ENV 6438: PHYSICAL & CHEMICAL PROCESSES FOR DRINKING WATER TREATMENT
FINAL EXAMINATION

Spring 2020 — University of South Florida
Monday, May 4 — Prof. J.A. Cunningham

Instructions:

1. Read these instructions carefully before you begin working on the exam.
2. Work on your own paper.
3. There are three possible ways to submit your completed exam:
   a. My preferred method is to have you upload a PDF file to the "final exam" assignment on Canvas. This requires you to be able to scan your completed work to a PDF file.
   b. The second possible way is to e-mail me your work, in either a single file (preferred) or in a series of files (not preferred): cunning@usf.edu.
   c. The third way is to send your work to me via text: 813-846-0148. Text is the worst option, and I definitely prefer either upload or e-mail, but text is OK as a last resort.
4. Stop working at **noon**. Then, you have 15 minutes to scan your work and deliver it to me electronically by 12:15 PM. You are on your honor to not work on the exam past noon.
5. If I do not receive your completed exam by 12:15 PM, you will be penalized for late delivery, at a rate that I deem appropriate.
6. This exam contains four questions. Answer question #1 – it is not really a "question", but perform the tasks required. Then, answer any ***two*** of the remaining three questions.
7. Some questions might have multiple parts. In those cases, the point value of each part is indicated. The total number of points possible is 200.
8. Unit conversion factors and other potentially-useful information are provided on the back of this page.
9. Show your work and state any important assumptions you make. I cannot award partial credit if I can't follow what you did.
10. Report a reasonable number of significant digits in your answers.
11. Include units in your answers. An answer without proper units is not correct!
12. You can use your course notes, your text book, a calculator, your computer, Google, Alexa, Siri, and/or any other resource that does not involve a live human being. However, *you may not ask assistance from, nor give assistance to, another live person*.
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. 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.

Potentially useful constants:

Ideal gas constant, R:	$8.314\ Pa \cdot m^3 \cdot mol^{-1} \cdot K^{-1} = 82.06 \times 10^{-6}\ atm \cdot m^3 \cdot mol^{-1} \cdot K^{-1}$
Boltzmann's constant, k:	1.381×10^{-23} J/K
Gravitational acceleration, g:	9.81 m/s^2
Molecular weight of water, H_2O:	18.01 g/mole
Density of water at 25 °C:	0.997 g/mL = 997 kg/m^3
Viscosity of water at 18 °C:	0.89×10^{-3} Pa·s = 0.89×10^{-3} kg/(m·s)

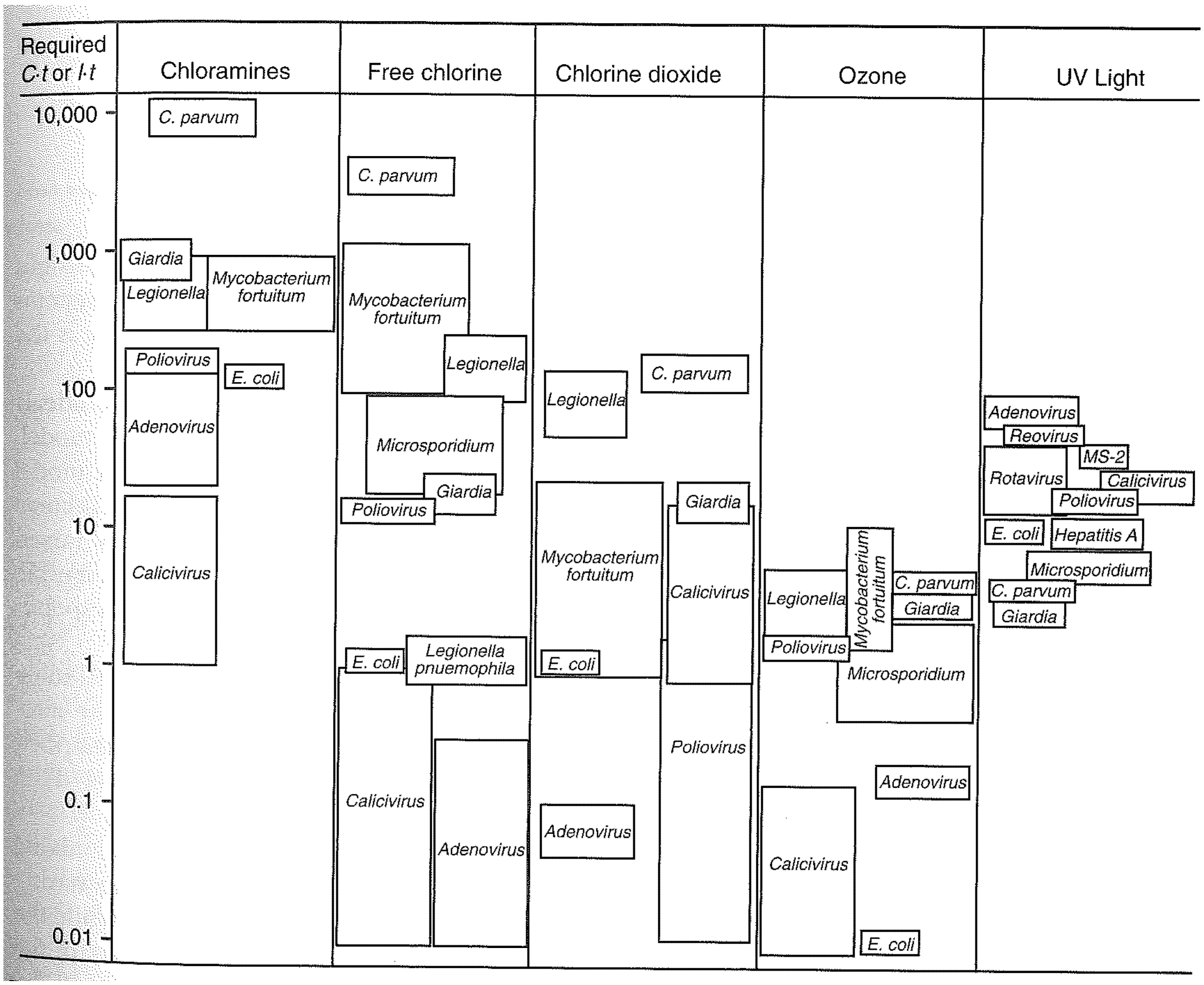
Potentially useful conversion factors:

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	Al = 26.98 g/mole	Ca = 40.08 g/mole
Fe = 55.85 g/mole			

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. Every student should create a "cover page" for his/her exam this year. On the cover page, do the following:
    a. Print your name legibly.
    b. Write out, by hand, the following pledge: "I affirm that I have not received any aid on this exam from any other person, nor given any aid to any other person."
    c. Before submitting your exam, sign your name below the pledge. Your signature indicates that you are, in fact, affirming the truth of the statement. <u>*Students who violate this pledge will receive an FF grade for the semester*</u>.

    <u>I will not grade your exam unless this cover page, including signature, is included as the first page of your submitted exam</u>.

2. (100 pts) *Flocculation; Sedimentation; Filtration*

I was wondering which is more effectively removed at a water treatment plant, viruses or bacteria. As you know by now, when I am wondering about something, we all get to find out together! For the purposes of this problem, we will treat viruses and bacteria as spheres. Viruses have a diameter of about 0.1 μm and a density of about 1350 kg/m^3. Bacteria have a diameter of about 1.0 μm and a density of about 1100 kg/m^3.

a. (20 pts) Show that neither bacteria nor viruses are effectively removed via the process of conventional sedimentation. Assume a water temperature of 25 °C and an overflow rate of 1.5 m/hr for the sedimentation basin. (This is a pretty reasonable value.)

Now that we know sedimentation is not a good mechanism for removing viruses or bacteria, we can consider flocculation and filtration, both which seem a bit more promising.

During flocculation, if the pathogen "sticks" to a floc, then probably it will be subsequently removed via sedimentation or filtration, because these processes are good at removing large flocs. However, some pathogens might make it through flocculation without adhering to a floc. It is possible to derive (with a mass balance, of course!) the following expression for the concentration of pathogens exiting a single-stage flocculation basin:

$$\frac{N_1}{N_0} = \frac{1}{1 + \alpha\, \beta\, \tau\, N_f}$$

where N_1 is the number concentration of pathogens exiting the flocculation basin, N_0 is the number concentration of pathogens entering, α is the "sticking efficiency" between the pathogen and the floc, β is the second-order rate coefficient for collisions between pathogens and flocs, τ is the average hydraulic residence time of the flocculation basin, and N_f is the number concentration of flocs.

b. (30 pts) Consider a flocculation basin with an average residence time of 30 min and an average velocity gradient $G = 60\ s^{-1}$. Assume that all collisions between a pathogen and a floc are successful, i.e., result in the pathogen adhering to the floc. Suppose that the concentration of flocs in the basin is $N_f = 1\times10^{10}$ flocs/m^3, and that flocs can be treated as spheres of diameter 30 μm and density 1350 kg/m^3. These all seem like reasonable estimates or approximations. Estimate N_1/N_0 for both viruses and bacteria. Ignore pathogen-pathogen collisions; only consider pathogen-floc collisions. If you make any other assumptions or approximations, state them clearly.

We know (from part a) that the pathogens that "escape" the flocculation basin are able to pass through sedimentation without being removed. Therefore, the concentration of pathogens that reaches the filters is the concentration that exited flocculation, i.e., N_1.

problem 2 continues →

2. continued

   c. (30 pts) Consider a granular-medium filter that consists of sand grains with a uniform diameter of 0.7 mm. The porosity of the filter is 0.40 and the depth of the filter is 1.5 m. The filter loading rate ("velocity") is 5.0 $(m^3/hr)/m^2$ = 5.0 m/hr. Those all seem like reasonable values. Assume that all collisions between a pathogen and a sand grain are successful, i.e., result in the pathogen collecting on the grain. Estimate N_2/N_1 for both viruses and bacteria, where N_1 is the concentration entering the filters and N_2 is the concentration exiting the filters.

   d. (10 pts) Combine your answers from (b) and (c) to determine the overall removal of viruses and bacteria. You can report either fraction removed or percent removed.

   e. (10 pts) Which was removed more effectively, viruses or bacteria? Briefly explain why (a few sentences).

3. (100 pts) *Disinfection; Reactor theory*

   The City of Doerrville has a problem at their water-treatment plant. They have been disinfecting their water with chlorine gas, but they are often finding *Escherischia coli* bacteria in their finished water. They had been dosing at 5.3 mg/L (as Cl_2), but when they started seeing *E. coli* in the treated water, they increased the dose to 8.9 mg/L. It didn't help – in fact, if anything, the situation got *worse* after they increased the chlorine dose, which seemed odd to the plant manager.

   To figure out what was going on, the city ran some batch reactor tests in their lab at the water treatment plant. They created a series of 8 batch reactors with filtered water from the facility; they dosed each reactor with a different concentration of chlorine (using sodium hypochlorite solution rather than Cl_2 gas for the lab study); they waited 10 minutes; then they analyzed for the concentration of *E. coli* in the treated water. The results are given in the table below. The initial concentration of *E. coli* was 235 colony-forming units (CFU) per liter of filtered water.

Reactor number	Chlorine dose (mg/L as Cl_2)	*E. coli* conc. after 10 min (CFU / L water)
1	0.0	234
2	3.5	48
3	5.3	21
4	7.1	10
5	8.9	46
6	10.6	233
7	12.4	0
8	14.2	0

   a. (15 pts) Assume that disinfection of *E. coli* follows first-order kinetics according to Chick's Law and the Chick-Watson Law. For reactors 1 through 6, estimate/calculate the first-order rate constant, k_1, for disinfection of *E. coli*. (Each reactor will have a different value of k_1, so you have to do the calculation six times.) Report your answers in units of min^{-1}. Use the data in the table to make your estimates of k_1.

   b. (15 pts) Make a graph of k_1 versus the chlorine dose for the first six reactors. The graph doesn't have to be extremely fancy, but if you do a good job on the graph, it might help with the next part(s) of the problem.

   c. (10 pts) Describe in words why you think the Doerrville plant is having problems with *E. coli* in their finished water.

problem 3 continues →

3. continued

    d. (15 pts) Estimate/calculate the concentration of ammonia, NH_3, in the water. Report your answer in units of mol/L and as mg/L as N.

    e. (15 pts) Following the batch study, the facility began dosing their water at a concentration of 12.4 mg/L (as Cl_2). Estimate/calculate the *residual* chlorine concentration you would expect to see in the disinfection chamber. Would that residual be free chlorine or combined chlorine?

    f. (15 pts) Estimate/calculate the first-order rate coefficient, k_1, when the facility was dosing at 12.4 mg/L. The data from the batch experiments won't help – instead, use the graph on p 3 of this exam. From that graph, it is possible to estimate a value of λ, the coefficient of specific lethality. Then you can estimate k_1 from λ.

    g. (15 pts) The disinfection chamber at the facility can be modeled as a series of 5 completely mixed flow reactors (CMFRs) in series, where each of the 5 stages has an average residence time of 10 min. Estimate/calculate the percent removal of *E. coli* when the facility doses at 5.3 mg/L (the original value) and at 12.4 mg/L (the newest value). Will the higher dose solve the problem in Doerrville?

4. (100 pts) *Reverse osmosis*

   One of the challenges with performing calculations for reverse osmosis is that we often have information about the feed water, but the quality of the water changes as it moves through the system. The water that exits a membrane module as "concentrate" is different from the water that entered as "feed". Therefore it might not be valid to use feed-water characteristics to perform all of our calculations. One way to deal with this is to sub-divide a membrane element into sub-elements and then perform calculations for each one separately; example 17-5 in the text does this, as does one of the problems on HW 8. However, here we will take a different strategy – I will lead you through it. Consider RO treatment of salty water according to the following.

   - (*background info*) A water treatment plant has three stages of RO treatment. The first stage consists of 96 pressure vessels. Each pressure vessel houses 7 spiral-wound membrane elements. Each membrane element is 20 cm diameter and 1.0 m length.
   - Each of the first-stage pressure vessels receives a feed flow rate of 16,400 L/hr. (This works out to about 10 mgd feed rate for the entire treatment plant.)
   - The active membrane surface area in each pressure vessel (total for the 7 membrane elements) is 260 m^2.
   - The average trans-membrane pressure in the first-stage pressure vessels is 40 bar.
   - The feed water contains 11,700 mg/L of NaCl. Other ions can be neglected for the purposes of this exam.
   - The temperature of the feed water is 25 °C.
   - The water mass-transfer coefficient for the membranes is k_w = 1.3 L/(m^2·bar·hr).
   - The salt mass-transfer coefficient for the membranes is k_s = 0.50 L/(m^2·hr).
   - For the purposes of this problem, assume that the osmotic coefficient is 0.95 for the feed water and 1.0 for the permeate.
   - For the purposes of this problem, ignore concentration polarization.

   a. (8 pts) Estimate/calculate the osmotic pressure of the feed water, in units of bar.
   b. (8 pts) For now, assume that the permeate is pure water, i.e., contains no salt. Use this assumption, along with the osmotic pressure of the feed water, to estimate/calculate the water flux through the membranes. Report your answer in units of L/(m^2·hr).
   c. (8 pts) Using the same assumptions, estimate/calculate the salt flux through the membrane, in units of mg/(m^2·hr).
   d. (8 pts) Estimate/calculate the salt concentration in the permeate, in units of mg/L.
   e. (10 pts) Estimate/calculate the recovery and the rejection in the first-stage pressure vessels.

problem 4 continues →

4. continued
   f. (6 pts) Estimate/calculate the volumetric flow rate of concentrate exiting the pressure vessel. Hint: you know the feed flow rate, and you calculated the permeate flow rate.
   g. (10 pts) Estimate/calculate the concentration of salt in the concentrate stream exiting the pressure vessel. Hint: perform a mass balance, using the pressure vessel as a control volume, to balance the mass of salt.

All of that is nice, but it is based on two assumptions that might not be great. First, in the calculations above, we assumed that the permeate is pure water, but we know it's not. Second, we only used the feed-water characteristics, but the water in the feed-concentrate channel changes – it enters with a concentration of 11,700 mg/L, but it exits with the concentration that you just found in part (g). So let's do a second round of calculations, in which we update our assumptions.

   h. (8 pts) Re-calculate the osmotic pressure of water in the feed-concentrate channel. This time, instead of using the feed concentration (as you did in part a), use an *average* (arithmetic mean) salt concentration for the feed-concentrate channel.
   i. (8 pts) Estimate/calculate the osmotic pressure of the permeate. Use the salt concentration that you found in part d.
   j. (8 pts) Re-calculate the water flux through the membrane and the recovery. How much did your estimates change?
   k. (12 pts) Re-calculate the salt flux through the membrane and the rejection. How much did your estimates change? Hint: think about where to use "updated" values in your calculations, and where not to.
   l. (6 pts) Now assess our initial approach to this problem. Is it acceptable to use feed-water characteristics to represent the feed-concentrate channel for the entire pressure vessel?

END OF EXAMINATION