ENV 4001: ENVIRONMENTAL SYSTEMS ENGINEERING

Spring 2021	University of South Florida
Final Examination	Civil & Environmental Engineering
Monday, May 3, 2021	Prof JA Cunningham

Instructions:

1. Sign in to Canvas and launch the Final Exam with Proctorio. The Final Exam in Canvas doesn't contain very much information, but it does include places to submit your numerical answers. The actual exam questions are in this document on the pages that follow.
2. This exam contains six questions. ***Answer the first four problems. Then choose <u>one of the last two questions</u>***.
3. Some questions have multiple parts. The point value of each part is indicated.
4. The total number of points possible is 120. (Problem 4 has an opportunity for extra credit, so in theory, you could earn higher than 120/120, but in reality, you might not have time to do the entire test and the extra-credit portion. Consider it to be a 120-point exam.)
5. Unit conversion factors and other potentially useful information are provided on the next three pages.
6. Answer each question on your own paper. **<u>Put your name on each page of paper</u>**.
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 as appropriate. An answer without proper units is not correct!
10. You are allowed to use your text book, your course notes, or any other printed materials. However, *you may not receive help from another live person*.
11. A hand-held calculator is recommended.
12. **<u>Numerical answers should be uploaded and submitted in Canvas by noon. The test will close at noon</u>**. Answers submitted by noon are eligible for full credit.
13. *After* submitting your answers in Canvas, scan your work and send it to me by e-mail (cunning@usf.edu). E-mail me your file before 12:15 PM. *Answers in your scanned work must match the numerical answers that you uploaded to Canvas*. It is easier for me if you use Outlook (rather than Canvas) to send me your file, but I can live with Canvas if you don't have Outlook.
14. **<u>Don't cheat</u>**. Cheating will result in appropriate disciplinary action according to university policy. More importantly, cheating indicates a lack of personal integrity.
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.

Potentially useful constants:

Ideal gas constant, *R*:	8.314 $Pa \bullet m^3 \bullet mol^{-1} \bullet K^{-1}$ = 82.06×10^{-6} $atm \bullet m^3 \bullet mol^{-1} \bullet K^{-1}$
Gravitational acceleration, *g*:	9.81 m/s^2
Molecular weight of water, H_2O:	18.01 g/mole
Density of water at 18 °C:	0.9985 g/mL = 998.5 kg/m^3
Viscosity of water at 18 °C:	1.06×10^{-3} Pa•sec
Density of air at 18 °C:	1.21 kg/m^3
Viscosity of air at 18 °C:	1.81×10^{-5} Pa•sec

Potentially useful conversion factors:

Pressure:	1 atm = 760 mm Hg = 760 torr = 101325 Pa
	1 Pa = 1 N/m^2 = 1 $kg/(m \bullet sec^2)$
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 = 10^6 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

TABLE A–2 Saturation Values of Dissolved Oxygen in Fresh Water Exposed to a Saturated Atmosphere Containing 20.9% Oxygen Under a Pressure of 101.325 kPa[a]

Temperature (°C)	Dissolved Oxygen ($mg \cdot L^{-1}$)	Saturated Vapor Pressure (kPa)
0	14.62	0.6108
1	14.23	0.6566
2	13.84	0.7055
3	13.48	0.7575
4	13.13	0.8129
5	12.80	0.8719
6	12.48	0.9347
7	12.17	1.0013
8	11.87	1.0722
9	11.59	1.1474
10	11.33	1.2272
11	11.08	1.3119
12	10.83	1.4017
13	10.60	1.4969
14	10.37	1.5977
15	10.15	1.7044
16	9.95	1.8173
17	9.74	1.9367
18	9.54	2.0630
19	9.35	2.1964
20	9.17	2.3373
21	8.99	2.4861
22	8.83	2.6430
23	8.68	2.8086
24	8.53	2.9831
25	8.38	3.1671
26	8.22	3.3608
27	8.07	3.5649
28	7.92	3.7796
29	7.77	4.0055
30	7.63	4.2430
31	7.51	4.4927
32	7.42	4.7551
33	7.28	5.0307
34	7.17	5.3200
35	7.07	5.6236
36	6.96	5.9422
37	6.86	6.2762
38	6.75	6.6264

[a]For other barometric pressures, the solubilities vary approximately in proportion to the ratios of these pressures to the standard pressures.

Source: Calculated by G. C. Whipple and M. C. Whipple from measurements of C. J. J. Fox, *Journal of the American Chemical Society*, vol. 33, p. 362, 1911.

from "Principles of Environmental Engineering and Science", 2nd edition, by Davis and Masten

TABLE 6–4 Slope Factors for Potential Carcinogens[a]

Chemical	CPS_0 ($kg \cdot day \cdot mg^{-1}$)	CPS_i ($kg \cdot day \cdot mg^{-1}$)
Arsenic	1.5	15.1
Benzene	0.015	0.029
Benzo(*a*)pyrene	7.3	N/A
Cadmium	N/A	6.3
Carbon tetrachloride	0.13	0.0525
Chloroform	0.0061	0.08
Chromium (VI)	N/A	42.0
DDT	0.34	0.34
1,1-Dichloroethylene	0.6	0.175
Dieldrin	16.0	16.1
Heptachlor	4.5	4.55
Hexachloroethane	0.014	0.014
Methylene chloride	0.0075	0.00164
Polychlorinated biphenyls	0.04	N/A
2,3,7,8-TCDD[b]	1.5×10^5	1.16×10^5
Tetrachloroethylene[b]	0.052	0.002
Trichloroethylene[c]	w	0.006
Vinyl chloride[b]	1.9	N/A

CPS_0 = cancer potency slope, oral; CPS_i = cancer potency slope, inhalation; w = withdrawn from IRIS.

[a] Values are frequently updated. Refer to IRIS and HEAST for current data.

[b] *Annual Health Effects Assessment Summary Tables* (HEAST) U.S. Environmental Protection Agency, 540/R-94/036, 1994.

[c] U.S. Environmental Protection Agency, National Center for Environmental Assessment http://www.epa.gov/ncea

Source: With the exceptions noted this information is taken from the U.S. Environmental Protection Agency, IRIS database, September 2005.

TABLE 6–5 RfDs for Chronic Noncarcinogenic Effects for Selected Chemicals[a]

Chemical	Oral RfD ($mg \cdot kg^{-1} \cdot day^{-1}$)	Chemical	Oral RfD ($mg \cdot kg^{-1} \cdot day^{-1}$)
Acetone	0.9	Phenol	0.3
Barium	0.2	PCB	
Cadmium	0.0005	Aroclor 1016	7.0×10^{-5}
Chloroform	0.01	Aroclor 1254	2.0×10^{-5}
Cyanide	0.02	Silver	0.003
1,1-Dichloroethylene	0.05	Tetrachloroethylene	0.01
Hydrogen cyanide	0.02	Toluene	0.2
Methylene chloride	0.06	1,2,4-Trichlorobenzene	0.01
Pentachlorophenol	0.03	Xylenes	0.2

[a] Values are frequently updated. Refer to IRIS for current data.

Source: U.S. Environmental Protection Agency IRIS database, 2005.

from "Principles of Environmental Engineering and Science", 2nd edition, by Davis and Masten

1. (10 pts) *solid waste management*

   List and briefly explain two risks associated with improper management of solid waste. Then briefly explain how proper waste management mitigates those risks. Please note:

   - One paragraph is probably sufficient for your answer (no need to write a long essay).
   - You can type your response into the window in Canvas before noon, *or* you can write it out by hand and send it with your scanned work by 12:15 – whichever you prefer.
   - If you type your answer into Canvas, then on your scanned work, just write me a little note like "please see my response in Canvas" – that way I'll be sure not to miss your response while I am grading.

2. (15 points) *risk assessment* *ppppp*

   In the Tampa Bay area, we incinerate a lot of our solid waste rather than putting it in a landfill. When we burn solid waste, the combustion process generates some hazardous chemicals. One of these is 2,3,7,8-tetrachlorodibenzo-*p*-dioxin. This chemical is also called 2,3,7,8-TCDD, or just "dioxin" for short. Dioxin is toxic and is strongly carcinogenic, so you don't want to breathe it or ingest it.

   Suppose the County where I live is planning on building a solid-waste incinerator 4.0 km away from my house. If they do, it might increase my risk of contracting cancer, because the incinerator will emit carcinogenic chemicals (like dioxin) into the air that I breathe.

   Further suppose that I am willing to accept an incremental risk of 1×10^{-6} due to the presence of dioxin in the air. I am an adult male that weighs 68 kg, I have lived in my house for 20 years, and I plan on staying in my house for another 15 years. *Estimate/calculate the allowable concentration of dioxin that can be in my air*. Report your answer in units of $\mu g/m^3$, and report two significant digits. State your assumptions clearly and show all your work.

3. (25 pts) *air pollution* *ppppp*

Let's think a bit more about the incinerator from problem 2 that the County wants to build near my house. Based on our calculations from problem 2, the health officials at the County decided that an acceptable concentration of dioxin in the air in my neighborhood would be 5.0×10^{-8} μg/m^3. Let's see what this means for the proposed incinerator.

I found a report called *Incineration and Dioxins: Review of Formation Processes* [Environment Australia, 1999] that estimates we emit 25 μg of dioxin for each 1 metric tonne of solid waste that we burn. (One metric tonne is the same as 1000 kg. Sometimes this is also called a megagram, Mg.) We also know that, on average, one person generates about 2.0 kg of solid waste each day.

a. (5 pts) Suppose that the proposed incinerator will serve a population of 180,000 people. Estimate/calculate the emission rate of dioxin from the incinerator. Report your answer in units of μg/d.

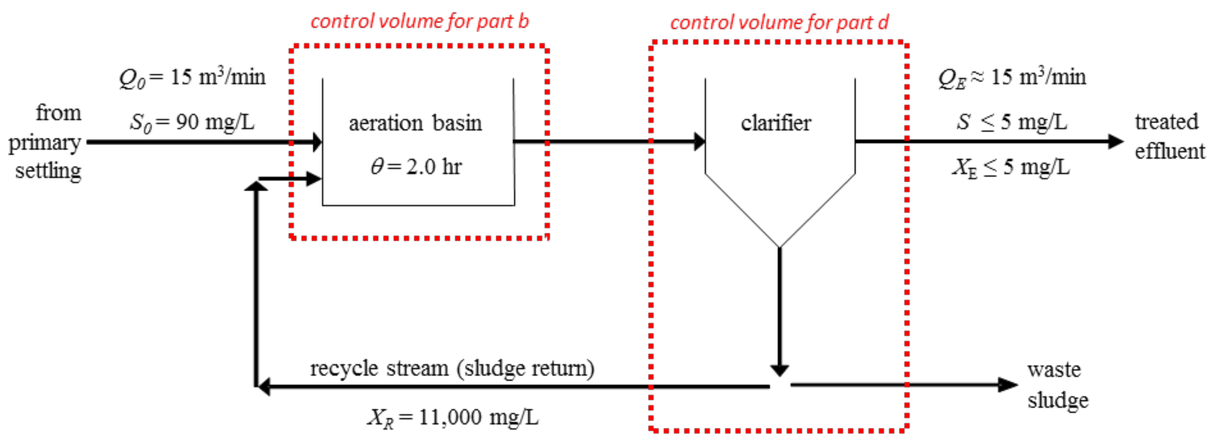
b. (16 pts) Estimate/calculate the required height of the stack at the incinerator to ensure that the allowable concentration of dioxin is not exceeded at my house. Report your answer in units of m. Recall that the County is proposing to build the incinerator 4.0 km from my house. Please make the following assumptions:

   - Consider a mostly-cloudy day with a wind speed (measured at a height of 10 m above ground surface) of 4.0 m/s.
   - To be protective of my health, consider "worst-case" conditions in terms of the wind direction.
   - Ignore plume buoyancy, i.e., assume that the effective stack height is equal to the physical stack height.
   - In your calculations, we'd like to use the wind speed at the stack height, but we don't know the stack height (it's what we're trying to find). Therefore, in your calculations, just use the wind speed measured at 10 m above ground surface.
   - Assume that the ground is perfectly reflective.
   - Assume "open-country" conditions between the incinerator and my house.

c. (4 pts) Do you think it is feasible for the County to build the new incinerator and still protect my health at the same time? Explain based on your answer to part (b).

4. (25 pts) *wastewater treatment, mass balances* *ppppp*

A particular wastewater treatment plant treats 15 m^3/min of primary effluent via the activated sludge process for secondary treatment, as we studied this semester. The following diagram illustrates the secondary treatment process. The system operates at steady state.



Here are some things that we know about the secondary treatment process.

- The concentration of soluble carbon arriving from primary treatment, expressed as oxygen demand, is S_0 = 90 mg/L.
- The concentration of soluble carbon in the treated effluent stream, expressed as oxygen demand, is not allowed to exceed 5 mg/L. We'll assume S = 5 mg/L (at the limit).
- The concentration of suspended solids in the treated effluent stream is not allowed to exceed 5 mg/L. We'll assume X_E = 5 mg/L.
- The average hydraulic residence time in the aeration basin is θ = 2.0 hr.
- The bacterial concentration in the return activated sludge (recycle) is X_R = 11,000 mg/L.
- The Monod kinetic parameters for the bacteria in the aeration basin are as follows.
  Half-velocity coefficient K_S = 60 mg/L
  Yield coefficient Y = 0.65
  Maximum specific growth rate μ_{max} = 3.0 d^{-1}.
  First-order death (decay) rate coefficient k_d = 0.10 d^{-1}.

a. (5 pts) Estimate/calculate the required solids retention time (SRT), in units of days, that will allow the facility to meet its treatment goal of ≤ 5 mg/L BOD in the effluent.

b. (12 pts) Write a mass balance for the mass of soluble substrate, using the control volume indicated in the figure (i.e., the aeration basin). From your mass balance, *estimate/calculate the biomass concentration that must be maintained in the aeration basin* to meet the conditions given. Report your answer in units of mg/L. Does your value look reasonable?

problem 4 continues →

4. continued *ppppp*

c. (8 pts) Estimate/calculate the sludge wasting rate that is required to maintain these conditions, i.e., the rate at which solids exit the system in the WAS. Report your answer in units of kg/d. Hint: you know the SRT – that is useful. You also know θ, you know X, you know X_E, you have a decent estimate of Q_E….

d. BONUS – UP TO 12 POINTS OF EXTRA CREDIT! Write a mass balance for the mass of bacterial cells (biomass), using the control volume indicated in the figure. From your mass balance, estimate/calculate the flow rate of the sludge recycle stream, Q_R. Report your answer in units of m^3/min. Does Q_R/Q_0 look reasonable?

5. (45 pts) *environmental chemistry; water treatment* *ppppp*

We studied wastewater treatment this semester, but we focused mostly on removal of BOD. In practice, wastewater treatment plants don't just remove BOD, they also remove nitrogen and phosphorus. One of the ways to remove phosphorus is to add alum, $Al_2(SO_4)_3 \bullet 14H_2O$, to the wastewater. When the alum dissolves in the wastewater, it releases Al^{3+} into the water. The Al^{3+} then removes phosphorus by precipitating phosphate as $AlPO_4$. The solubility product constant for precipitation/dissolution of $AlPO_4$ is 6.3×10^{-19} (according to Wikipedia).

Suppose we are treating wastewater by alum addition. The pH of the wastewater is 5.3, and the concentration of Al^{3+} in the wastewater (at equilibrium) is 0.2 mg/L.

a. (8 pts) Estimate/calculate the concentration of phosphate, PO_4^{3-}, in the water. Report your answer in units of mg/L as P. (Hint: how many P atoms are in a molecule of PO_4^{3-}? …and what is the molar mass of the P atom?)

Phosphate, PO_4^{3-}, is in equilibrium with some other chemical species. Consider the fact that phosphoric acid, H_3PO_4, is a triprotic acid:

$H_3PO_4 \leftrightarrow H^+ + H_2PO_4^-$

$H_2PO_4^- \leftrightarrow H^+ + HPO_4^{2-}$

$HPO_4^{2-} \leftrightarrow H^+ + PO_4^{3-}$

b. (18 pts) Estimate/calculate the concentrations of H_3PO_4, $H_2PO_4^-$, and HPO_4^{2-} in the wastewater. For each of them, report the concentration in units of mg/L as P.

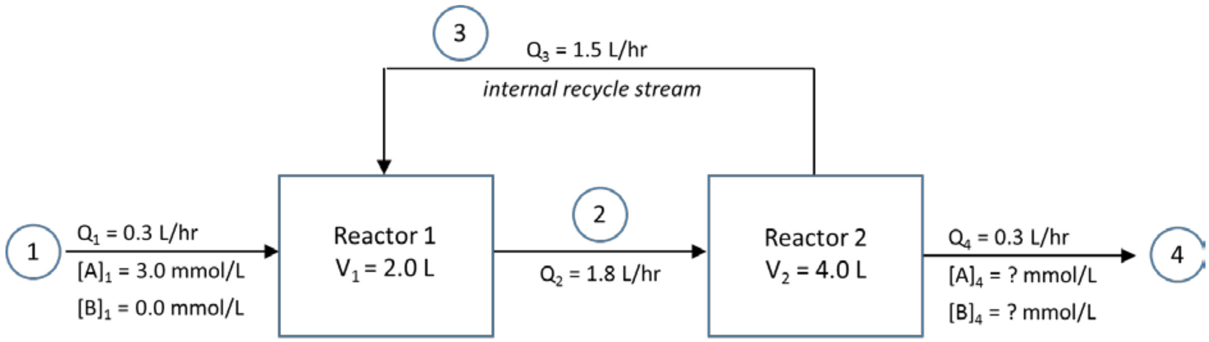
c. (4 pts) The sum of the four individual concentrations constitutes the concentration of "total phosphorus" or "TP". Often, the permit requirement at the wastewater treatment plant is no greater than 1.0 mg/L of TP. Did we meet the requirement in this case?

In practice, the alum is often dosed into the wastewater just upstream of a clarifier. That way, the $AlPO_4$ precipitate can sink to the bottom of the clarifier and be removed from the wastewater, effectively removing the phosphorus. Let's suppose that the $AlPO_4$ particles settle according to "discrete" or "type 1" sedimentation, which is what we studied in class this term; this might not actually be true, but we'll use it for the purposes of this exam. The density of $AlPO_4$ is 2.57 g/cm^3 = 2570 kg/m^3. A typical overflow rate in a clarifier at a wastewater treatment plant is about 36 (m^3/d)/(m^2) under average flow conditions.

d. (15 pts) Estimate/calculate how big the $AlPO_4$ precipitate particles must be in order to achieve 100% removal in the clarifier. Report your answer in units of μm. Assume that $AlPO_4$ precipitate particles are spherical. (This is another questionable assumption, but again, good enough for this exam.)

6. (45 pts) *reactor theory, mass balances* *ppppp*

One of my Ph.D. students built a treatment system in the laboratory to treat contaminated water. (This is a true story – the system is running in the lab right now!) She is trying to remove two contaminants from the water; for this exam, we will call them Chemical A and Chemical B. The treatment system looks approximately like the figure below. I have numbered the four streams 1 through 4, and I have indicated the flow rate of each stream.



(The actual treatment system is a little more complicated than this, but this simplified version is fine for the purposes of this exam.)

My Ph.D. student observed that the system was removing one of the chemicals pretty well, but not the other one. To diagnose the problem, I told her that we should do some mass balances. (…which should surprise nobody at this point.) In addition to the information shown in the figure above, we have the following information:

- Reactor 1 and Reactor 2 are both completely mixed flow reactors.
- The system operates at steady state.
- In Reactor 1, Chemical A does not react. However, Chemical B is removed with a first-order rate coefficient $k = 0.33\ \text{hr}^{-1}$.
- In Reactor 2, Chemical A is converted to Chemical B, A → B, according to first-order kinetics. The rate coefficient is $k = 4.0\ \text{hr}^{-1}$.

Our job is to use this information to estimate the concentrations of A and B in the effluent stream, i.e., stream 4. We will proceed as follows.

(a) (14 pts) Write a mass balance for Chemical A. For the control volume, use the entire treatment system. Then use your mass balance to solve for $[A]_4$. Hint: use the information given above in the bullet points.

(b) (10 pts) Now write a mass balance for Chemical B. Use Reactor 2 for the control volume. Hint: think carefully about the source term in your mass balance. Clearly indicate which concentrations in the mass balance are known, and which are unknown. How many unknowns do you have?

problem 6 continues →

6. continued

(c) (8 pts) Write another mass balance for Chemical B. This time, for the control volume, use Reactor 1. Clearly indicate which concentrations in the mass balance are known, and which are unknown. How many unknowns do you have?

(d) (8 pts) Solve for $[B]_4$. Hint: if you need another equation, think about how $[B]_3$ is related to $[B]_4$, remembering that Reactor 2 is a completely mixed flow reactor.

(e) (5 pts) Notice that in the influent stream, $[A]_1 + [B]_1 = 3.0$ mmol/L. What is $[A]_4 + [B]_4$ in the effluent stream? If we consider the contaminants together, what fractional removal did we achieve in the treatment system?

My student and I did these calculations to help us understand what we need to adjust in the treatment system to improve its performance. A mass balance is a very, very useful tool!

END OF EXAMINATION