DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING
UNIVERSITY OF CALIFORNIA, BERKELEY
E11, MAY 16, 2005

FINAL EXAM

Name and Student ID: Solution________________________

Instructions: Answer the questions that follow directly on these pages in the spaces provided. Use the back of the page if you need more room for your answer. If you believe there is insufficient information provided to answer a question completely, state reasonable assumptions and proceed from there.

This exam is closed-book/closed-notes. Calculators are allowed.

Time: 180 minutes.

Question:	Score:	Out of:
1	_____	14
2	_____	6
3	_____	10
4	_____	8
5	_____	7
6	_____	7
7	_____	11
BONUS	_____	
TOTAL	_____	63

Useful Data and Formulas:

Atomic masses: H=1, C=12, N=14, O=16, S=32, Cl=35.5 g mol^{-1}

Ideal gas law: PV = nRT

Ideal gas constant R = 0.08205 L atm K^{-1} mol^{-1}

Specific heat of water = 4.2 kJ kg^{-1} $°C^{-1}$

Latent heat of vaporization = 2.4 kJ g^{-1}

Latent heat of fusion = 0.33 kJ g^{-1}

Dissociation of hydrochloric acid: $HCl \leftrightarrow H^+ + Cl^-$

Equilibrium reactions and constants:

$H_2O \leftrightarrow H^+ + OH^-$	$K_w = 10^{-14}$ M^2
$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$	$K_1 = 10^{-6.35}$ M
$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$	$K_2 = 10^{-10.33}$ M

CMFR general equation: $dC/dt = S - LC$

Solution to CMFR general equation: $C(t) = C_o\exp(-Lt) + (S/L)[1-\exp(-Lt)]$

Settling velocity for particles in water:

$v_s = (\rho-\rho_w)\, d^2\, g/(18\mu)$, where ρ_w and μ are the density and dynamic viscosity of water

$\mu = 0.01$ g cm^{-1} s^{-1}

$g = 9.81$ m s^{-2}

Sedimentation basin efficiency, $\eta = v_s/v_c$

Radiative forcing of greenhouse gases as function of concentration, $F = f(C)$:

Linear region, $\Delta F = k_1\, \Delta C$

Square root region, $\Delta F = k_2\, \Delta \sqrt{C}$

Logarithmic region, $\Delta F = k_3\, \Delta(\ln C)$

1. BASIC CONCEPTS IN ENVIRONMENTAL ENGINEERING (14 points)

a) Explain the difference between a primary and secondary air pollutant, and list three primary and three secondary pollutants for which the EPA has established ambient air quality standards (3 points). (Hint: A correct answer need not list six different pollutants.)

Primary: directly emitted, e.g. from combustion

CO, SO_2, Pb, PM

Secondary: formed from precursors in the atmosphere

O_3, NO_2, PM

b) What three ingredients are necessary for tropospheric ozone formation (1 point)?

NO_x, VOC, sunlight

c) If the higher heating value of acetic acid (CH_3COOH) is 30.8 kJ g^{-1}, what is the lower heating value (4 points)?

$$C_2H_4O_2 + \text{air} \rightarrow 2CO_2 + 2H_2O$$

$$MW = 24 + 4 + 32 = 60 \text{ g/mol}$$

$$LHV = HHV - \frac{m_w}{m_f} \lambda_v$$

$$LHV = \frac{30.8 \text{ kJ}}{g\, C_2H_4O_2} - \left[\frac{2 \text{ mol } H_2O}{\text{mol } C_2H_4O_2} \cdot \frac{18 g\, H_2O}{\text{mol } H_2O} \cdot \frac{\text{mol } C_2H_4O_2}{60 g\, C_2H_4O_2} \cdot \frac{2.4 \text{ kJ}}{g\, H_2O} \right]$$

$$LHV = (30.8 - 1.44) \text{ kJ}/g\, C_2H_4O_2$$

$$\boxed{LHV = 29.36 \text{ kJ}/g\, C_2H_4O_2}$$

1. BASIC CONCEPTS IN ENVIRONMENTAL ENGINEERING (continued)

d) State the purpose of each of the following process categories in wastewater treatment and briefly state the mechanism of each process (3 points).

Primary: removal of suspended particles; by gravitational settling (ie., sedimentation)

Secondary: removal of BOD; by bacterial decomposition of organics

Tertiary: removal of nutrients (N, P) or metals; by biodegradation or chemical addition.

e) In recent years, the phosphate (PO_4^{3-}) content of detergents has been reduced. What environmental problem is associated with the presence of phosphates in detergents (1 point)?

Eutrophication: nutrient enrichment of aquatic systems that leads to algae blooms

f) You are hired by the automotive industry to conduct a life cycle assessment (LCA) to quantify the impact of automobiles on global warming. Explain what is meant by LCA and state what processes you would consider in your analysis (2 points).

LCA: a "cradel to grave" evaluation of a product (or service) including production, use and disposal.

Consider greenhouse gas emissions during the manufacturing, shipment, in-use life, and eventual disposal of the automobiles.

2. POPULATION GROWTH (6 points)
In the table below, data on the age distribution and age-specific death and birth rates are shown for a hypothetical population.

a) Calculate the population in each age group and the total population in the year 2020 (3 points). (Show enough of your work so that I can see how you get your answers).

Age group (yrs)	2000 Population (millions)	Survival rate, L_{x+20}/L_x	Birth rate, b_x	2020 Population (millions)
0-20	2.0	0.96		1.76
20-40	1.6	0.97	1.1	1.92
40-60	1.3	0.85		1.55
60-80	1.0	0.55		1.11
80-100	0.5	0.00		0.55
TOTAL	6.4			6.89

$= 1.6(1.1)$
$= 2.0(0.96)$
$= 1.6(0.97)$

$(P_{20-40})\, b_x$

$(P_{0-20})\left(\dfrac{L_{20-40}}{L_{0-20}}\right)$

b) Define the replacement fertility rate (1 point).

The number of children a woman must have to replace herself with one daughter in the next generation.

c) Even though the birth rate in this population is about equal to the replacement fertility rate, the population grew from 2000 to 2020. Explain why (1 point)?

The population is young: many more people were in or near their reproductive years than in their old age when dying generally occurs. Thus, births outnumbered deaths.
This is known as population momentum.

d) Why is a logistic growth model better than an exponential growth model for projecting population growth (1 point)?

The logistic model accounts for the fact that exponential growth cannot be sustained indefinitely.

3. UP IN SMOKE (10 points)
Incineration is a treatment process that is used for many organic materials, including chlorinated solvents. Given the following reaction for the combustion of liquid dichloropropane:

$$C_3H_6Cl_2 + \overset{4}{a}\, O_2 \rightarrow \overset{3}{b}\, CO_2 + \overset{2}{c}\, H_2O + \overset{2}{d}\, HCl$$

a) Determine the stoichiometeric coefficients for this reaction (2 points).

b = 3 carbon balance
d = 2 chlorine "
c = 2 hydrogen "
a = 4 Oxygen "

b) Calculate the volume (in m^3) of <u>air</u> (T=298K, P=1atm) required for the stoichiometric combustion of one kilogram of dichloropropane (4 points).

$MW = 36 + 6 + 71 = 113\ g/_{mol\ DCP}$

$$\frac{4\ mol\ O_2}{mol\ DCP} \cdot \frac{mol\ air}{0.21\ mol\ O_2} \cdot \frac{mol\ DCP}{113g\ DCP} \cdot 10^3 g\ DCP \cdot \frac{24.4L\ air}{mol\ air} \cdot \frac{m^3}{10^3 L} = \boxed{4.1 m^3\ air}$$

air is 21% O_2 by volume

from ideal gas law

$$\frac{V}{n} = \frac{RT}{P} = \frac{(298K)\left(0.08205 \frac{L\,atm}{mol\,K}\right)}{1\,atm}$$

$$\frac{V}{n} = 24.4\ L/mol$$

3. UP IN SMOKE (continued)

c) Assume that the combustion products are allowed to cool and the water is in the liquid phase. The CO_2 and HCl dissolve in the water. Consider all of the ionic species present in solution and write the electroneutrality equation for the solution. State the units of the terms in the equation (2 points).

$HCl \rightarrow H^+ + Cl^-$

$H_2O \rightarrow H^+ + OH^-$

$CO_2 \rightarrow H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \rightleftharpoons CO_3^{2-} + H^+$

mol/L or M : $[H^+] = [OH^-] + [HCO_3^-] + 2[CO_3^{2-}] + [Cl^-]$

eq/L : $(H^+) = (OH^-) + (HCO_3^-) + (CO_3^{2-}) + (Cl^-)$

d) Of the two carbonate species listed in your electroneutrality equation, which has the higher concentration? Briefly explain your answer (2 points).

$[HCO_3^-] >> [CO_3^{2-}]$

with two acids present (hydrochloric and carbonic), the solution is going to be acidic (i.e., pH << 7)

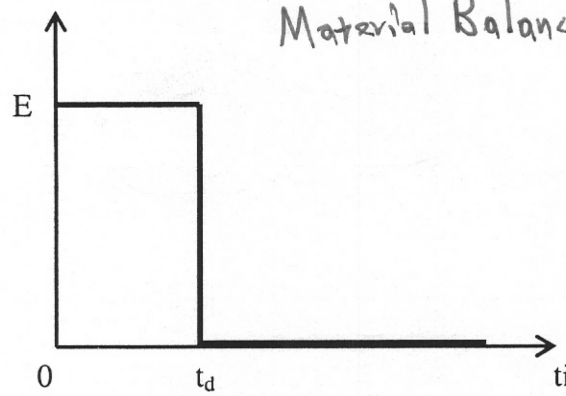
Consider the relative amounts of carbonate ions for a neutral solution pH = 7.

$$\frac{[HCO_3^-]}{[CO_3^{2-}]} = \frac{[H^+]}{K_2} = \frac{10^{-7}}{10^{-10.33}} \approx 2000.$$

So, even at neutral pH, $[HCO_3^-] >> [CO_3^{2-}]$

4. CMFR REACTOR MODEL (8 points)

Consider an initially pristine well mixed vessel with volume V (m^3) and volumetric inflow and outflow rates Q ($m^3\ s^{-1}$). Assume the incoming fluid is pristine. At time t_o, a nonreactive chemical is released into the volume with an emission rate E ($g\ s^{-1}$). After a period of time t_d (s^{-1}) that is much less than the characteristic time of the system, the emission of the chemical stops, as illustrated in the figure below. When answering the questions below, be sure to express your answers only in terms of the parameters specified in the problem statement.



Material Balance: $V\frac{dC}{dt} = Q\cancel{C_{in}} + E - Q\,C_{out}$, $C_{in} \to \phi$

$$\boxed{\frac{dC}{dt} = \frac{E}{V} - \frac{Q}{V} C_{out}}$$

a) Write an expression for the peak value of the outlet concentration, C_{out} (4 points).

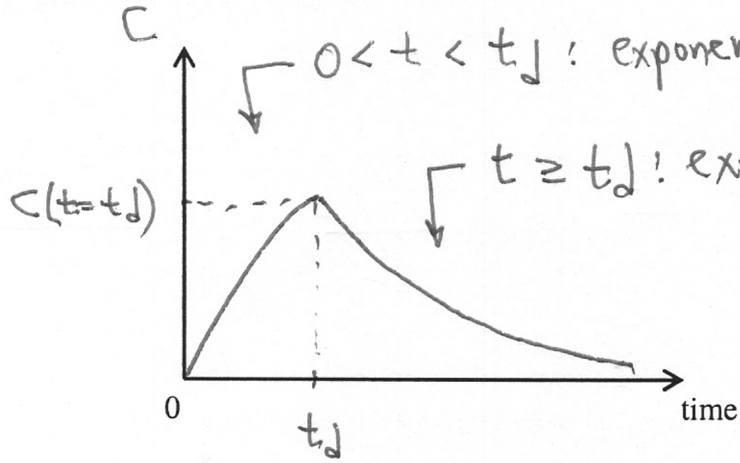
- General Solution: $C(t) = C_o \exp\left(-\frac{Q}{V}t\right) + E/Q\left[1-\exp\left(-\frac{Q}{V}t\right)\right]$
- Initially pristine means $C_o = \phi$
- $T > t_d$ means steady state concentration (ie, $\frac{E}{Q}$) is not reached
- Thus, max. concentration occurs @ $t = t_d$

$$\boxed{C(t=t_d) = \frac{E}{Q}\left[1-\exp\left(-\frac{Q}{V}t_d\right)\right]}$$

b) Sketch a graph of the C_{out} versus time. In your sketch, be as specific as possible about the concentration and time scales. (2 points).

$0 < t < t_d$: exponential increase to $C(t=t_d)$

$t \geq t_d$: exponential decay since $E = \phi$



4. CMFR REACTOR MODEL (continued)

c) When applying the CMFR model, we assume that the concentration in the vessel is the same as the outlet concentration. Why (1 point)?

It is assumed that the vessel is completely mixed and the concentration in the vessel is homogeneous and equal to the outlet concentration.

d) What is the characteristic time of this system (1 point)?

$$\boxed{\tau = \frac{1}{L} = \frac{V}{Q}} \; [=] \; \frac{m^3}{m^3/s} = s$$

5. BIOCHEMICAL OXYGEN DEMAND (7 points)
The same bacteria that use oxygen to degrade organic matter in water (and cause the "demand" for oxygen) are also biodegradable when they die. In other words, bacteria also exert a biochemical oxygen demand (BOD). The chemical formula for bacteria can be simplified as $C_5H_7O_2N$.

a) Write a balanced chemical reaction for the conversion of 1 mole of bacterial cells to CO_2, H_2O, and NH_3, with bacteria and oxygen (not air) as the reactants (2 points).

$$C_5H_7O_2N + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_3$$

b) Calculate the theoretical oxygen demand (in mg L^{-1}) in a sample that contains 40 mg L^{-1} of bacterial cells (2 points)?

$$MW = 60 + 7 + 32 + 14 = 113 \text{ g/mol}$$

$$\frac{5 \text{ mol } O_2}{\text{mol bacteria}} \cdot \frac{\text{mol bacteria}}{113 \text{g bacteria}} \cdot \frac{40 \text{ mg bacteria}}{L} \cdot \frac{32 \text{g } O_2}{\text{mol } O_2} = \boxed{56.6 \frac{mg}{L}}$$

[Note: Nitrogenous BOD (NBOD) not considered here: $NH_3 \xrightarrow{O_2} NO_2^-$ (nitrification)]

c) The BOD of the same water sample was also determined by conducting a 5-day BOD test in the laboratory. A 300-ml BOD bottle was filled with 30 ml of the sample plus dilution water. The initial concentration of dissolved oxygen was 9 mg L^{-1} and after 5 days the concentration had dropped to 4.3 mg L^{-1}. What is the BOD_5 (mg L^{-1}) of the sample (2 points)?

$$BOD_5 = \frac{(9.0 - 4.3) \text{ mg}}{\text{L diluted sample}} \cdot \left(\frac{300 \text{ml diluted sample}}{30 \text{ ml sample}}\right)$$

$$\boxed{BOD_5 = 47 \text{ mg/L}}$$

d) Give one reason for why the BOD_5 measured in the laboratory was less than the theoretical BOD calculated from the chemical formula (1 point).

- $BOD_5 < BOD_{ultimate}$; there is some BOD remaining after 5 days
- Some carbon may be bound in non-biodegradable form ~~[illegible]~~

6. A QUESTION OF CLARIFICATION (7 points)
You would like to construct a settling basin to remove 85% of the particles in your influent. A characterization of the influent particles indicated that they are all 15 μm diameter spherical particles of density 2.4 g cm^{-3}.

$15\,\mu m = 0.0015\,cm = 1.5\times10^{-3}\,cm$

a) Calculate the settling velocity of the particles (cm s^{-1}) in the basin (2 points).

$$V_s = \frac{(\rho-\rho_w)\,d^2 g}{18\mu} = \frac{(2.4-1.0)\,g/cm^3\,(1.5\times10^{-3}\,cm)^2\,(981\,cm/s)}{18\,(0.01\,g/cm\cdot s)}$$

$$\boxed{V_s = 0.017\,cm/s}$$

b) Calculate the critical settling velocity to achieve the desired 85% removal rate of these particles (1 point).

$\eta = V_s/V_c$; when $V_s = V_c$, $\eta = 100\%$

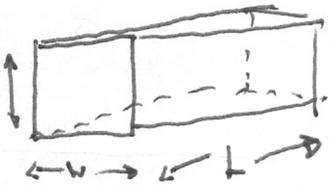
For $\eta = 85\%$, V_s must be less than V_c

$$\boxed{V_c = \frac{V_s}{0.85} = 0.02\,cm/s}$$

c) Given that the settling basin will be 5 m wide and 10 m long, what influent flow rate ($m^3\,h^{-1}$) would this unit be able to treat within the given constraints (4 points)? (Hint: equate two system characteristic times.)

flow rate $= Q = uHW$

u = velocity of water along length of basin



- Equate characteristic settling time $\tau_s = \frac{H}{V_c}$ and water residence time $\tau_w = L/u$

$$\frac{H}{V_c} = \frac{L}{u} \Rightarrow uH = V_c L \Rightarrow uHW = V_c LW$$

$$\therefore Q = uHW = V_c LW = (0.02\times10^{-2}\,m/s)\left(\frac{3600\,s}{hr}\right)(5\,m)(10\,m) = \boxed{36\,\frac{m^3}{hr}}$$

7. CLIMATE CHANGE (11 points)

a) List five greenhouse gases (GHG) that contribute to anthropogenic global warming. Include and identify in your answer the GHG that has exerted the largest radiative forcing since the beginning of the industrial era (2 points).

CO_2, CH_4, N_2O, O_3, CFCs (halocarbons)

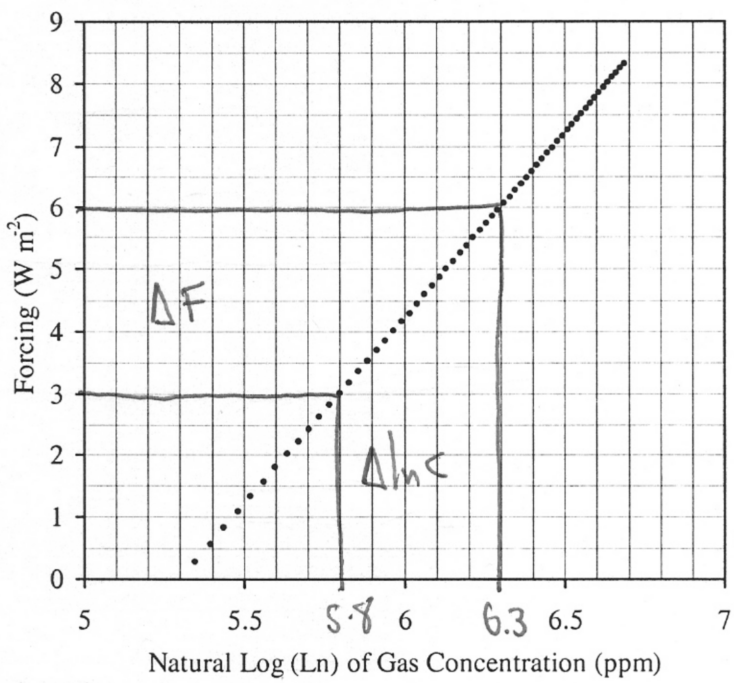
↑ largest forcing

b) What is meant by "direct" and "indirect" aerosol radiative forcings (2 points)?

Direct: scattering and absorption of sunlight by aerosols

Indirect: aerosols act as cloud condensation nuclei; increases cloud lifetime and albedo

c) A plot of radiative forcing versus GHG concentration is shown below. For this GHG, write a general equation that can be used to calculate the change in radiative forcing, ΔF, expected for a change in gas concentration. The equation should be written in terms of ΔF, initial and final concentrations, C_0 and C, and the proportionality parameter, k, where you have determined the value and units of k (3 points).



$$\Delta F = k\,\Delta(\ln C)$$

$$F_2 - F_1 = k(\ln C - \ln C_0)$$

$$(6-3)\frac{W}{m^2} = k(6.3 - 5.8)$$

$$k = \frac{3}{0.5}\ \frac{W}{m^2} = 6\,W/m^2$$

$$\boxed{\Delta F = 6\frac{W}{m^2}\ln\frac{C}{C_0}}$$

7. CLIMATE CHANGE (continued)

d) Assuming a climate sensitivity parameter of 0.7 °C per W m^{-2}, and using the value of k calculated above, calculate the equilibrium ΔT for a change in the GHG concentration from 350 to 900 ppm (2 points).

$$\Delta F = (6\,W/m^2)\ln\left(\frac{900}{350}\right) = 5.67\ W/m^2$$

$$\Delta T = \left(\frac{0.7\ ^\circ C}{W/m^2}\right)\left(5.67\ \frac{W}{m^2}\right) = \boxed{4.0\ ^\circ C}$$

e) Which GHG is the subject of questions c and d? Justify your answer (1 point).

CO_2

1.) logarithmic saturation region

2.) concentration of several hundred ppm

f) In what region of the electromagnetic spectrum do GHGs absorb radiation (1 point)?

Infrared (IR)

BONUS QUESTIONS (1 point each)

i) Fill in the three missing words of Professor Horne's song:

"Fixing our planet from pollution and toil. We'll construct a wetland with anoxic soil."

ii) Why did NASA lose the Mars Climate Orbiter in 1999?

Confusion about units: one team was working in SI while another team was using English units

iii) Including maintenance, how much does it cost ($ per person per year) to provide safe drinking water with Dr. Gadgil's UV Water Works?

$1.50 / person·year

iv) In what year did the Earth's population reach six billion?

1999 (2000 accepted)