NAME

GROUND RULES: This exam consists of 6 sets of questions/problems. You are permitted three sheets of notes, but otherwise the exam is closed-book/closed-note. Do your work on the paper provided. Be sure your name is on every page you submit, and that the problem number and your answer are clearly marked. The total score possible is 60 points, and the time allowed is 180 minutes. Use the time to maximize your score. If you need a conversion factor, or you are not clear about what a problem requires, ask. [*Hint:* The final two pages of the exam contain many equations, conversion factors, etc. All are true. Some may be useful. (*Note*: These pages reproduced the inside covers, both front and back, from the text. They are not reproduced in this sample.)] GOOD LUCK!

SCORE

#1 (14 possible) ____________ #2 (12 possible) ____________

#3 (12 possible) ____________ #4 (8 possible) ____________

#5 (8 possible) ____________ #6 (6 possible) ____________

EXAM TOTAL (out of 60) EQ \x( )

Note: The overall average score for the 42 students who took this exam was 42.7 (71%). For the 31 undergraduate students the average score was 40.0 (67%).

COURSE SCORE (%) EQ \x( ) EQ \x( ) COURSE GRADE

Your "course score" is the weighted average of the percentage of possible points you achieved during the semester. The relative weights and your scores are indicated below:

element	weight (%)	your score (%)
assignments	25	_______
midterms	30	_______
final exam	45	_______

1. WARM-UP EXERCISES (14 points; 2 each)

(a) Fick's law in one dimension is J = - D dC/dx. Define each of the variables in the equation (J, D, C, and x) and give the associated dimensions.

(b) Darcy's law in one dimension can be written U = -K dh/dl. Define each of the variables in the equation (U, K, h, and l) and give the associated dimensions.

(c) Particle-laden water enters a gently stirred CMFR. Within the CMFR, particles that settle to the bottom remain there. The CMFR volume is V and the water flow rate through it is Q. The CMFR is in the shape of a right-circular cylinder with its axis oriented vertically, such that V = AH where H is the height of water and A is the cross-sectional area. All particles have the same settling velocity v_t. For a long period prior to the time of interest, the inlet particle concentration was C_1, and the system was at steady state. Then, at t = 0, the inlet particle concentration is suddenly increased to C_2. What is the characteristic time required for the new steady-state condition to be established?

(d) Wastewater is discharged at a point at the edge of a river. As the wastewater is transported by advection downstream, it mixes across the river by turbulent diffusion. The river has width W, mean water velocity U, and turbulent diffusivity ε. Determine the characteristic distance L downstream from the point of discharge at which the wastewater plume reaches the opposite shore.

(e) A circular sedimentation basin has a diameter D (m) and mean water depth H (m), such that the volume is $V = (\pi/4)D^2H$. Water flows horizontally, uniformly and in a laminar manner from the central axis radially towards the outer circumference. The volumetric flow rate is Q ($m^3\ h^{-1}$). In terms of these parameters, what is the overflow rate?

(f) When chlorine is applied to water as a disinfectant, some of it is consumed rapidly because it oxidizes chemical impurities in the water. Write a balanced redox reaction for the oxidation of Fe^{2+} to Fe^{3+} in water by hypochlorous acid.

(g) Ethanol (C_2H_6O) has been proposed as a gasoline additive in place of MTBE. Write a balanced reaction for the complete, stoichiometric combustion of ethanol using air (modeled as $O_2 + N_2$ in a 1:3.78 molar ratio) as the oxidizer.

2. TRY THESE! (12 points; 3 each)

(a) The proposed water quality standard for nickel is 0.1 mg L^{-1} (= 1.7 μM). It forms a solid hydroxide as described by the following equilibrium relationship

$$Ni(OH)_2 \Leftrightarrow Ni^{2+} + 2\ OH^- \qquad K_{sp} = 6.5 \times 10^{-18}\ M^3$$

The equilibrium nickel concentration can be lowered by raising the pH, causing solid $Ni(OH)_2$ to form and settle. What is the minimum pH needed to ensure that the equilibrium concentration of dissolved Ni^{2+} does not exceed the standard? [*Hint:* $K_w = 10^{-14}\ M^2$]

(b) A sealed container has a volume of 1 m^3 and contains air at T = 298 K, P = 1 atm. Through a rubber septum, 100 g of benzene (MW = 78 g/mol) is injected. What is the total pressure in the vessel at equilibrium? [*Data*: The (saturation) vapor pressure of benzene is 0.126 atm.]

(c) A CMFR contains water at a volume V = 2 m^3. Water flows through the reactor at a balanced rate $Q = 0.5\ m^3\ h^{-1}$. Consider a nonreactive contaminant. Within the reactor, the contaminant concentration is C, and the initial condition is $C(t=0) = 0$. Given the following time-dependent inlet concentration, what is the maximum concentration, C_{max}, in the reactor?

(d) The growth kinetics of microbial cell mass concentration (X) can be described by the relationship

$$\frac{dX}{dt} = r_g X$$

where r_g is the cell growth rate. (In general, one would need to include a decay term in the expression, but for short time periods decay may be safely ignored.) The cell growth rate varies with substrate (food) concentration according to the Monod equation

$$r_g = \frac{Y k_m S}{K_s + S}$$

where Y is the cell-yield coefficient, k_m is the maximum cell growth rate, S is the substrate concentration, and K_s is the half-saturation constant. An experiment is conducted in a batch reactor. It is arranged to maintain a constant substrate concentration, S. Adequate oxygen and nutrients are provided so that they do not limit cell growth. Cell mass concentration is monitored as a function of time. Define t_d to be the time required for cell mass concentration to double. Derive an expression that relates t_d to the parameters Y, k_m, K_s and S.

3. ON WATER QUALITY ENGINEERING (12 points; 1 each)

Provide a brief answer to each of the following questions.

(a) In water softening by the lime-soda process, lime ($Ca(OH)_2$) is added to raise the pH. Under what circumstances would soda (Na_2CO_3) be added?

(b) As the final step of water softening by the lime-soda process, the pH must be reduced to near neutral. What reagent is most commonly used for this purpose?

(c) The most common hardness ions in drinking water are Mg^{2+} and Ca^{2+}. In water softening by ion exchange, what ion is most commonly exchanged for the hardness ions.

(d) Name two processes in drinking water treatment that are commonly configured as PFRs.

(e) Before the development of a rapid-sand filter, slow-sand filtration was used. A rapid-sand filter is cleaned by backwashing. How is a slow-sand filter cleaned?

(f) What is the active chemical compound in chlorine disinfection?

(g) In some localities, drinking water disinfection is now done with chloramines instead of with chlorine. What advantage do chloramines possess relative to chlorine?

(h) What two chemical elements contribute most to eutrophication?

(i) What is a NAPL?

(j) Explain how coagulation and flocculation can improve the efficiency of a sedimentation basin.

(k) Which of the following membrane processes would be suitable for desalinating sea water? Name all that apply: electrodialysis, reverse osmosis, nanofiltration, ultrafiltration.

(l) By what mechanism does a trickling filter remove BOD from wastewater?

4. ON AIR QUALITY ENGINEERING (8 points; 1 each)
Provide a brief answer to each of the following questions.
(a) What overall approach is used to control excessive ozone levels in urban air?
(b) Natural gas is favored over coal as a fuel source for producing electricity in California because it is less polluting. Name two primary criteria pollutants for which natural gas is markedly (i.e. an order of magnitude or more) better than coal.
(c) What distinguishes *thermal* NO_x from *fuel* NO_x?
(d) Why would it be technically improper to refer to the particle emissions from diesel engines as *ash*?
(e) What is meant by a *photolytic* reaction? Give one specific example of such a reaction.
(f) Name two practical options for reducing particulate air pollution from fireplace use.
(g) Name two approaches that are being used to reduce tailpipe emission rates (g emitted per mi driven) of CO from gasoline-fueled motor vehicles.
(h) Name two approaches that can be used to reduce tailpipe emission rates (g emitted per mi driven) of particulate matter from diesel-fueled motor vehicles.

5. DRINKING WATER DISINFECTION (8 points)
[Reference: CN Haas, Disinfection, in *Water Quality and Treatment: A Handbook of Community Water Supplies*, 5th Edition, American Water Works Association, 1999.]
The data in the figure shows the time required for 99% inactivation of *E. coli* by free chlorine in a batch reactor. Use the data in this figure for the following problems. Also assume that Chick's law applies: $N(t) = N(0)\, e^{-kt}$.
(a) What is the rate constant, k, when the concentration is C = 1 mg/L? (2 points)
(b) Consider the disinfection stage of a drinking water treatment plant. The unit is configured as a PFR. The free chlorine concentration is 1 mg/L and the contact time is 1 min. What percent inactivation of *E. coli* is expected? (3 points)
(c) After leaving the water treatment plant, the water contains a residual concentration of 0.1 mg/L. It travels to a storage reservoir that behaves like an ideal CMFR, with a hydraulic detention time of 1000 min. Considering the storage reservoir alone, what percent inactivation of *E. coli* is expected? (3 points)

6. ENVIRONMENTAL TOBACCO SMOKE CONTROL BY AIR FILTRATION (6 points)
Consider indoor air pollution by fine particulate matter, which results from smoking a single cigarette in a house. The time-dependent emissions rate E(t) is depicted in Figure 6(a). Figure 6(b) shows a schematic of the house for uncontrolled conditions. The concentration profile of environmental tobacco smoke (ETS) particles that results from this episode is shown in Figure 6(c). Assume throughout the problem that the following data apply: $Q = 3\ m^3\ min^{-1}$; $V = 350\ m^3$; $E^* = 1.5$ mg min^{-1}; $t^* = 7$ min; and $C(0) = 0$. Do not include any particles entering the house from outdoor air. Define C* as the peak indoor concentration. Define τ as the time after the cigarette is smoked needed for the concentration to drop to C*/e. [*Note:* For this problem τ is defined to have a precise value — it is not a magnitude estimate.]
(a) Referring to Figure 6(c), evaluate C* and τ for the uncontrolled condition. Assume that particles are only removed by means of ventilation. (3 points)
(b) Now consider the case depicted in Figure 6(d). Here, a control device has been introduced. It consists of a fibrous filter plus a fan. The fan draws indoor air through the filter at a flow rate $Q_f = 2\ m^3\ min^{-1}$ and then discharges the filtered air into the

indoor environment. The parameter η =0.9 is the single-pass efficiency of the filter, i.e. the fraction of particles entering the control device that are removed. Again, a single cigarette is smoked. Now particles are removed by a combination of ventilation and filtration. The time-dependent ETS particle concentration follows the same profile shown in Figure 6(c); however, the values of C* and τ may differ. Evaluate C* and τ for this case. (3 points).