

TU Delft
Faculty of Civil Engineering and Geosciences
Subfaculty Civil Engineering
Section Sanitary Engineering

CT4470 Drinking water I - Technology

Date : June 2004
Time : 9.00-12.00 h

There are 6 questions of equal weight. In all questions it is important to show insight in the influence of process parameters on the treatment step in consideration, in order to be able to optimise design and operation.

During the examination a A4-tje with own notes may **NOT** be used.

If there are uncertainties about the question, do not hesitate to ask the supervisor.

Motivate your answer and check if the answer is complete and practical.

Overview of questions

1. Sedimentation
2. Coagulation/flocculation
3. Aeration
4. Rapid sand filtration
5. Activated carbon
6. Softening
7. Membrane filtration

General data

Table 1 – Atom mass of important elements in water chemistry.

Element	Atom mass	Element	Atom mass
H	1	S	32
C	12	Cl	35,5
N	14	K	39
O	16	Ca	40
F	19	Mn	55
Na	23	Fe	56
Mg	24	As	75
Al	27	Pb	207
P	31		

Table 2 - Dynamic and kinematic viscosity as function of temperature.

Temperature [°C]	Dynamic viscosity [10^{-3} Pa·s]	Kinematic viscosity [10^{-6} m ² /s]
0	1,79	1,79
5	1,52	1,52
10	1,31	1,31
15	1,15	1,15
20	1,01	1,01
25	0,90	0,90
30	0,80	0,80

Relevant formulas in water chemistry

bij T = 10°C

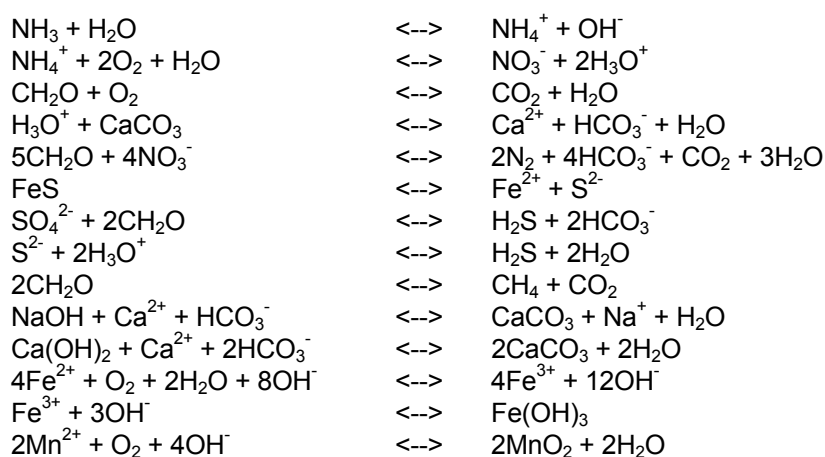
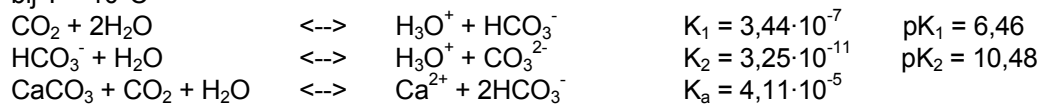


Table 3 - k_D -values for different gasses as function of temperature.

k_D	0°C	10°C	20°C
Nitrogen	0,023	0,019	0,016
Oxygen	0,049	0,039	0,033
Methane	0,055	0,043	0,034
Carbon dioxide	1,710	1,230	0,942
Hydrogen sulfide	4,690	3,650	2,870
Tetrachloroethene	-	3,380	1,880
Trichloroethene	-	4,100	2,390
Chloroform	-	9,620	5,070

Universal gas constant $R = 8,3142 \text{ J}/(\text{K}\cdot\text{mol})$

Table 4 – Composition of air in atmosphere ($T = 10^\circ\text{C}$, $p = 1 \cdot 10^5 \text{ Pa}$)

Gas	Volume percentage [%]
Nitrogen	78,1
Oxygen	20,95
Carbon dioxide	0,003
Argon	0,93
Rest gasses	0,0002

Relevant formula

$$c = \frac{p}{R \cdot T} \cdot MW$$

$$RQ = \frac{Q_i}{Q_w}$$

$$K_1 = 1 - \exp(-k_2 \cdot t)$$

$$K_3 = \frac{1 - \exp\left(-k_2 \cdot t \cdot \left(1 + \frac{k_D}{RQ}\right)\right)}{1 + \frac{k_D}{RQ}}$$

$$K_5 = \frac{1}{1 + \frac{1}{k_2 \cdot t} + \frac{k_D}{RQ}}$$

$$l_0 = \frac{H_0}{L} = 180 \cdot \frac{v}{g} \cdot \frac{(1 - p_0)^2}{p_0^3} \cdot \frac{v}{d^2}$$

$$H_{\max} = (1 - p) \cdot L \cdot \frac{\rho_f - \rho_w}{\rho_w}$$

$$\frac{c_0}{c_e} = 1 + \exp\left(k_2 \cdot \text{EBCT} \cdot \left(1 - \frac{BV \cdot c_0}{q \cdot p}\right)\right)$$

$$J = \frac{Q}{A_{\text{mem}}} = \frac{K_w \cdot (\text{TMD} - \Delta\pi)}{v}$$

$$\pi = \sum \frac{R \cdot T \cdot c_i \cdot z_i}{MW_i}$$

$$\text{Ret} = 1 - \frac{c_p}{c_f}$$

$$G = \sqrt{\frac{P}{\mu \cdot V}}$$

$$s_0 = \frac{Q}{B \cdot H}$$

$$\text{Re} = \frac{v_0 \cdot R}{v}$$

$$R = \frac{B \cdot H}{B + 2 \cdot H}$$

$$\frac{dc}{dt} = k_2 \cdot (c_s - c)$$

$$K = \frac{c_e - c_0}{c_s - c_0}$$

$$K_2 = \frac{1}{1 + \frac{1}{k_2 \cdot t}}$$

$$K_4 = \frac{1 - \exp\left(-k_2 \cdot t \cdot \left(1 - \frac{k_D}{RQ}\right)\right)}{1 - \frac{k_D}{RQ} \cdot \exp\left(-k_2 \cdot t \cdot \left(1 - \frac{k_D}{RQ}\right)\right)}$$

$$K = 1 - (1 - k)^n$$

$$H = 130 \cdot \frac{v^{0.8}}{g} \cdot \frac{(1 - p_e)^{1.8}}{p_e^3} \cdot \frac{v^{1.2}}{d^{1.8}} \cdot L_e$$

$$q_{\max} = \frac{x}{m} = K \cdot c_s^n$$

$$BV = \frac{Q \cdot T}{V} = \frac{T}{\text{EBCT}}$$

$$\text{TMD} = \frac{P_f + P_c}{2} - P_p = P_f - \frac{\Delta P_{\text{hydr}}}{2} - P_p$$

$$\gamma = \frac{Q_p}{Q_f}$$

$$\beta = \exp\left(\frac{J \cdot \delta}{D_i}\right)$$

$$P = \rho \cdot g \cdot Q \cdot \Delta H$$

$$r = (1 - p_0) + \frac{1}{s_0} \cdot \int_0^{p_0} s dp$$

$$\text{Fr} = \frac{v_0^2}{g \cdot R}$$

$$\tau = \frac{\lambda}{8} \cdot \rho_w \cdot v_s^2$$

1 Sedimentation

The flock removal is done in an open sedimentation pond. The sedimentation pond is divided in three streets. The dimensions of one street are:

- L = 200 m
- W = 20 m
- H = 1.5 m

The design capacity of the existing sedimentation is 6.000 m³/h. The water company is evaluating the possibilities of increasing the capacity to 6000 m³/h. Some possible scenario's are:

- no change to the existing sedimentation
- increase the depth of all streets to 2.5 m
- increase the length of all streets to 300 m
- increase the number of streets to 4 (width=20 m)

- 1.1 mention the advantages and the disadvantages of the four scenario's
- 1.2 calculate the surface load, the Reynolds number and the Camp number for the four scenario's at 10 °C.

2 Coagulation and flocculation

- 2.1 Three different mechanisms can cause coagulation. Mention the characteristics of the three mechanisms.
- 2.2 With a velocity of 750 m³/h the water is fed to two units. The coagulant is added in a cascade with a height of 0,2 m. The shear of mixing (G_c) at a temperature of 10 °C is for this situation 1500 sec⁻¹. The coagulation and flocculation compartments are a bit over dimensioned and therefor if the velocity is below 500 m³/h only one unit is used. Calculate the shear at a velocity of 500 m³/h and a temperature of 10°C (one unit in use).
- 2.3 The shear (G_v) in the first flocculation compartment is 100 s⁻¹ (10°C, 750 m³/h, 2 units). The flocculation is assisted with a stirring device. Calculate the shear in this compartment at low velocities (500 m³/h, temperature of 10 °C, one unit in use).
- 2.4 What are the possibilities in this process to improve the flocculation at different temperatures.

3 Aeration

The composition of air is given in table 1. For the removal of methane from groundwater a water company uses cascade aeration. The aeration consists of 5 stages and the total falling height is 2 m. The concentration of methane in the raw water is 0,8 mg/l and after the first stage 0,54 mg/l.

Table 1 – composition of air (10°C, 101325 Pa).

Gas	Volume percentage [%]
N ₂	78,084
O ₂	20,948
Ar	0,934
CO ₂	0,034
CH ₄	0,00001

- 3.1 Calculate the equilibrium concentration of methane in water at a pressure of 101325 Pa and a temperature of 10°C.
- 3.2 Calculate the methane removal after 5 cascade stages.
- 3.3 Calculate the value of $k_2 \cdot t$ for only one cascade stage with the assumption that the RQ of one cascade stage is 0,4.
- 3.4 Explain why the removal of CO₂ with the cascade is less compared to the removal of CH₄.

4. **Rapid sand filtration**

process design and process parameters of a rapid sand filter:

- bed height L: 1,2 m
- d_0 : 0,85 mm
- p_0 : 38%
- v : 8 m/h
- T_r : 24 h
- T_q : 18 h
- Temperature: 10 C

Question:

- 4.1 Calculate the clean bed resistance of the filter.

The effluent quality should be improved. The suspended solid concentration in the effluent is too high. The operator suggests 4 alternatives to improve the situation:

- a. increase the bed height L from 1,2 till 1,6 m
 - b. change the sand with a finer sand fraction of $d_0 = 0,65$ mm
 - c. lower the surface load to $v_{new} = 5$ m/h
 - d. decrease T_r from 24 h to 16 h
- 4.2. what is your opinion about every alternative. Consider the effluent quality, the ease of operation and the costs. Express and explain your preference for one of the options.
 - 4.3. Mention one alternative in order to increase the effluent quality which was not mentioned yet.

5 **Activated carbon**

A water company is facing a concentration of 0.5 µg/l atrazine in the surface water. With activated carbon the water company wants to reduce the concentration below the legislated concentration of 0.1 µg/l. Two options are evaluated:

- a. dosing of powdered activated carbon before the coagulation

- b. Granular Activated Carbon filtration after the rapid sand filters. GAC-filters should be build.

The Freundlich constants for atrazine are:

$$\begin{aligned} K &= 20 \quad (\text{g/kg})(\text{m}^3/\text{g})^n \\ n &= 0.77 \quad - \\ \rho &= 400 \quad \text{kg/m}^3 \end{aligned}$$

- 5.1. Calculate for both option the minimal dose in g/m^3 .

In the period from September to may the concentration of atrazine is below $0.1 \mu\text{g/l}$. There is a period (several month) with a low water demand.

- 5.2. Explain the differences of both options with respect to the following criteria:
- investment costs
 - running costs
 - process operation of the installation with different water productions
 - water quality
- 5.3. Which option is your choice and why?

6. Softening

Of a water type the water composition is known:

Ca^{2+}	100 mg/l
Mg^{2+}	6.1 mg/l
HCO_3^-	347.7 mg/l
CO_2	11.44 mg/l
Na^+	10.8 mg/l

The legislation for the water composition is:

- totale hardness = 1.5 mmol/l
- concentration $\text{HCO}_3^- > 2$ mmol/l
- concentration $\text{Na}^+ < 5.2$ mmol/l

- 6.1 What is the total hardnes of this water?
- 6.2 Which chemical is most suited for this water and how much should be dosed?
- 6.3 There is a possibility to soften in a split stream. How large should the split stream be if this spilt stream can be softened to 0.7 mmol/l.
- 6.4 Calculate the chemical dose and the drinking water composition if softening is split stream is used (the same chemical as chosen in 6.2).
- 6.5 Calculate how many chemicals are used per hour in 6.2 and 6.4 at a total water production of $100 \text{ m}^3/\text{h}$. Explain the differences.

7 Membranfiltration

In figure 1 a membrane filtration installation is shown for reverse osmosis with spiral wound membrane elements.

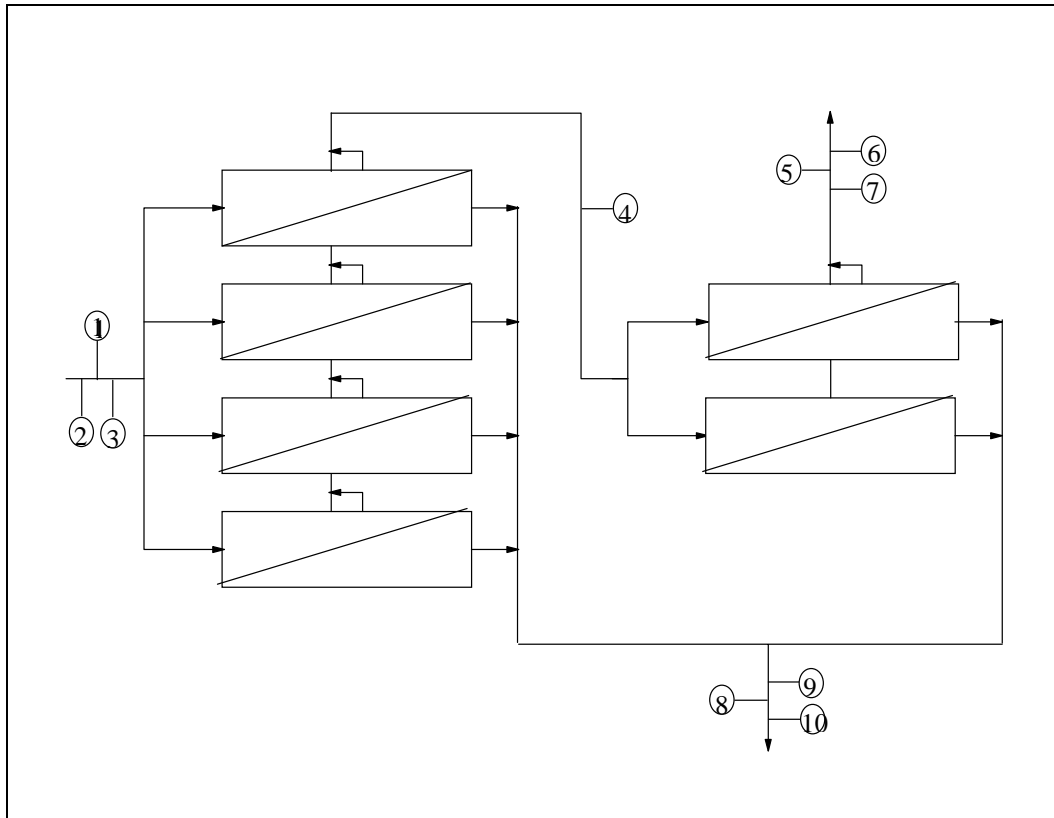


figure 1 – Membrane unit with different measuring devices.

7.1 In the figure different meters are shown. The values on these measuring devices are shown below. Put the right values at the right place.

$P = 17.9 \text{ bar};$ $P = 16.5 \text{ bar};$ $P = 15.2 \text{ bar};$ $P = 1.0 \text{ bar}$
 $Q = 45.5 \text{ m}^3/\text{h};$ $Q = 34.1 \text{ m}^3/\text{h};$ $Q = 11.4 \text{ m}^3/\text{h}$
 $C = 3920 \text{ mg/l};$ $C = 1000 \text{ mg/l};$ $C = 20 \text{ mg/l}$

7.2 If the installation is used for some time the cross-flow velocity and the permeate flux can decrease.

- What can be the cause of this decrease?
What should an operator do with the feed pressure and the concentrate pressure in order to get the original values back (The permeate pressure is constant) in the following cases:
- The cross-flow velocity as well as the permeate flux are too low.
- The cross-flow velocity is too low but the permeate production is OK
- The cross-flow velocity is OK but the permeate production is too low.

7.3 What is the recovery of one stage if the recovery's of both stages are the same?

Answers

1.1 No change

advantages: no extra costs, no realisation problems
 disadvantages: lower quality through higher Reynolds-number, higher surface loading

deeper settling tank:
 advantages: longer retention time (only important for flocculent settling)
 disadvantages: extra costs, Re and surface loading remain bad

longer settling tank:
 advantages: low surface loading, stable flow
 disadvantages: changing discharge construction, costs, Re remains bad

extra settling tank:
 advantages: low surface loading, best Reynolds-number, quality
 disadvantages: connection to floc formation, settling

1.2

	no change	deeper	longer	extra lane
$Q_{\text{per straat}} [\text{m}^3/\text{h}]$	2000	2000	2000	1500
$L [\text{m}]$	200	200	300	200
$B [\text{m}]$	20	20	20	20
$H [\text{m}]$	1.5	2.5	1.5	1.5
$s_0 [\text{m/s}]$	$1.39 \cdot 10^{-4}$	$1.39 \cdot 10^{-4}$	$9.26 \cdot 10^{-5}$	$1.04 \cdot 10^{-4}$
$Re [-]$	18439	16964	18438	13829
$C_p [-]$	$2.68 \cdot 10^{-5}$	$6.29 \cdot 10^{-6}$	$2.68 \cdot 10^{-5}$	$1.51 \cdot 10^{-5}$

- 2.1 electrostatic coagulation: compression of double layer
 adsorptive coagulation: formation of positive iron hydroxide ions that adsorb onto negative colloids
 precipitation coagulation: formation of neutral hydroxide flocs that encapsulate colloids.

- 2.2 At design capacity the water flow over 2 units, or $750/2 = 375 \text{ m}^3/\text{h}$ per unit. The velocity gradient for rapid mixing is then:

$$G_c = \sqrt{\frac{\rho_w \cdot g \cdot \Delta H}{\tau_c \cdot \mu}} = 1500 \text{ sec}^{-1} \text{ or a contact time of } 0.67 \text{ seconds.}$$

When $500 \text{ m}^3/\text{h}$ instead of $375 \text{ m}^3/\text{h}$ flows over one unit, the contact time is $375/500 \cdot 0.67 = 0.50$ seconds. The velocity gradient then is 1730 sec^{-1} .

- 2.3 Velocity gradient for floc formation remains the same and is independent of flow.

$$G = \sqrt{\frac{P}{\mu \cdot V}}$$

- 2.4 - change of mixing velocity
 - change of dosing of coagulant

- 3.1 To calculate the saturation concentration of methane in water the following formula is used:

$$c_s = k_D \cdot c_g; \quad c_g = \frac{P \cdot MW}{R \cdot T}$$

k_D for methane at 10°C → $k_D = 0.043$

$P = 0.0001/100 \cdot 101325 = 0.1013 \text{ Pa}$

$c_g = 0.1013 \cdot 16 / (8.31 \cdot 283) = 6.9 \cdot 10^{-4}$

$c_s = 0.043 \cdot 6.9 \cdot 10^{-4} = 2.96 \cdot 10^{-5} \text{ mg/l}$

3.2 Removal efficiency of one step: $k = \frac{c_e - c_o}{c_s - c_o} = \frac{0.54 - 0.80}{0 - 0.80} = 0.33$

removal efficiency of 5 steps: $K = 1 - (1 - k)^n = 1 - (1 - 0.33)^5 = 0.87$

3.3 For a cascade the formula for ideal mixing without neglecting mass balance is used:

$$K = \frac{1}{1 + \frac{1}{k_2 \cdot t} + \frac{k_D}{RQ}}$$

The removal efficiency per step is 0.33, the effective RQ for a cascade is 0.4. With these values $k_2 \cdot t$ can be calculated:

$$K = \frac{1}{1 + \frac{1}{k_2 \cdot t} + \frac{k_D}{RQ}} \Rightarrow 0.33 = \frac{1}{1 + \frac{1}{k_2 \cdot t} + \frac{0.043}{0.4}} \Rightarrow k_2 \cdot t = 0.52$$

3.4 The k_D -value of CO₂ is much higher than the k_D -value of methane. With the same cascade of question 3.3, the removal efficiency is:

$$K = \frac{1}{1 + \frac{1}{k_2 \cdot t} + \frac{k_D}{RQ}} = \frac{1}{1 + \frac{1}{0.52} + \frac{1.23}{0.4}} = 0.167$$

4.1. Clean bed resistance: $l_0 = 180 \cdot \frac{1}{g} \cdot (1 - p_0)^2 / p_0^3 \cdot v / d_0^2$
 $l_0 = 0.52 \quad H = L \cdot l_0 = 1.2 \cdot 0.53 = 0.62 \text{ m}$

- 4.2. a. L to 1.6 m: T_r lower, T_q higher, break through occurs later, changing the filter (higher walls, higher back wash gutters) is expensive and must be possible in the installation.
- b. d_0 to 0.65: T_r lower, T_q higher, improvement of quality, but back wash frequency increases. Costs of changing sand are only once.
- c. v to 5 m/h: break through will occur later. Capacity of the filter decreases, thus new filters must be built ⇒ high investment costs.
- d. T_r to 16 h: break through is avoided, seems to be the best solution: no extra costs.

4.3. Applying multi layer filtration, for example 0.7 m sand with 0.8 m anthracite.

5.1. PAC: $q = K \cdot (C_{\text{effluent}})^n = 20 \cdot (0.1 \cdot 10^{-3})^{0.77} = 0.0166 \text{ g/kg}$

$$\text{PAC}_{\text{min}} = (0.5 \cdot 10^{-3} - 0.1 \cdot 10^{-3}) \cdot 1000 / 0.0166 = 24.1 \text{ g/m}^3$$

GAC: $q = 20 \cdot (0.5 \cdot 10^{-3})^{0.77} = 0.0574 \text{ g/kg}$

$$W = c_o \cdot 1000 / q = 0.5 \cdot 10^{-3} \cdot 1000 / 0.0574 = 8.7 \text{ g/m}^3$$

- 5.2. a. low for PAC, much higher for GAC
 b. little higher (costs of PAC) for PAC, for GAC some what lower (regeneration costs)
 c. for PAC the dosing is easy to adapt for variable flows, for GAC the surface loading must be varied by using more or less filters.
 d. quality is better when using GAC.

5.3. GAC because of better effluent water quality.

6.1 $100/40 + 6.1/24 = 2.5 + 0.25 = 2.75 \text{ mmol/l}$

6.2 dosing of caustic soda: 1.51 mmol/l

Ca²⁺: 1.25 mmol/l

Mg²⁺: 0.25 mmol/l

Na⁺: 1.98 mmol/l

HCO₃⁻: 4.71 mmol/l

CO₂: 0 mmol/l

dosing of lime: 1.51 mmol/l

Ca²⁺: 1.25 mmol/l

Mg²⁺: 0.25 mmol/l

Na⁺: 0.47 mmol/l

HCO₃⁻: 3.22 mmol/l

CO₂: 0 mmol/l

Lime is best alternative

6.3 $Q \cdot 1.5 = (Q-R) \cdot 2.75 + R \cdot 0.7 \rightarrow 1.25 \cdot Q = 2.05 \cdot R \rightarrow R = 0.61 \cdot Q$

6.4 dosing of lime: 2.31 mmol/l

softened water	no-softened water	mixed quality
Ca ²⁺ : 0.45 mmol/l	2.50 mmol/l	1.25 mmol/l
Mg ²⁺ : 0.25 mmol/l	0.25 mmol/l	0.25 mmol/l
Na ⁺ : 0.47 mmol/l	0.47 mmol/l	0.47 mmol/l
HCO ₃ ⁻ : 1.60 mmol/l	5.70 mmol/l	3.20 mmol/l
CO ₂ : 0 mmol/l	0.26 mmol/l	0.10 mmol/l

6.5 at full treatment of water flow
 $100 \cdot 1.51 = 151 \text{ mol/h}$

at 61% split treatment
 $61 \cdot 2.31 = 141.9 \text{ mol/h}$

the difference occurs because the non-softened water contains CO₂.

7.1 feed: P = 17.9 bar
 c = 1000 mg/l
 Q = 45.5 m³/h

concentrate: P = 15.2 bar
 c = 3920 mg/l
 Q = 11.4 m³/h

product: P = 1.0 bar
 c = 20 mg/l
 Q = 34.1 m³/h

Extra point: P = 16.5 bar

- 7.2
- a) fouling and/or scaling
 - b) feed pressure higher
 - c) feed pressure higher, concentrate pressure lower
 - d) feed pressure higher and concentrate pressure higher

7.3

$$45.5x + 45.5(1-x) = 34.1$$
$$x = 0.5$$