ENV 4417: WATER QUALITY AND TREATMENT

Fall 2015
Exam #1
Thursday, October 15

University of South Florida
Civil & Environmental Eng.
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Instructions:

1. You may read these instructions, but do not turn the page or begin working until instructed.
2. This exam contains three questions. ***Answer any two***.
3. If you attempt all three questions, make sure that you indicate clearly which two you want me to grade. If it isn't clear, then I will choose which two I feel like grading.
4. Some questions might have multiple parts. In those cases, the point value of each part is indicated. The total number of points possible is 100.
5. Unit conversion factors and other potentially useful information are provided on pages 2 and 3.
6. Answer each question in the space provided. If you need more space, you can attach additional pages as needed, but make sure to put your name on them.
7. Show your work and state any important assumptions you make. I cannot award partial credit if I can't follow what you did.
8. Report a reasonable number of significant digits in your answers.
9. Include units in your answers. An answer without proper units is not correct!
10. The exam is closed-book, but you are allowed one personal note sheet of standard 8.5-by-11 or A4 paper. You may write anything you want on it, both front and back, but it must be hand-written.
11. A hand-held calculator is recommended. Other electronic devices are not permitted. Calculators may not be pre-programmed with formulae from the class.
12. Time limit: 60 minutes. Stop working when asked. If you continue working after time has been called, you will be penalized at a rate of 1 point per minute.
13. Don't cheat. Cheating will result in appropriate disciplinary action according to university policy. More importantly, cheating indicates a lack of personal integrity.
14. Please print your name legibly in the space provided below, and turn in this exam at the end of the period.
15. Hints:
    - Read each question carefully and answer the question that is asked.
    - Watch your units. If you take good care of your units, they will take good care of you.
    - Work carefully and don't rush.

Name: ANSWER KEY

Potentially useful constants:

Ideal gas constant, R:	8.314 Pa•m^3•mol^{-1}•K^{-1} = 82.06×10^{-6} atm•m^3•mol^{-1}•K^{-1}
Gravitational acceleration, g:	9.81 m/s^2
Molecular weight of water, H_2O:	18.01 g/mole
Density of water at 25 °C:	0.9970 g/mL = 997.0 kg/m^3
Viscosity of water at 25 °C:	0.890×10^{-3} Pa•sec
Density of water at 15 °C:	0.9991 g/mL = 999.1 kg/m^3
Viscosity of water at 15 °C:	1.136×10^{-3} Pa•sec

Potentially useful conversion factors:

Pressure:	1 atm = 760 mm Hg = 760 torr = 14.7 lb$_{force}$/in^2 = 101,325 Pa
	1 Pa = 1 N/m^2 = 1 kg/(m•sec^2)
	1 bar = 10^5 Pa
Mass:	1 kg = 1000 g = 10^6 mg = 10^9 µg
	1 kg = 2.207 lb$_{mass}$
	1 t (metric tonne) = 1000 kg = 2207 lb$_{mass}$
	1 ton (English ton) = 2000 lb$_{mass}$
Length:	1 km = 1000 m = 10^5 cm = 10^6 mm = 10^9 µm
	1 ft = 12 in = 30.48 cm = 0.3048 m
Temperature:	25 °C = 298.15 K
Volume:	1 m^3 = 1000 L = 10^6 mL = 10^6 cm^3
	1 gal = 3.785 L
Work/Energy:	1 BTU = 1.055 kJ
Power:	1 MW = 10^6 W = 10^6 J/s = 10^6 N•m/s
Area :	1 ha = 10^4 m^2

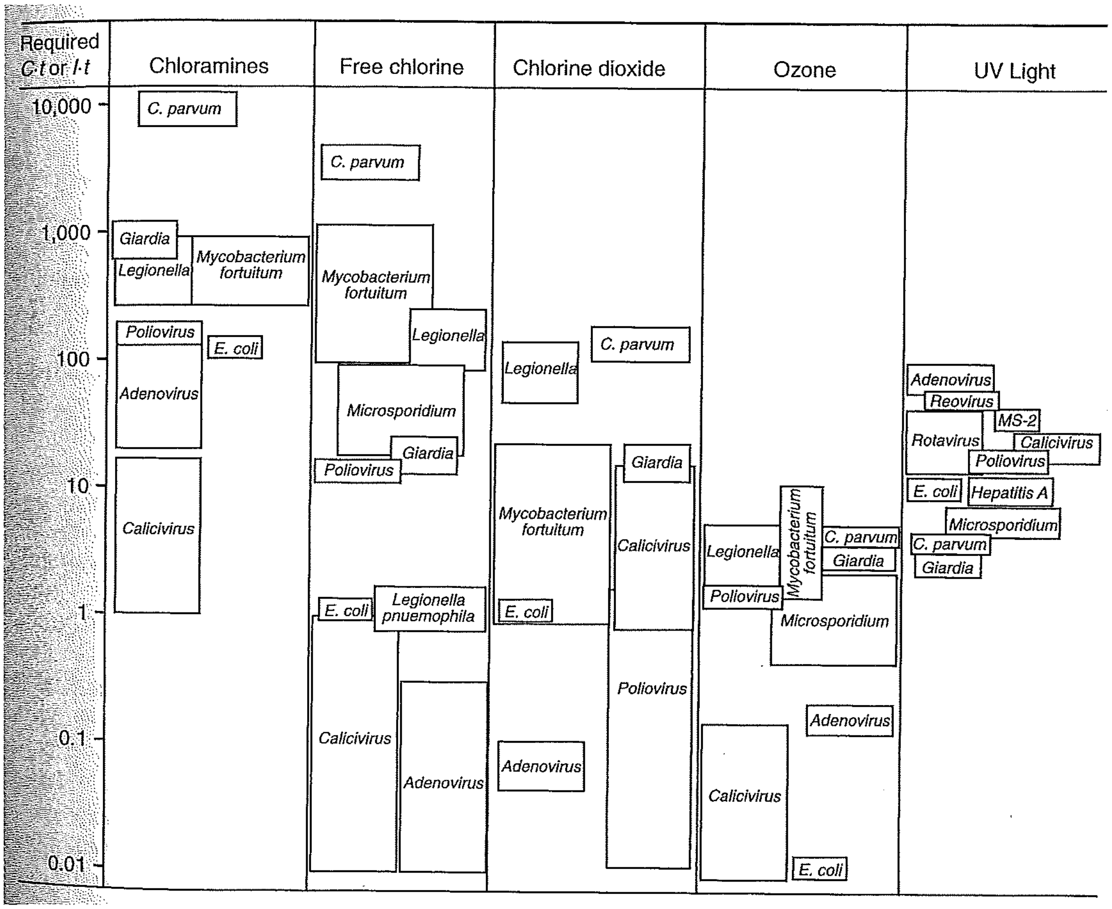
Atomic Masses:

H = 1.008 g/mole	C = 12.011 g/mole	N = 14.007 g/mole	O = 15.999 g/mole
P = 30.974 g/mole	S = 32.06 g/mole	Cl = 35.453 g/mole	Br = 79.904 g/mole
Na = 22.99 g/mole	Mg = 24.31 g/mole	Ca = 40.08 g/mole	Fe = 55.85 g/mole

pK$_A$ values of some common acids (at ambient temperature):

$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$	pKa = 6.35
$HOCl \leftrightarrow H^+ + OCl^-$	pKa = 7.54
$NH_4^+ \leftrightarrow H^+ + NH_3$	pKa = 9.2
$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$	pKa = 10.33

The following chart shows the *C*t* values required for 99% inactivation of selected pathogens (in a batch or plug-flow reactor), depending on which disinfectant is used.



From *Water Treatment: Principles and Design*, 3rd Edition, 2012; Crittenden JC, Trussell RR, Hand DW, Howe KJ, Tchobanoglous G; John Wiley & Sons, Inc. / MWH.

1. (50 pts) Imagine that you are designing a disinfection system for a city's water treatment plant.

- The design flow rate is 6.0 million gallons per day, which is equivalent to 15.8 m^3/min.
- The disinfectant will be chlorine, administered as chlorine gas.
- You must design the system to remove 99% of Giardia. (Actually the federal standard for Giardia is more stringent than this, but for the purposes of this exam, we will use 99% removal of Giardia as our requirement.)
- You may assume that the chlorine contactor works as an ideal plug-flow reactor. Of course we know that no reactor can be truly plug-flow, but for this exam, it is OK to assume perfect plug-flow.
- The water contains 2.1 mg/L of ammonia nitrogen, i.e., 2.1 mg/L of NH_3 as N.
- The water contains organic matter that exerts a chlorine demand of 2.0 mg/L (as Cl_2).

Your job is to *specify the* ***volume of the reactor*** *(in units of m^3) and the* ***chlorine dose rate*** *(in units of kg/d)* to meet the requirement of 99% inactivation of Giardia. *You must show your work and/or explain your recommendation in a way that I can follow.*

Hint #1: There is no single "right" answer to this problem. Your job is to come up with a design that is reasonable and will get the job done.
Hint #2: Use the chart on page 3.

- From p 3, we see that 99% inactivation of Giardia requires $Ct \approx 1000$ for chloramines or $Ct \approx 20$ for free chlorine.
- Therefore I recommend free chlorine. It is ~50 times stronger than chloramine.
- So we need $Ct \approx 20 \ \frac{mg}{L} \cdot min$ ... Let's choose $3 \ \frac{mg}{L}$ residual and 7 min contact time.
  (You could choose 4 mg/L and 5 min, or 2 mg/L and 10 min, etc.)
- 7 min contact time $\Rightarrow$ $V = Q\Theta = \left(15.8 \ \frac{m^3}{min}\right)(7 \ min) = \underline{\underline{110 \ m^3 \text{ reactor volume}}}$

Now, what chlorine dose rate is required to give a residual of $3 \ \frac{mg}{L}$ free chlorine?

- We must break the ammonia ... assume $8 \ \frac{mg \ Cl_2}{mg \ NH_3\text{-}N}$ is required to break the ammonia.

more space to work on problem 1:

$$2.1\ \frac{mg}{L}\ NH_3\text{-}N \ * \ 8\ \frac{mg\ Cl_2}{mg\ NH_3\text{-}N} = 16.8\ \frac{mg}{L}\ Cl_2 \text{ to break ammonia}$$

$2.0\ \frac{mg}{L}\ Cl_2$ for demand by organics

$3.0\ \frac{mg}{L}\ Cl_2$ residual as free chlorine

$21.8\ \frac{mg}{L}\ Cl_2$ dose required

What is that in kg/d?

$$\left(6\times10^6\ \frac{gal}{d}\right)\left(\frac{3.785\ L}{1\ gal}\right)\left(21.8\ \frac{mg\ Cl_2}{L}\right)\left(\frac{1\ kg}{10^6\ mg}\right) = \underline{\underline{495\ kg/d}}$$

So if we dose ~500 kg/d of Cl_2 gas into the water in a 110-m^3 PFR with a 7-min residence time, we should be able to inactivate 99% of Giardia.

We might want to build in a little margin of safety by making the reactor a little bigger and/or increasing the dose a little. But don't increase the dose too much! -- you'll form DBPs and the water will taste bad.

2. (50 pts) Imagine that you are designing a softening system to remove hardness from a city's water supply.

- The design flow rate is 6.0 million gallons per day, which is equivalent to 15.8 m^3/min.
- The influent water contains the following major ions at the following concentrations:
  $[Ca^{2+}]$ = 64.1 mg/L $[Mg^{2+}]$ = 15.8 mg/L $[Na^{+}]$ = 11.5 mg/L
  $[HCO_3^{-}]$ = 152.5 mg/L $[SO_4^{2-}]$ = 105.7 mg/L $[Cl^{-}]$ = 10.6 mg/L
- The pH of the influent water is 7.33.

a. (10 pts) Estimate/calculate the hardness of the influent water, in units of mg/L as $CaCO_3$.

$$[Ca^{2+}] = 64.1 \frac{mg}{L} * \frac{1\ mmol}{40.08\ mg} = 1.6 \frac{mmol}{L} * 2 \frac{meq}{mmol} = 3.2 \frac{meq}{L}$$

$$[Mg^{2+}] = 15.8 \frac{mg}{L} * \frac{1\ mmol}{24.31\ mg} = 0.65 \frac{mmol}{L} * 2 \frac{meq}{mmol} = 1.3 \frac{meq}{L}$$

4.5 meq/L hardness

$$4.5 \frac{meq}{L} * \frac{100\ mg\ CaCO_3}{2\ meq} = 225 \frac{mg}{L} \text{ as } CaCO_3$$

b. (40 pts) Suppose that we want to soften the water by removing all (or very close to all) of the calcium. However, we do not want to remove the magnesium. Specify the chemical(s) to be added to the water for the calcium removal, and the rate(s) at which the chemical(s) will be added, in units of kg/d.

$$[HCO_3^-] = 152.5 \frac{mg}{L} * \frac{1\ mmol}{61.016\ mg} = 2.5 \frac{mmol}{L} * \frac{1\ meq\ HCO_3^-}{mmol} = 2.5 \frac{meq}{L}\ HCO_3^-$$

So we have 3.2 meq/L of Ca^{2+}, but only 2.5 meq/L of HCO_3^-.

Therefore we have some non-carbonate hardness... 0.7 meq/L of non-carbonate hardness.

Use lime $Ca(OH)_2$ to remove the carbonate hardness

Use soda ash Na_2CO_3 to remove the non-carbonate hardness

2. continued

more space to work on part b:

Lime addition : $Ca^{2+} + Ca(OH)_2 + 2\ HCO_3^- \rightarrow 2\ CaCO_3(s) + 2\ H_2O$

$$2.5\ \frac{meq\ Ca^{2+}}{L} * \frac{1\ mmol\ Ca^{2+}}{2\ meq} * \frac{1\ mmol\ Ca(OH)_2}{1\ mmol\ Ca^{2+}} * \frac{74.09\ mg\ Ca(OH)_2}{1\ mmol\ Ca(OH)_2} = 92.62\ \frac{mg\ Ca(OH)_2}{L}$$

$$6 \times 10^6\ \frac{gal}{d} * \frac{3.785\ L}{gal} * 92.62\ \frac{mg\ Ca(OH)_2}{L} * \frac{1\ kg}{10^6\ mg} = 2100\ kg/d\ \text{lime}$$

Soda ash addition : $Ca^{2+} + Na_2CO_3 \rightarrow 2\ Na^+ + CaCO_3(s)$

$$0.7\ \frac{meq\ Ca^{2+}}{L} * \frac{1\ mmol\ Ca^{2+}}{2\ meq} * \frac{1\ mmol\ Na_2CO_3}{1\ mmol\ Ca^{2+}} * \frac{105.99\ mg\ Na_2CO_3}{1\ mmol\ Na_2CO_3} = 37.10\ \frac{mg\ Na_2CO_3}{L}$$

$$6 \times 10^6\ \frac{gal}{d} * \frac{3.785\ L}{gal} * 37.10\ \frac{mg\ Na_2CO_3}{L} * \frac{1\ kg}{10^6\ mg} = 840\ kg/d\ \text{soda ash}$$

Add 2100 kg/d lime and 840 kg/d soda ash to remove the Ca^{2+}.

That is a lot of chemicals! About 3 tons per day when combined.

c. (BONUS of up to 10 EXTRA points – only if you have extra time!) Estimate the concentrations of cations and anions that will be in the water following the calcium removal. Report your answers in units of meq/L.

Ca^{2+} : removed $\Rightarrow [Ca^{2+}] \approx 0$ meq/L.

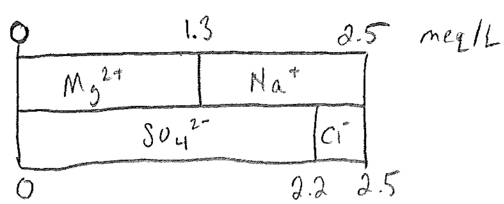
Mg^{2+} : no change $\Rightarrow [Mg^{2+}] \approx 1.3$ meq/L

Na^+ : Started with $11.5\ \frac{mg}{L} = 0.5$ meq/L, then added 0.7 meq/L $\Rightarrow$ 1.2 meq/L Na^+.

HCO_3^- : removed $\Rightarrow [HCO_3^-] \approx 0$ mg/L

$$SO_4^{2-} :\ 105.7\ \frac{mg}{L} * \frac{1\ mmol\ SO_4^{2-}}{96\ mg\ SO_4^{2-}} = 1.1\ \frac{mmol}{L} * 2\ \frac{meq\ SO_4^{2-}}{mmol} = 2.2\ \frac{meq}{L}\ SO_4^{2-}$$

$$Cl^- :\ 10.6\ \frac{mg}{L} * \frac{1\ mmol\ Cl^-}{35.453\ mg\ Cl^-} = 0.3\ \frac{mmol}{L} * 1\ \frac{meq\ Cl^-}{mmol} = 0.3\ \frac{meq}{L}\ Cl^-$$



3. (30 pts) Imagine that you are designing a reverse-osmosis system for a city's water treatment plant. The city's water source is brackish groundwater.

- The design flow rate is 6.0 million gallons per day, which is equivalent to 15.8 m^3/min.
- The brackish groundwater contains 2,300 mg/L of Na^+ and 3,545 mg/L of Cl^-. Concentrations of other ions can be ignored for the purposes of this problem.
- The temperature of the brackish groundwater is 15 °C.
- The city got a good deal from a vendor on RO4U spiral-wound membrane elements. Each element has a membrane area of 35 m^2. The mass-transfer coefficient for water through the membrane is 0.87 L/(m^2•hr•bar). The mass-transfer coefficient for salt through the membrane is 0.61 L/(m^2•hr).

a. (35 pts) Assume that your design criterion is that salt rejection must be at least 98.5%. Specify the *trans-membrane pressure* that you recommend to provide this rejection. Report your answer in units of bar.

$$\text{Rejection} = 0.985 \Rightarrow C_{salt}^{permeate} = 0.015 * C_{salt}^{feed} = (0.015)(5{,}845 \tfrac{mg}{L}) = 88 \text{ mg/L}$$

$$C_{salt}^{permeate} = 88 \text{ mg/L} = F_s / F_w$$

$$F_s = k_s \,\Delta C \approx \left(0.61 \tfrac{L}{m^2 \cdot hr}\right)\left(5845 \tfrac{mg}{L} - 88 \tfrac{mg}{L}\right) = 3512 \tfrac{mg}{m^2 \cdot hr}$$

$$F_w = k_w (\Delta P - \Delta\pi)$$

$$\therefore \frac{F_s}{F_w} = \frac{3512 \text{ mg/m}^2\cdot hr}{\left(0.87 \tfrac{L}{m^2\cdot hr\cdot bar}\right)(\Delta P - \Delta\pi)} = 88 \tfrac{mg}{L} \Rightarrow \Delta P - \Delta\pi = \frac{3512 \text{ mg/m}^2\cdot hr}{\left(0.87 \tfrac{L}{m^2\cdot hr\cdot bar}\right)\left(88 \tfrac{mg}{L}\right)}$$

$\Delta P - \Delta\pi = 45.87$ bar. Need ~46 bar of pressure <u>above</u> the osmotic pressure in order to produce what we want.

$\Delta P = 45.87 \text{ bar} + \Delta\pi$ ... what is $\Delta\pi$?

$$\pi \text{ of feed} = CRT = \left(0.1 \tfrac{mol}{L} Na^+ + 0.1 \tfrac{mol}{L} Cl^-\right)\left(\tfrac{1000\ L}{m^3}\right)\left(8.314 \tfrac{Pa \cdot m^3}{mol \cdot K}\right)(288.15\ K)$$

$$= 479{,}136 \text{ Pa} = 4.79 \text{ bar}$$

3. continued

more space for part a:

Π of permeate is negligible, so $\Delta\Pi \approx 4.79$ bar.

$\Delta P = 45.87 \text{ bar} + 4.79 \text{ bar} = 50.66 \text{ bar} \approx$ 51 bar trans-membrane pressure

This TMP will produce enough water flux so the $C_{salt}^{permeate}$ will be low

b. (15 pts) The city has enough money in the budget to purchase 100 spiral-wound RO4U membrane elements from the vendor. Assuming the trans-membrane pressure you specified in part (a), will the city be able to meet the design flow rate of 6.0 MGD with 100 membranes? Show your calculations to support your answer. (No credit for just a lucky guess of "yes" or "no".)

Water flux $F_w = k_w(\Delta P - \Delta\Pi)$.

$$F_w = \left(0.87 \frac{L}{m^2 \cdot hr \cdot bar}\right)(45.87 \text{ bar}) = 39.9 \ L/m^2 \cdot hr$$

$$100 \text{ membranes} * 35 \ m^2 * 39.9 \frac{L}{m^2 \cdot hr} = 140{,}000 \ L/hr$$

$$140{,}000 \frac{L}{hr} * \frac{24 \ hr}{d} * \frac{1 \ gal}{3.785 \ L} = 886{,}000 \frac{gal}{L} = 0.886 \text{ MGD}$$

No, we are not even close To 6 MGD with 100 membrane elements. The city will have to either come up with a lot more money, or else find a different membrane ... no Ro4U!

END OF EXAM