the tank fills up, as long as the feed continues, liquid flows out through a pipe at the top, thereby maintaining a constant level. The tank is well-mixed via a motor-driven propeller. Multiple products are made in the reactor in different runs, but although the tank is drained (from the bottom) between runs, some residue remains, and it is too expensive to take the time to completely clean the old product out of the tank. Instead, at the end of a run, (a) the feed & mixer are turned off and the tank is drained as much as possible, during which time the feed valves are adjusted for the next product to be made; (b) the tank is refilled with the new feed at a very high flow rate; (c) the mixer is restarted, while feed is maintained at a very high rate until the overall composition is close enough to the specs for the new product (with overflow diverted to a holding tank as the old product is swept out of the reactor by the new feed); (d) the feed is turned off (with the overflow still diverted) and the reaction now proceeds until the new product composition in the reactor meets specs, at which time; and (e) the feed is restarted at the normal operating rate, the overflow is switched to a product-accumulation tank, and production continues until enough of the new product has been made. For each step, circle all terms that apply:

a. (1 pt.) Batch **(Semi-Batch)** Continuous **(Transient)** Steady-State

b. (1 pt.) Batch **(Semi-Batch)** Continuous **(Transient)** Steady-State

c. (1 pt.) Batch Semi-Batch **(Continuous)** **(Transient)** Steady-State

d. (1 pt.) **(Batch)** Semi-Batch Continuous **(Transient)** Steady-State

e. (1 pt.) Batch Semi-Batch **(Continuous)** Transient **(Steady-State)** *

a. outflow only, so not continuous or batch
rxr. contents changing, so transient
b. inflow only, otherwise as in a.
c. material entering <u>and</u> leaving, so continuous
OP still being removed, so transient
d. no flow in or out, so batch; rxn. is occurring, so transient
e. flow in and out, NP concentration holding steady, so continuous / S-S

* In reality, there might still be very small traces of OP in the rxr. at the beginning of e., but if they are low enough for NP to be on-spec., it is S-S ~~for~~ for practical purposes.

12. (5 pts.) Pressure Statics – Imagine two points A and B, some **horizontal** distance apart, but connected by a network of pipes, valves, vessels, etc. The system between A & B is known to be entirely filled with one or more liquids, and it is not open to the atmosphere at any point. With no measurements and no mathematical analysis, I can state: "The Pressure at Point A **must** be equal to the Pressure at Point B" only when five other things are true about A and B and the network between them. Name them:

a. A & B must be at the same height

b. Same fluid all the way from A to B

c. No flow – static system

d. No closed valves – continuous fluid from A to B

e. No significant Temperature difference between A & B *

* Liquids do expand/contract with signif. Temp. change, and that would change the density

Name: ANSWER KEY **Last 4 Digits of Student I.D.#:** ____________

CBE 140 Midterm – Spring Semester 2014 – Open-Book Section – 110 Points (out of 150 Total)

(Textbook, notes, other references, and calculators OK, but no "connected" devices)

1. (10 pts.) Cal CBE student Nora Lenderby goes home for Spring Break, but she absent-mindedly leaves the water in her kitchen sink running full blast. The sink drain is open, so there is no flood, but a **lot** of water has run down the drain by the time she returns (one week later). On her next monthly Water Bill, Nora discovers that she is being charged for 3.1 acre-feet of water, and the bill is for several thousand dollars, when her normal monthly Bill is less than $50. Recalling that an acre was originally defined as a strip of land 22 yards wide by 220 yards long, Nora sets out to check the Water Company's math. What does she conclude – is 3.1 acre-feet a reasonable figure for a sink faucet running wide open for a week?

Assuming that most of Nora's monthly Bill was due to the faucet running while she was away:

$$\dot{Q} = 3 \frac{\text{acre-ft}}{\text{week}}$$

This is a valid flow rate, but it wouldn't mean much physically to most people, so let's target units appropriate for a faucet & a kitchen sink, say gal/min or L/min

$$\frac{22 \text{ yards} \times 220 \text{ yards}}{} \left| \frac{3^2 \text{ ft}^2}{\text{yard}^2} \right. = 43{,}560 \frac{\text{ft}^2}{\text{acre}}$$

$$\dot{Q} = \frac{3 \text{ acre-ft}}{\text{week}} \left| \frac{1 \text{ week}}{7 \text{ days}} \right| \frac{1 \text{ day}}{24 \text{ hrs}} \left| \frac{1 \text{ hr}}{60 \text{ min}} \right| \frac{43{,}560 \text{ ft}^2}{\text{acre}} \left| \frac{7.48 \text{ gal}}{\text{ft}^3} \right.$$

$$= 97 \frac{\text{gal}}{\text{min}}$$

No, this is not a flow any kitchen faucet can generate. (Think about filling a 1-gal pitcher from a faucet – 1 gal/min is about right; 97 gal/min – no way!

2. (10 pts.) My friend's thoroughbred racehorse, a filly named *You Bettor Not,* including the weight of the jockey, saddle and other gear, plus any additional weight ("handicap") assigned to her, weighs about 1200 lb_m at the starting gate. Her top speed is about 40 miles/hr, and she takes about 2.0 seconds to accelerate from zero miles/hr at the starting gate to that top speed. Assuming that *You Bettor Not* expends energy at a constant rate to accelerate to her top speed, how many standard "horsepower" is she generating?

$$\text{Kinetic Energy} = \frac{1}{2} m v^2 \quad (m = \text{mass},\ v = \text{velocity})$$

{ • Remember from Physics Class or • FeR Eqn. 7.2-1a }

$$E_K = \frac{1}{2} \left| \frac{1200\ lbm}{} \right| \frac{40^2\ mi^2}{hr^2} \left| \frac{1^2\ hr^2}{3600^2\ s^2} \right| \frac{5280^2\ ft^2}{mi^2}$$

(You could also get this by dimensional analysis alone, but then you would not have the "1/2" coefficient)

$$= 2.07 \times 10^6\ \frac{lb_m - ft^2}{s^2}$$

$$\frac{2.07 \times 10^6\ lb_m\ ft^2}{s^2} \left| \frac{lbf - s^2}{lb_m - ft \cdot 32.2} \right. = 64{,}000\ ft\text{-}lb_f$$

($\frac{lbf - s^2}{lb_m - ft \cdot 32.2}$ = g_c)

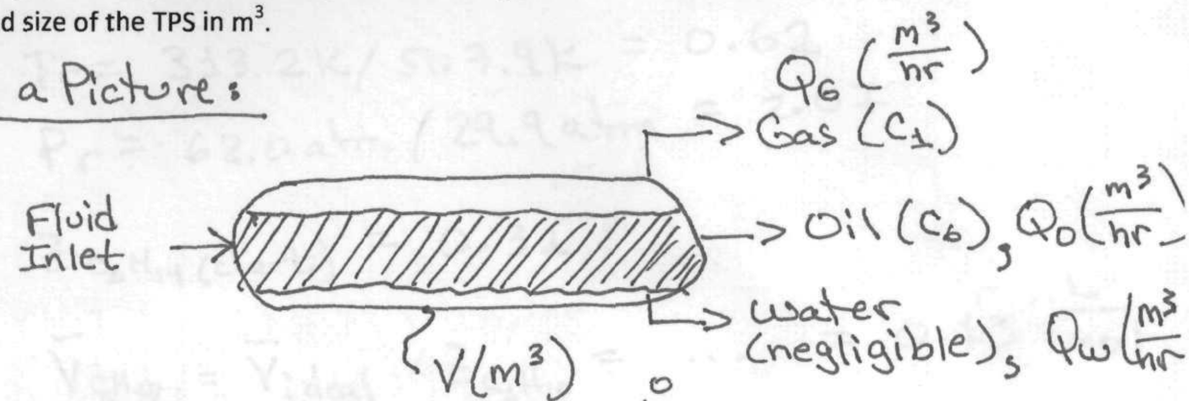
$$\text{Power} = \frac{\text{Energy}}{\text{Time}} = \frac{64{,}000\ ft\text{-}lbf}{2.0\ s} \left| \frac{1.341 \times 10^{-3}\ hp}{0.7376\ ft\text{-}lbf} \right.$$

$$= 58\ hp!$$ Go YBN!

{ Note: A car weighs ~3× as much as YBN, and E_K at 60 mph is 2.25× E_K at 40 mph, so a car achieving the same performance would do 0-60 in (2.0 s)(2.25) = 4.5 sec and need (3)(58) = 174 hp to do it! }

3. (30 pts.) In oil & natural gas production, once the produced fluids reach the surface, the first step is usually to send them to a Three-Phase Separator (TPS). The fluid is fed into one end, has some time to settle as it flows down the length of the TPS, and then at the far end, liquid water comes out the bottom of the TPS, gases come out the top, and organic liquids come out the middle. For this problem, consider a TPS operating at 40.0 °C. and 62.0 atm. The water production is small enough to be neglected, the organic liquid phase can be approximated as pure hexane (C_6H_{14}; T_c = 234.7 °C.; P_c = 29.9 atm), and the gas phase as pure methane (CH_4; T_c = 32.2 °C.; P_c = 48.2 atm). The well produces 13,000 kmol total per day, 20 mol% methane and 80 mol% hexane. In order to give the gas and liquid time to separate properly, the TPS has to allow a "residence time" of one hour – in other words, it must have a volume large enough to hold the total volume of fluids produced in one hour. Using the Compressibility Factor Chart provided (see Final Page of Exam), and assuming that the two phases have no mutual solubility, estimate the required size of the TPS in m^3.

Draw a Picture:



$$V = 1\,hr \times (Q_G + Q_O + \cancel{Q_W})\quad (Q_W = 0)$$

Strategy:

- Compute $\bar{V}_{ideal}\ (\frac{m^3}{mol})$
- Get Z_G & Z_O from the Chart
- Compute $\bar{V}_G = \bar{V}_{ideal} \times Z_G$ & $\bar{V}_O = \bar{V}_{ideal} \times Z_O$
- Compute $\dot{Q}_G = F_{TOTAL}(\frac{mol}{hr}) \times X_G \times \bar{V}_G$ (& same for $\dot{Q}_O$)
- Get $V = 1hr \times (Q_G + Q_O)$

(cont.)

$$\bar{V}_{ideal} = \frac{RT}{P} = \frac{0.0821 \text{ L-atm}}{\text{mol-K}} \Big| \frac{313.2 \text{ K}}{62.0 \text{ atm}} = 0.415 \frac{\text{L}}{\text{mol}}$$

CH_4:

$T_r = 313.2\text{K} / (273.2 + 32.2)\text{K} = 1.03$

$P_r = 62.0 \text{ atm} / 45.8 \text{ atm} = 1.35$

Z_{CH_4} (chart) $= 0.31$

$\bar{V}_{CH_4} = \bar{V}_{ideal} \times Z_{CH_4} = (.415 \frac{\text{L}}{\text{mol}})(0.31) = 0.13 \frac{\text{L}}{\text{mol}}$

C_6H_{14}:

$T_r = 313.2\text{K} / 507.9\text{K} = 0.62$

$P_r = 62.0 \text{ atm} / 29.9 \text{ atm} = 2.07$

$Z_{C_6H_{14}}$ (chart) $= 0.31$

$\bar{V}_{C_6H_{14}} = \bar{V}_{ideal} \times Z_{C_6H_{14}} = \ldots = 0.13 \frac{\text{L}}{\text{mol}}$

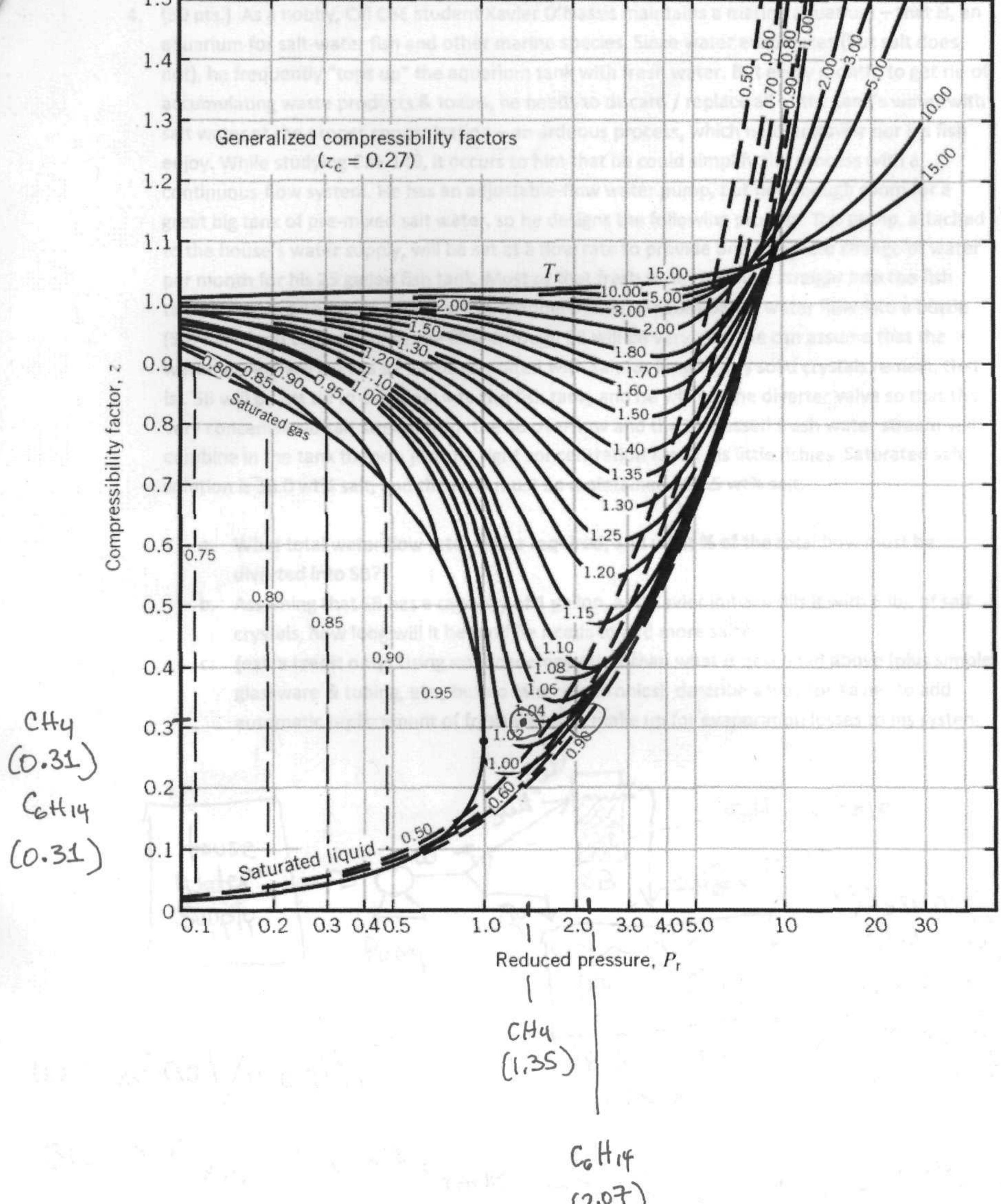
$\bar{V}_{AVG.} = 0.13 \text{ L/mol}$ (since $V_{CH_4} = V_{C_6H_{14}} = 0.13 \text{ L/mol}$)

$$V = \frac{1 \text{ hr}}{} \Big| \frac{13{,}000 \text{ mol}}{\text{day}} \Big| \frac{1 \text{ day}}{24 \text{ hrs}} \Big| \frac{0.13 \text{ L}}{\text{mol}} \Big| \frac{1 \text{ m}^3}{1000 \text{ L}}$$

$= 0.07 \text{ m}^3$

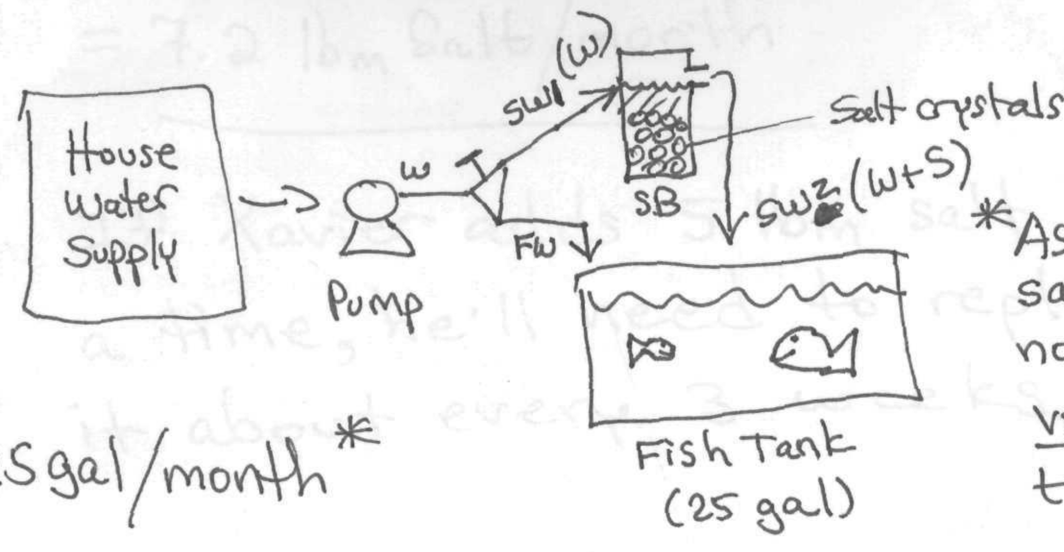
(was supposed to be 13,000 <u>kmol</u>/day, which would give $V = 70 \text{ m}^3$, a much more reasonable # for a real TPS)

3. (chart)


Generalized compressibility factors
(z_c = 0.27)
Compressibility factor, z
Reduced pressure, P_r
T_r
Saturated gas
Saturated liquid
CH4 (0.31)
C6H14 (0.31)
CH4 (1.35)
C6H14 (2.07)

4. (30 pts.) As a hobby, Cal CBE student Xavier O'Nassis maintains a marine aquarium – that is, an aquarium for salt-water fish and other marine species. Since water evaporates (but salt does not), he frequently "tops up" the aquarium tank with fresh water. But every month, to get rid of accumulating waste products & toxins, he needs to discard / replace all of the tank's water with salt water at the proper concentration – an arduous process, which neither Xavier nor his fish enjoy. While studying CBE 140, it occurs to him that he could simplify the process with a continuous-flow system. He has an adjustable-flow water pump, but not enough room for a great big tank of pre-mixed salt water, so he designs the following process: The pump, attached to the house's water supply, will be set at a flow rate to provide one complete change of water per month for his 25 gallon fish tank. Most of that fresh water will flow straight into the fish tank. But a diverter valve will be set to channel a small amount of the water flow into a bottle (SB) full of salt crystals. Since the flow through SB will be very slow, he can assume that the water leaving will always be 100% saturated with salt (as long as any solid crystals remain, that is). SB will be set up to overflow into the fish tank, and he will set the diverter valve so that the very concentrated salt stream from the SB overflow and the by-passed fresh water stream will combine in the tank to form just the right concentration for all his little fishies. Saturated salt solution is 36.0 wt% salt, and the tank must be maintained at 3.5 wt% salt.

a. What total water flow rate will be required, and what % of the total flow must be diverted into SB?
b. Assuming that SB has a capacity of 1 gallon, and Xavier initially fills it with 5 lb_m of salt crystals, how long will it be until he needs to add more salt?
c. **(extra credit only)** Using no technology other than what is described above (plus simple glassware & tubing, etc., but no fancy electronics), describe a way for Xavier to add automatic replacement of fresh water to make up for evaporation losses to his system.



*Assume salt adds no signif. <u>volume</u> to SW1

$w = 25\ gal/month$ *

$$SW2 \times X_{S_{SW2}} = W \times X_{S_{TANK}} \rightarrow SW2 = W \times \frac{X_{S,TANK}}{X_{S,SW2}}$$

. (cont.)

$$SW2 = \frac{25\ \text{gal}}{\text{mo.}} \left| \frac{0.035\ \text{lbm S}}{\text{lbm Water}} \right| \frac{1\ \text{lbm Water}}{0.36\ \text{lbm S}}$$

$$= 2.4\ \frac{\text{gal}}{\text{month}}$$

$$\text{So \% Diverted} = \frac{2.4\ \frac{\text{gal}}{\text{mo.}}}{25\ \frac{\text{gal}}{\text{mo.}}} \times 100 = 9.7\%$$

$$\frac{2.4\ \text{gal}}{\text{month}} \left| \frac{8.3\ \text{lbm}\ H_2O}{\text{gal}} \right| \frac{0.36\ \text{lbm Salt}}{\text{lbm}\ H_2O}$$

$$= 7.2\ \text{lbm Salt/month}$$

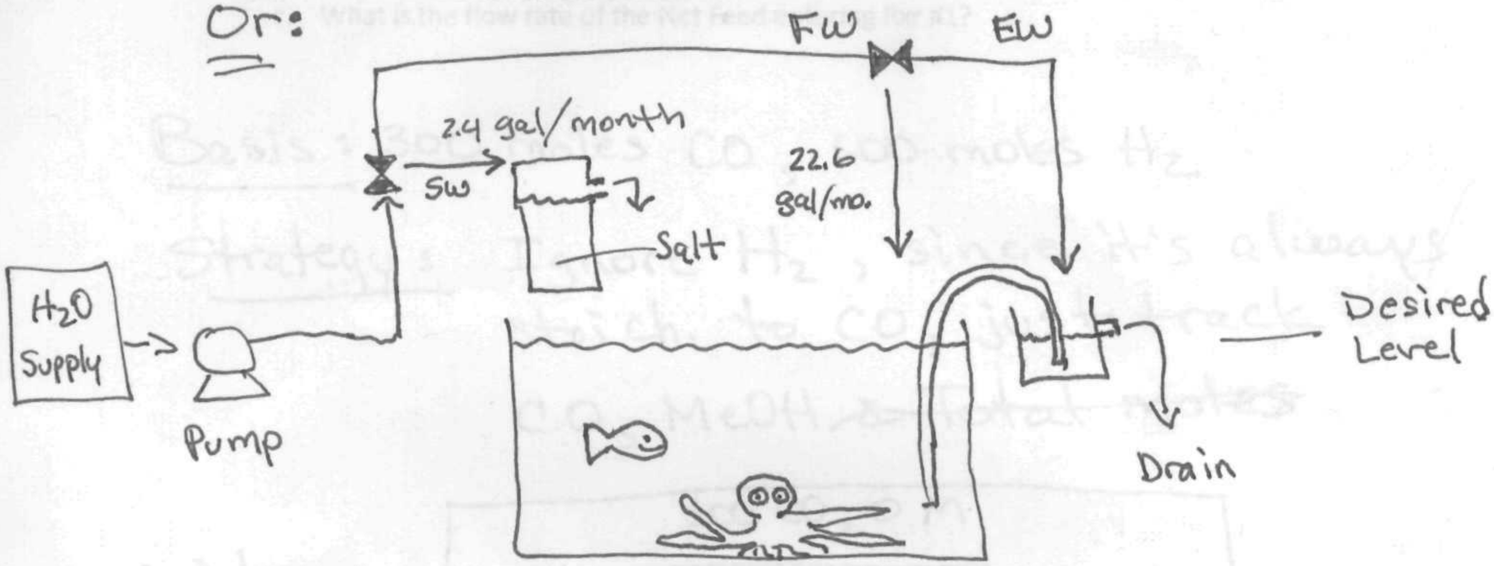
If Xavier adds 5 lbm salt at a time, he'll need to replace it about every 3 weeks.

cont.)

EC

One option is to monitor evaporation for a few months, figure out gal/month lost by evaporation, and increase rate of fresh water addition to account for that, keeping salt water addition rate constant.

Or:



Keep SW rate the same, add a second diverter valve, keep FW rate the same, set "EW" greater than evap. rate, then the "siphon" system shown will allow FW to flow back into tank whenever level drops below desired.

Stoich.!

5. (30 pts.) Methanol is synthesized according to the reaction: CO + 2H2 → CH3OH. Because of heat-management issues, the Fresh Feed (FF) is "split" among three reactors as follows: one-third of the FF enters Rxr #1, where 50% conversion is achieved; the product from Rxr #1 enters Rxr #2, along with another one-third of the FF. In Rxr #2, 40% conversion of the total entering CO is achieved. The product from Rxr #2 enters Rxr #3, along with the final one-third of the FF. → 30% conversion achieved

   a. What is the composition of the product exiting Rxr #3?
   b. What is the net % conversion for the process as a whole?

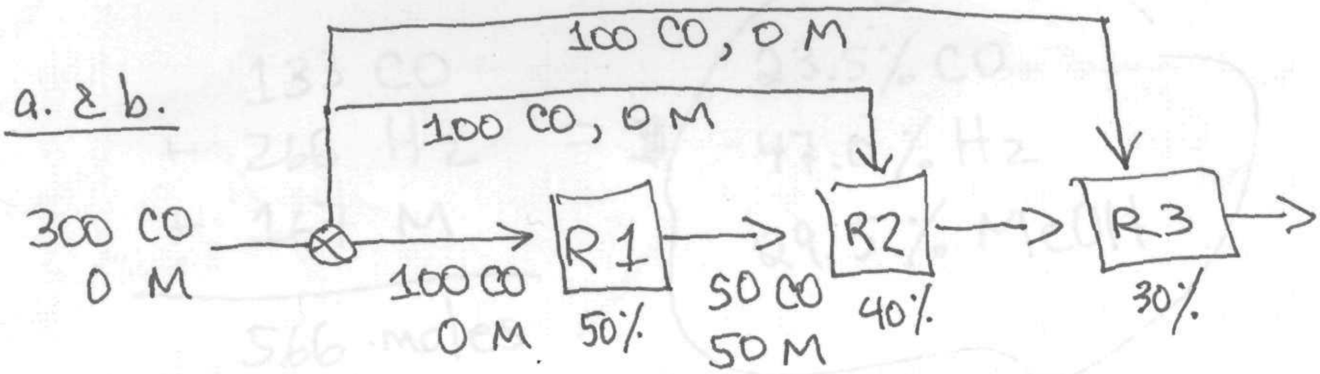
Now, assume that the methanol can be completely removed from the Rxr #3 product stream, and the unreacted CO and H2 recycled and mixed with the FF before it is split into three equal parts (as before). Assume the reactors each provide the same % conversion as before.

   c. What is the flow rate of the Net Feed entering Rxr #1?

Basis: 300 moles CO, 600 moles H_2

Strategy: Ignore H_2, since it's always stoich. to CO, just track CO, MeOH ~~& Total moles~~

a. & b.



① R1 bal. – Simple – 100 mol CO in, 50% Conv., 50 mol CO and 50 mol M out

② R2 bal – 50 mol CO + 50 mol M from R1 plus 100 CO and 0 M from bypassed feed

150 CO × 40% Conv. + 50 mol M = 110 M,

leaving 150 CO × 60% = 90 CO

5. (cont.)

③ R3 bal: 90 CO + 100 CO = 190 CO

110 M + 0 M = 110 M

(from R2) (BP Feed)

(190 CO) × 30% Conv. = 57 M

" × 70% Non " = 133 CO

R3 out = 133 CO + 167 M

$\frac{167\ M_{made}}{300\ CO_{fed}} = 55.6\%$ Conv.

→ 133 CO means 266 H_2, so:

133 CO
+ 266 H_2
+ 167 M

566 moles

= 23.5% CO, 47.0% H_2, 29.5% MeOH

6. **(Extra Credit Only)** This is problem #11 from the Closed Book Section. An old type of liquid-phase reactor is the so-called "overflow reactor." This kind of reactor is fed slowly through a pipe at the bottom, and once the tank fills up, as long as the feed continues, liquid flows out through a pipe at the top, thereby maintaining a constant level. The tank is well-mixed via a motor-driven propeller. Multiple products are made in the reactor in different runs, but although the tank is drained (from the bottom) between runs, some residue remains, and it is too expensive to take the time to completely clean the old product out of the tank. Instead, at the end of a run, (a) the feed & mixer are turned off and the tank is drained as much as possible, during which time the feed valves are adjusted for the next product to be made; (b) the tank is refilled with the new feed at a very high flow rate; (c) the mixer is restarted, while feed is maintained at a very high rate until the overall composition is close enough to the specs for the new product (with overflow diverted to a holding tank as the old product is swept out of the reactor by the new feed); (d) the feed is turned off (with the overflow still diverted) and the reaction now proceeds until the new product composition in the reactor meets specs, at which time; and (e) the feed is restarted at the normal operating rate, the overflow is switched to a product-accumulation tank, and production continues until enough of the new product has been made. For each step, circle all terms that apply:

   a. For Extra Credit Only, plot the concentration of the Old Product (OP) and the New Product (NP) in the tank during periods a, b, c, d, and e. The "target" product concentrations for OP & NP are shown as dashed lines, and the plot only needs to be **qualitatively** correct.