THE UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE AND ENGINEERING
CIV 582S—ADVANCED CONTAMINANT HYDROGEOLOGY
Final Examination—Apr. 23, 2001

Examiner: Brent Sleep
Instructions:
Type X examination: any aids permitted.
Answer all questions. If doubt exists as to the interpretations of any question, a clear statement of assumptions made should be included with the answer.

Question	1a	1b	2a	2b	2c	3	4	5a	5b	5c	5d
Marks	5	5	4	6	5	10	10	5	5	5	5

1. a) Measurements of soil moisture at a field site made using time domain reflectometry indicate that the water saturation at the ground surface is 0.1. At 1 m below the ground surface the saturation is 0.5. Tensiometer measurements indicate that the water pressures are -2 m at the ground surface and -1.0 m at the depth of 1 m below the ground surface. If the irreducible water saturation is 0.05, the maximum saturation is 1.0, and the soil can be characterized using the Brooks-Corey relationship determine p_d and λ, and depth to the water table if there is no water flow. The soil porosity is 0.4 and the soil hydraulic conductivity is 10^{-3} cm/sec.

   b) A capillary tube of diameter 0.1 mm was placed in a pan containing a fluid with a density of 1400 kg/m^3 . The fluid moved up the capillary tube to a height of 4 cm. If the air-fluid contact angle was 10 degrees, determine the air-liquid interfacial tension.

2. **a)** Determine the minimum thickness of LNAPL in a well (i.e. the thickness of the oil layer that would form in the well when $z_{ao} = z_{ow}$) in terms of soil Brooks-Corey parameters, and LNAPL and water densities.
b) A fractured clay aquitard has a matrix porosity of 0.4, and a permeability of 10^{-17} m^2. The fracture apertures are 100 micron, and the fracture spacing (fractures are vertical) is 50 cm. A well screened below the aquitard has a water level of 100 m.a.s.l., while one above the aquitard has a water level of 102 m. Determine the times for a contaminant to move from the top to the bottom of the aquitard through the fractures and through the clay matrix.
c) PCE was spilled into a fractured rock system. Discuss the movement of the PCE DNAPL and the dissolved phase, and the impact of rock properties on movement of DNAPL and dissolved phases.

3. Toluene has been injected into a sand column continuously. The Darcy velocity is 0.5 m/day, the sand porosity is 0.3, the sand f_{oc} is 0.02, the sand bulk density is 1.8 g/cm^3, the longitudinal dispersivity is 5 cm, the effective diffusion coefficient is 1 x 10^{-10} m^2/sec, and the toluene has a log K_{oc} of 2.0. The inlet toluene concentration was constant at 100 mg/L. Determine the concentration of toluene 0.3 m from the inlet after 5 days.

4. A company has proposed using steam flushing for remediation of PCB DNAPL (Aroclor 1242) contamination in a silty-sandy aquifer. A second company has proposed the use of surfactant flushing for this problem. Outline the advantages and disadvantages of each method for this problem.

5. A phase one investigation at an plastics manufacturing facility reveals that **ethylene dichloride** (1,2-DCA) was used as feedstock for chemical manufacture for many years in the 1950's and that many barrels of 1,2-DCA were dumped in a pit on the site. The site consists of a sandy aquifer overlaying a thick clay aquitard at 30 m below the ground surface. The water table at the site is 5 m below the ground surface.
    a) Discuss the movement of 1,2-DCA NAPL at this site, and steps you would take to determine the location of the 1,2-DCA NAPL.
    b) Discuss the potential for natural attenuation at this hypothetical site.
    c) Outline the steps you would take to establish if natural attenuation is occurring at the site.
    d) Discuss the application of free phase recovery, followed by pump and treat or biosparging to remediation of this site, indicating the advantages and disadvantages of these technologies for this problem.

BLE 7.7 Volatilization Parameters for Selected Chemicals

Chemical	M (g/mol)	Solubility[a] mg/L	Solubility[a] mol/m³	Vapor pressure at 20°C mm Hg	Vapor pressure at 20°C atm	Henry's law Const. H Atm-m³/mol	Henry's law Const. H Non-dim	Phase Exchange Coeff. (cm/hr) Liquid k_l	Phase Exchange Coeff. (cm/hr) Gas k_g	Mass Transfer Coefficient K_L (cm/hr)	Half life (hr)
					Low volatility ($H < 3 \times 10^{-7}$)						
3-Bromo-1-propanol	139	1.7×10^{-3}	1233	0.1	1.3×10^{-4}	1.3×10^{-6}	5.4×10^{-5}	16	1600	2.4×10^{-3}	9480
Dieldrin	381	0.25	6.6×10^{-4}	1×10^{-7}	1.3×10^{-10}	1.3×10^{-6}	5.4×10^{-5}	12	990	8.8×10^{-3}	7840
					Middle range ($3 \times 10^{-7} < H < 10^{-3}$)						
Lindane	290.9	7.3	2.5×10^{-3}	9.4×10^{-6}	1.2×10^{-8}	4.8×10^{-7}	2.0×10^{-5}	14	1130	0.025	2760
m-Bromonitrobenzene	170	104	58.8	0.07	9.2×10^{-5}	3.6×10^{-6}	1.5×10^{-4}	16	1500	0.11	626
Pentachlorophenol	266	14	5.3×10^{-3}	1.4×10^{-4}	1.8×10^{-7}	3.4×10^{-6}	1.4×10^{-4}	12	1130	0.17	406
p-t-Butylphenol	150	10^4	6.7	0.046	6.1×10^{-5}	9.1×10^{-6}	3.8×10^{-4}	17	1400	0.59	117
Aldrin	365	0.2	5.5×10^{-4}	6×10^{-6}	7.9×10^{-9}	1.4×10^{-5}	6.1×10^{-4}	12	1010	1.0	68
Nitrobenzene	123	2×10^3	16.3	0.27	3.5×10^{-4}	2.2×10^{-5}	9.3×10^{-4}	20	1700	1.5	45
DDT	354.5	1.2×10^{-3}	$3.4^{*} \times 10^{-6}$	1×10^{-7}	1.3×10^{-10}	3.8×10^{-5}	1.7×10^{-3}	13	1025	1.5	35
Phenanthrene	178	1.29	7×10^{-3}	2.1×10^{-6}	2.8×10^{-9}	3.9×10^{-5}	1.7×10^{-3}	18	1450	2.2	31
Acetylene tetrabromide	344	650	1.9	0.3	3.9×10^{-4}	2.1×10^{-5}	8.9×10^{-4}	13	1000	5.3	13.1
Aroclor 1242	254	0.24	9.5×10^{-4}	4.1×10^{-4}	5.3×10^{-7}	5.6×10^{-4}	2.4×10^{-2}	15	1210	9.9	7
Ethylene dibromide	188	4.3×10^3	22.9	11.6	1.5×10^{-2}	6.4×10^{-4}	2.8×10^{-2}	16	1400	13.4	6.1
					High volatility ($H > 10^{-3}$)						
Ethylene dichloride	99	8.0×10^3	80.8	67	0.09	1.1×10^{-3}	4×10^{-2}	22	1900	17.1	4
Naphthalene	128	33	0.026	0.23	3×10^{-4}	1.15×10^{-3}	4.9×10^{-2}	23	1763	16.9	4.1
Biphenyl	154	7.5	0.05	0.06	7.5×10^{-5}	1.5×10^{-3}	6.8×10^{-2}	19	1554	16.2	4.3
Methylene chloride	85	1.3×10^4	155	349	0.46	3×10^{-3}	0.13	25	2000	23.8	3
Chlorobenzene	113	472	4.2	11.8	1.6×10^{-2}	3.7×10^{-3}	0.165	22	1820	15.1	4.6
Chloroform	119	8×10^3	67	246	0.32	4.8×10^{-3}	0.2	20	1700	18.9	3.7
o-Xylene	106	175	1.7	6.6	8.7×10^{-3}	5.1×10^{-3}	0.22	23	1870	22	3.2
Benzene	78	1780	22.8	95.2	1.25×10^{-1}	5.5×10^{-3}	0.24	27	2180	26	2.7
Toluene	92	515	5.6	28.4	3.7×10^{-2}	6.6×10^{-3}	0.28	25	2010	29	2.9
Perchloroethylene	166	400	2.4	14.3	2×10^{-1}	8.3×10^{-3}	0.34	17	1430	16.4	4.2
Ethyl benzene	106	152	1.45	9.5	1.25×10^{-2}	8.7×10^{-3}	0.37	23	1870	22.3	3.3
Trichloroethylene	131	1×10^3	7.6	60	8×10^{-2}	9.1×10^{-3}	0.42	21	1700	20.4	3.4
Mercury	201	3×10^{-3}	1.5×10^{-5}	1.3×10^{-3}	1.7×10^{-6}	1.1×10^{-2}	0.48	17	1360	16.6	4.2
Methyl bromide	95	1.3×10^4	137	1.4×10^3	1.8	1.3×10^{-2}	0.56	23	2000	22.3	3.1
Cumene (isopropyl benzene)	120	50	0.416	4.6	6.1×10^{-3}	1.5×10^{-2}	0.62	22	1760	21.6	3.2
1,1,1-Trichloroethane	133	950	7.1	100	0.13	1.8×10^{-2}	0.77	19	1650	18.7	3.7
Carbon tetrachloride	154	800	5.2	91	0.12	2.3×10^{-2}	0.97	19	1500	18.8	3.7
Methyl chloride	50.5	7.4×10^3	146	3.6×10^3	4.74	2.4×10^{-2}	0.36	30	2600	29	2.4
Ethyl bromide	109	900	8.3	460	6.1×10^{-1}	7.3×10^{-2}	3.1	22	1800	22	3.1
Vinyl chloride	62.5	90	1.44	2580	3.4	2.4	99	28	2400	28	2.5
2,2,4-Trimethyl pentane	114	2.44	2.1×10^{-2}	49.3	6.5×10^{-2}	3.1	129	22	1810	22	3.1
n-Octane	137	0.66	5.8×10^{-3}	14.1	1.85×10^{-2}	3.2	136	22	1810	22	3.1
Fluoro-trichloromethane	137					5		11.3	1090	11.3	6.1
Ethylene	28	131	4.7		>40	>86	>360	40	3700	40	1.7

[a] Source: Mackay and Leinonen, 1975; Mackay et al., 1979; Mackay and Wolkoff, 1973; Verschueren, 1977

Source: Lyman et al., 1990

Values of erf (β) and erfc (β) for positive values of β

β	erf (β)	erfc (β)
0	0	1.0
0.05	0.056372	0.943628
0.1	0.112463	0.887537
0.15	0.167996	0.832004
0.2	0.222703	0.777297
0.25	0.276326	0.723674
0.3	0.328627	0.671373
0.35	0.379382	0.620618
0.4	0.428392	0.571608
0.45	0.475482	0.524518
0.5	0.520500	0.479500
0.55	0.563323	0.436677
0.6	0.603856	0.396144
0.65	0.642029	0.357971
0.7	0.677801	0.322199
0.75	0.711156	0.288844
0.8	0.742101	0.257899
0.85	0.770668	0.229332
0.9	0.796908	0.203092
0.95	0.820891	0.179109
1.0	0.842701	0.157299
1.1	0.880205	0.119795
1.2	0.910314	0.089686
1.3	0.934008	0.065992
1.4	0.952285	0.047715
1.5	0.966105	0.033895
1.6	0.976348	0.023652
1.7	0.983790	0.016210
1.8	0.989091	0.010909
1.9	0.992790	0.007210
2.0	0.995322	0.004678
2.1	0.997021	0.002979
2.2	0.998137	0.001863
2.3	0.998857	0.001143
2.4	0.999311	0.000689
2.5	0.999593	0.000407
2.6	0.999764	0.000236
2.7	0.999866	0.000134
2.8	0.999925	0.000075
2.9	0.999959	0.000041
3.0	0.999978	0.000022