UNIVERSITI SAINS MALAYSIA

Second Semester Examination
2015/2016 Academic Session

June 2016

EKC 376 – Downstream Processing of Biochemical and Pharmaceutical Products
[Proses Hiliran untuk Produk Biokimia dan Farmaseutikal]

Duration : 3 hours
[Masa : 3 jam]

Please ensure that this examination paper contains NINE printed pages and FOUR printed pages of Appendix before you begin the examination.

[Sila pastikan bahawa kertas peperiksaan ini mengandungi SEMBILAN muka surat yang bercetak dan EMPAT muka surat Lampiran sebelum anda memulakan peperiksaan ini.]

Instructions: Answer **ALL** questions.

*[**Arahan:** Jawab **SEMUA** soalan.]*

In the event of any discrepancies, the English version shall be used.

[Sekiranya terdapat sebarang percanggahan pada soalan peperiksaan, versi Bahasa Inggeris hendaklah diguna pakai].

Answer ALL questions.

1. [a] Define the relative centrifugal force (G) value and Σ factor in centrifugation process. Discuss their significances in the scaling up of centrifuges.

[8 marks]

[b] A viscous solution containing particles with density ρ_p = 1200 kg/m^3 is clarified by a tubular bowl centrifuge. The solution density ρ_f = 850 kg/m^3 and its viscosity $\mu = 8 \times 10^{-2}$ kg/(m.s). The centrifuge is 0.25 m high with diameters of D_0 = 0.02 m and D_1 = 0.01 m, and it is operated at 16000 × g.

[i] Calculate the largest critical particle diameter in the exit stream if the flow rate, $Q = 2 \times 10^{-3}$ m^3/h.

[12 marks]

[ii] The same solution is then handled using a scaled-up tubular bowl centrifuge having the same diameters and rotational speed. Find the length of this new centrifuge if it is operated at 1.5 times faster than that in part [i].

[5 marks]

2. [a] A fermentation broth containing gentamycin is colored by small amounts of an impurity. Before crystallization process can be conducted, the impurity has to be removed by adsorption using activated carbon which adsorbs only insignificant amounts of gentamycin. A series of laboratory experiments was made by stirring various amounts of the adsorbent into batches of the original solution until equilibrium was established. The equilibrium data in Table Q.2 was obtained at constant temperature.

Table Q.2: Equilibrium data for adsorption of gentamycin

kg carbon/kg solution	Equilibrium color (units of color/kg solution)
0.000	9.6
0.001	8.6
0.004	6.3
0.008	4.3
0.020	1.7
0.040	0.7

The color intensity was measured on an arbitrary scale, proportional to the concentration of the colored substance. It is desired to reduce the color to 10% of its original value. Determine the quantity of fresh activated carbon required per 1000 kg solution for a two-stage countercurrent operation.

[16 marks]

[b] Discuss three methods that can be used to create supersaturated solution for crystallization process.

[9 marks]

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Jawab SEMUA soalan.

1. [a] *Takrifkan nilai daya empar relatif (G) dan faktor Σ dalam proses pengemparan. Bincangkan kepentingannya dalam menaik skala pengempar.*

[8 markah]

[b] *Suatu larutan likat mengandungi partikel dengan ketumpatan $\rho_p = 1200\ kg/m^3$ dijernihkan menggunakan pengempar mangkuk tiub. Ketumpatan larutan $\rho_f = 850\ kg/m^3$ dan kelikatannya $\mu = 8 \times 10^{-2}\ kg/(m.s)$. Pengempar tersebut berketinggian 0.25 m dengan diameter $D_0 = 0.02$ m dan $D_1 = 0.01$ m, dan ia beroperasi pada 16000 × g.*

[i] *Kirakan diameter kritikal terbesar partikel pada aliran keluar sekiranya kadar aliran, $Q = 2 \times 10^{-3}\ m^3/jam$.*

[12 markah]

[ii] *Larutan yang sama kemudiannya dikendalikan menggunakan pengempar mangkuk tiub berskala besar yang mempunyai diameter-diameter dan kelajuan pusingan yang sama. Cari panjang pengempar baru ini sekiranya ia beroperasi 1.5 kali lebih laju berbanding di bahagian [i].*

[5 markah]

2. [a] *Suatu kaldu penapaian mengandungi gentamisin diwarnakan oleh sedikit bendasing. Sebelum proses penghabluran dilakukan, bendasing tersebut perlu disingkirkan melalui penjerapan menggunakan karbon teraktif yang menjerap hanya sebahagian kecil gentamisin. Eksperimen makmal secara bersiri telah dilakukan dengan mengaduk pelbagai jumlah penjerap ke dalam kelompok-kelompok larutan asal sehingga keseimbangan tercapai. Data keseimbangan dalam Jadual S.2 telah diperolehi pada suhu malar.*

Jadual S.2: Data keseimbangan untuk penjerapan gentamisin

kg karbon/kg larutan	*Warna keseimbangan (unit warna/kg larutan)*
0.000	*9.6*
0.001	*8.6*
0.004	*6.3*
0.008	*4.3*
0.020	*1.7*
0.040	*0.7*

Keamatan warna telah diukur pada skala arbitiari, berkadaran dengan kepekatan bahan berwarna. Warna tersebut perlu dikurangkan sehingga 10% daripada nilai asal. Tentukan kuantiti karbon teraktif baru yang diperlukan bagi 1000 kg larutan untuk operasi arus berlawanan dua-peringkat.

[16 markah]

[b] *Bincangkan tiga kaedah yang boleh digunakan untuk menghasilkan larutan tertepu lampau untuk proses penghabluran.* [9 markah]

3. [a] A chromatographic column was used to purify lactase. At a superficial velocity of 25 cm/h, the peak exits the column as shown in Figure Q.3.[a] Estimate:

[i] Calculate the time taken to achieve 95% yield?

[5 marks]

[ii] If the flow is increased to 50 cm/h and Taylor Dispersion controls, how long will it take to achieve the same yield? Comments on the peak broadness.

[5 marks]

[iii] The analysis of real column is more complicated due to wall effects. Suggest how could you minimize such effect.

[2 marks]

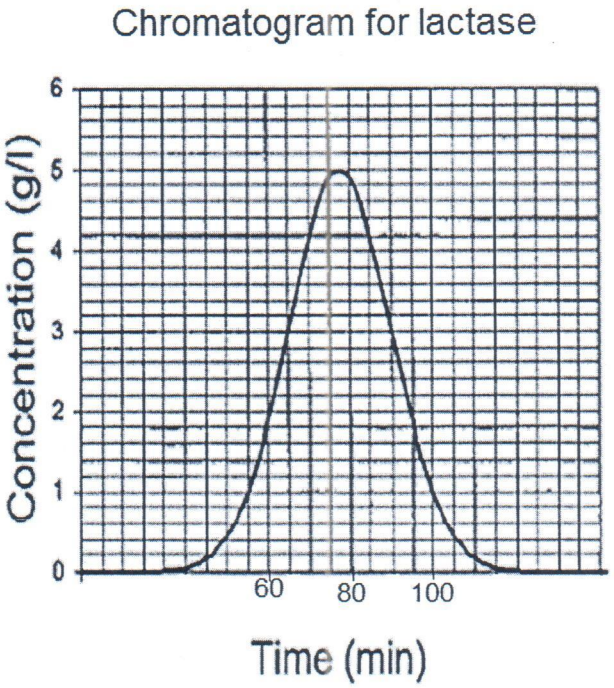


Figure Q.3.[a]: Chromatogram for Lactase separation

[b] Water is removed to pre-concentrate the milk using ultrafiltration at 50 °C and crossflow velocity of 100 cm/s. Hollow fibre units with the properties listed in Table Q.3.[b].[i] are used to filter the milk suspension with properties as stated in Table Q.3.[b].[ii]. Assume that the hydrodynamic conditions of the flow could be determined using the correlation of $Sh = 1.86\,\mathrm{Re}^{0.33}\,Sc^{0.33}\left(\frac{d_h}{L}\right)^{0.33}$.

Estimate the time required to collect 1 L of filtrate.

[13 marks]

3. [a] *Turus kromatografi digunakan untuk menulenkan laktase. Dengan halaju muka sebanyak 25 sm/j, puncak yang keluar dari turus adalah seperti yang ditunjukkan dalam Rajah S.3.[a]. Anggarkan :*

[i] Berapa lama turus harus dijalankan untuk mencapai 95% hasil?

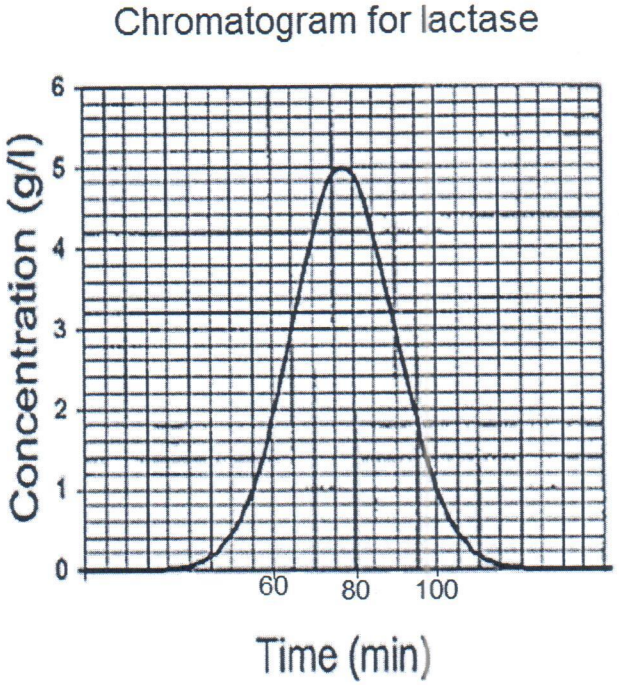
[5 markah]

[ii] Berapa lama ia harus dijalankan jika aliran meningkat kepada 50 sm/j di bawah kawalan penyebaran Taylor? Ulaskan keluasan puncaknya.

[5 markah]

[iii] Analisa turus sebenar adalah lebih rumit kerana kesan dinding. Cadangkan bagaimana anda boleh mengurangkan kesan tersebut.

[2 markah]



Rajah S.3.[a]: Chromatogram for Lactase separation

[b] *Air dikeluarkan dalam pra-pemekatan susu dengan menggunakan penurasan ultra pada 50 °C dan halaju aliran silang 100 sm/s. Unit serat berongga dengan sifat-sifat yang disenaraikan dalam Jadual S.3.[b].[i] digunakan untuk menapis ampaian susu dengan ciri-ciri seperti yang dinyatakan dalam Jadual S.3.[b].[ii]. Andaikan bahawa keadaan hidrodinamik aliran boleh ditentukan dengan menggunakan korelasi* $Sh = 1.86\,\mathrm{Re}^{0.33}\,Sc^{0.33}\left(\frac{d_h}{L}\right)^{0.33}$. *Anggarkan masa yang diperlukan untuk mengumpul 1 L turasan.*

[13 markah]

Table Q.3.[b].[i]: Properties of hollow fiber membrane units

	Specifications	Hollow Fiber
D_h	Diameter [cm]	0.11
L	Length [cm]	63.5
N_c	Number of fibers [-]	660.0
v	Superficial fluid velocity [cm/s]	100.0
ΔP	Pressure drop over length of tube [kg/cm^2]	0.9
γ_w	Shear rate at wall [s^{-1}]	7272.0

Table Q.3.[b].[ii]: Physical properties of milk

	Property	Value	Unit
ρ	Density	1.03	g/cm^3
μ	Viscosity	0.008	g/cm.s
D	Diffusivity	7.0×10^{-7}	cm^2/s
C_{bulk}	Bulk protein concentration	3.1%	weight/volume × 100
C_{gel}	Gel protein concentration (concentration polarization layer)	22.0%	weight/volume × 100

4. [a] There are concerns about the use of recycled solvents for extraction of herbal substances in the manufacturing of herbal medicinal products (HMPs). The extent to which recycled solvents are used in the manufacture of herbal preparations is not documented but it is clear that the quality of recycled solvents is a critical factor in controlling the quality of the resulting herbal preparations and ensuring batch to batch reproducibility. Potential differences in quality between fresh solvents and recycled solvents could lead to significant differences in the phytochemical composition of the resulting extracts and in certain cases could lead to higher level of contaminants or impurities.

[i] Elaborate two (2) criteria to be taken into account when considering the use of recycled solvents for extraction or other steps in the manufacture of herbal preparations.

[8 marks]

[ii] Suggest two (2) appropriate controls for recovered or recycled solvent.

[4 marks]

[b] Monoclonal antibodies were purified by a sequence of different chromatographic and membrane-based operations. Preliminary environmental assessments have suggested that the purification process to produce a monoclonal antibodies consumes 100-1000 kg of water per kilogram of purified protein. Based on this scenario,

[i] Outlined the whole downstream process based on RIPP scheme.

[5 marks]

Jadual S.3.[b].[i]: Ciri-ciri gentian geronggang unit membran

	Spesifikasi	*Gentian geronggang*
D_h	*Diameter [sm]*	0.11
L	*Panjang [sm]*	63.5
N_c	*Bilangan gentian [-]*	660.0
v	*Halaju permukaan bendalir [sm/s]*	100.0
ΔP	*Kejatuhan tekanan merentasi kepanjangan tiub [kg/sm^2]*	0.9
γ_w	*Kadar ricih pada dinding [s^{-1}]*	7272.0

Jadual S.3.[b].[ii]: Ciri-ciri fizikal susu

	Ciri-ciri	*Nilai*	*Unit*
ρ	*Ketumpatan*	1.03	g/sm^3
μ	*kelikatan*	0.008	g/sm.s
D	*kemeresapan*	7.0×10^{-7}	sm^2/s
C_{bulk}	*Kepekatan protein pukal*	3.1%	*berat/isipadu* × 100
C_{gel}	*Kepekatan gel protein (lapisan pengutuban kepekatan)*	22.0%	*berat/isipadu* × 100

4. [a] *Timbul keprihatinan tentang penggunaan pelarut dikitar semula untuk penyaringan bahan-bahan herba dalam pembuatan produk perubatan herba (HMPs). Keadaan pelarut kitar semula yang digunakan dalam pembuatan penyediaan herba masih tidak didokumenkan tetapi ia adalah jelas bahawa kualiti pelarut kitar semula adalah faktor genting dalam mengawal kualiti penyediaan herba terhasil dan memastikan kebolehulangan kelompok. Kemungkinan perbezaan kualiti antara pelarut asal dan pelarut yang dikitar semula boleh membawa kepada perbezaan yang ketara dalam komposisi fitokimia hasil saringan tersebut dan dalam kes-kes tertentu boleh membawa kepada pencemaran atau pengotoran pada tahap yang lebih tinggi.*

[i] *Huraikan dua (2) kriteria yang perlu diambil kira apabila mempertimbangkan penggunaan pelarut dikitar semula untuk pengeluaran atau langkah-langkah lain dalam pembuatan penyediaan herba.*

[8 markah]

[ii] *Cadangkan dua (2) kawalan yang sesuai untuk mengitar semula pelarut.*

[4 markah]

[b] *Antibodi monoklonal telah ditulenkan dengan turutan kromatografi yang berbeza dan operasi berasaskan membran. Penilaian alam sekitar awal telah mencadangkan bahawa proses penulenan untuk menghasilkan antibodi monoklonal telah menggunakan 100-1000 kg air bagi setiap kilogram protein yang ditulenkan. Berdasarkan senario ini,*

[i] *Gariskan proses hiliran keseluruhan berdasarkan skema RIPP.*

[5 markah]

[ii] Identify the unit operations that consumed huge amount of water. Justify your answer.

[4 marks]

[iii] Propose new innovation that has potential to reduce the amount of water needed for that process.

[4 marks]

[ii] Kenalpasti mengapa operasi unit tersebut menyumbang kepada penggunaan air yang banyak. Ulaskan jawapan anda.

[4 markah]

[iii] Cadangkan inovasi baru yang berpotensi untuk mengurangkan jumlah air yang diperlukan untuk pemprosesan hiliran.

[4 markah]

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Appendix

Common Engineering Conversion Factors

Length	Volume
1 ft = 12 in = 0.3048 m, 1 yard = 3 ft 1 mi = 5280 ft = 1609.344 m 1 nautical mile (nmi) = 6076 ft	1 ft^3 = 0.028317 m^3 = 7.481 gal , 1 bbl = 42 U.S. gal 1 U.S. gal = 231 in^3 = 3.7853 L = 4qt = 0.833 lmp.gal. 1 L = 0.001 m^3 = 0.035315 ft^3 = 0.2642 U.S. gal
Mass	**Density**
1 slug = 32.174 lb_m = 14.594 kg 1 lb_m = 0.4536 kg = 7000 grains	1 slug/ft^3 = 515.38 kg/m^3 , 1 g/cm^3 = 1000 kg/m^3 1 lb_m/ft^3 = 16.0185 kg/m^3 , 1 lb_m/in^3 = 27.68 g/cm^3
Acceleration & Area	**Velocity**
1 ft/s^2 = 0.3048 m/s^2 1 ft^2 = 0.092903 m^2	1 ft/s = 0.3048 m/s , 1 knot = 1 min/h = 1.6878 ft/s 1 min/h = 1.4666666 ft/s (fps) = 0.44704 m/s
Mass Flow & Mass Flux	**Volume Flow**
1 slug/s = 14.594 kg/s. 1 lb_m/s = 0.4536 kg/s 1 kg/m^2s = 0.2046 lb_m/ft^2s = 0.00636 slug/ft^2s	1 gal/min = 0.00228 ft^3/s = 0.06309 L/s 1 million gal/day = 1.5472 ft^3/s = 0.04381 m^3/s
Pressure	**Force and Surface Tension**
1 lb_f/ft^3 = 47.88 Pa, 1 torr = 1 mm Hg 1 psi = 144 psf, 1 bar = 10^5 Pa 1 atm = 2116.2 psf = 14.696 psia = 101,325 Pa = 29.9 in Hg = 33.9 ft H_2O 1 psia = 6.89476 x 10^4 g/(cm.s^2) = 6.89476 x 10^3 Pa	1 lb_f = 4.448222 N = 16 oz, 1 dyne = 1 g cm/s^2 = 10^{-5}N 1 kg_f = 2.2046 lb_f = 9.80665 N 1 U.S. (short) ton = 2000 lb_f , 1 N = 0.2248 lb_f 1 N/m = 0.0685 lb_f/ft
Power	**Energy and Specific Energy**
1 hp = 550 (ft.lb_f)/s = 745.7 W 1 (ft.lb_f)/s = 1.3558 W 1 Watt = 3.4123 Btu/h = 0.00134 hp	1 ft lb_f = 1.35582 J, 1 hp·h = 2544.5 Btu 1 Btu = 252 cal = 1055.056 J = 778.17 ft lb_f 1 cal = 4.1855 J, 1 ft.lb_f/lb_m = 2.9890 J/kg
Specific Weight	**Heat Flux**
1 lb_f/ft^3 = 157.09 N/m^3	1 W/m^2 = 0.3171 Btu/(h ft^2)
Viscosity	**Kinematic Viscosity**
1 slug/(ft.s) = 47.88 kg/(m.s) = 478.8 poise (p) 1 p = 1 g/(cm.s) 0.1 kg/(m.s) = 0.002088 slug/(ft s)	1 ft^2/h = 2.506 .10^{-5} m^2/s, 1 ft^2/s = 0.092903 m^2/s 1 stoke (st) = 1 cm^2/s = 0.0001 m^2/s = 0.001076 ft^2/s
Temperature Scale Readings	
°F = (9/5)°C + 32 °C = (5/9) (°F – 32) °R = °F + 459.69 °K = °C + 273.16	
Thermal Conductivity*	**Gas Constant***
1 cal/(s.cm.°C) = 242 Btu/(h.ft.°R) 1 Btu/(h.ft.°R) = 1.7307 W/(m.K)	R = 82.057 atm.cm^3/(gmol.K) = 62.361 mm Hg.L/(gmol.K) = 1.134 atm.ft^3/(lbmol.K) = 0.083144 bar.L/(gmol.K) = 10.73 psi. ft^3/(lbmol. °R) = 555.0 mm Hg.ft^3/(lbmol. °R)

- Note that the intervals in absolute (Kelvin) and °C are equal. Also, 1 °R = 1 °F.

Latent heat: 1 J/kg = 4.2995 × 10^{-4} Btu/lb_m = 10.76 lb_f.ft/slug = 0.3345 lb_f.ft/lb_m , 1 Btu/lb_m = 2325.9 J/kg

Heat transfer coefficient: 1 Btu/(h.ft^2.°F) = 5.6782 W/(m^2.°C).

Heat generation rate: 1 W/m^3 = 0.09665 Btu/(h ft^3)

Heat transfer per unit length: 1 W/m = 1.0403 Btu/(h ft)

Mass transfer coefficient: 1 m/s = 11.811 ft/h, 1 lb_{mol}/(h.ft^2) = 0.013562 kgmol/(s.m^2)

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Formulae

$$\frac{At}{V} = \frac{\mu\alpha\rho_0}{2\Delta P}\left(\frac{V}{A}\right) + \frac{\mu R_M}{\Delta P} \qquad R_C = \alpha\rho_0\left(\frac{V}{A}\right) \qquad \alpha = \alpha'(\Delta P)^s$$

$$\upsilon_g = \frac{\rho_p - \rho_f}{18\mu} D_p{}^2 g \qquad \upsilon_c = \frac{\rho_p - \rho_f}{18\mu} D_p{}^2 \omega^2 r$$

$$G = \frac{r\omega^2}{g} = \frac{r(2\pi n)^2}{g} \qquad Q = \upsilon_g\left[\frac{2\pi l R^2 \omega^2}{g}\right]$$

$$Q = \upsilon_g\left[\frac{2\pi n\omega^2}{3g}\left(R_0^3 - R_1^3\right)\cot\theta\right] \qquad Q = \upsilon_g\left[\frac{\pi l(R_0^2 - R_1^2)\omega^2}{g\ln(R_0/R_1)}\right]$$

$$\theta = 1 - \left(\frac{t_E - t_B}{2t_B}\right) \qquad q = Ky \qquad q = Ky^n \qquad q = \frac{q_0 y}{K + y}$$

$$\int_{x_0}^{x_1} f(x)dx = \frac{h}{2}\left(f(x_0) + f(x_1)\right)$$

where: $h = x_1 - x_0$

$$\int_{x_0}^{x_4} f(x)dx = \frac{h}{3}\left(f_0 + 4f_1 + 2f_2 + 4f_3 + f_4\right)$$

where: $h = \frac{x_4 - x_0}{4}$

$$t^* = \frac{L\rho_b q_{i,sat}}{\upsilon c_{io}} \qquad \frac{\text{LUB}}{\text{L}} = \left(1 - \frac{t_B}{t^*}\right) \qquad \int_0^t \left(1 - \frac{c_i}{c_{io}}\right)dt$$

$$R = \frac{t_{R2} - t_{R1}}{2(\sigma_1 + \sigma_2)} \qquad R = \frac{t_{R2} - t_{R1}}{0.5(w_1 + w_2)} \qquad [yield] = \frac{1}{2}\left\{1 + erf\left[\frac{t/t_o - 1}{\sqrt{2}\sigma'}\right]\right\}$$

$$J_v = k_{mt} \ln\frac{C_{gel}}{C_{Bulk}}$$

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Dimensionless number

Name	Description	Definition
Sherwood	$\frac{\text{Total mass transfer}}{\text{Diffusive mass transfer}}$	$\mathrm{Sh} = \frac{k_{mf} d_h}{D}$
Reynolds	$\frac{\text{Inertial forces}}{\text{Viscous forces}}$	$\mathrm{Re} = \frac{d_h \upsilon \rho}{\mu}$
Schmidt	$\frac{\text{Momentum transfer}}{\text{Mass transfer}}$	$\mathrm{Sc} = \frac{\mu}{\rho D}$
Peclet	$\frac{\text{Convective mass transfer}}{\text{Diffusive mass transfer}}$	$\mathrm{Pe} = \frac{d_h}{D}$
Grashof	$\frac{\text{Gravitational forces}}{\text{Viscous forces}}$	$\mathrm{Gr} = \frac{L^3 \rho^2 B' g \Delta t}{\mu^2}$
Froude	$\frac{\text{Inertial forces}}{\text{Gravitational forces}}$	$\mathrm{Fr} = \frac{\upsilon^2}{gL}$

Error function

x	Hundredths digit of x									
	0	1	2	3	4	5	6	7	8	9
0.0	0.00000	0.01128	0.02256	0.03384	0.04511	0.05637	0.06762	0.07886	0.09008	0.10128
0.1	0.11246	0.12362	0.13476	0.14587	0.15695	0.16800	0.17901	0.18999	0.20094	0.21184
0.2	0.22270	0.23352	0.24430	0.25502	0.26570	0.27633	0.28690	0.29742	0.30788	0.31828
0.3	0.32863	0.33891	0.34913	0.35928	0.36936	0.37938	0.38933	0.39921	0.40901	0.41874
0.4	0.42839	0.43797	0.44747	0.45689	0.46623	0.47548	0.48466	0.49375	0.50275	0.51167
0.5	0.52050	0.52924	0.53790	0.54646	0.55494	0.56332	0.57162	0.57982	0.58792	0.59594
0.6	0.60386	0.61168	0.61941	0.62705	0.63459	0.64203	0.64938	0.65663	0.66378	0.67084
0.7	0.67780	0.68467	0.69143	0.69810	0.70468	0.71116	0.71754	0.72382	0.73001	0.73610
0.8	0.74210	0.74800	0.75381	0.75952	0.76514	0.77067	0.77610	0.78144	0.78669	0.79184
0.9	0.79691	0.80188	0.80677	0.81156	0.81627	0.82089	0.82542	0.82987	0.83423	0.83851
1.0	0.84270	0.84681	0.85084	0.85478	0.85865	0.86244	0.86614	0.86977	0.87333	0.87680
1.1	0.88021	0.88353	0.88679	0.88997	0.89308	0.89612	0.89910	0.90200	0.90484	0.90761
1.2	0.91031	0.91296	0.91553	0.91805	0.92051	0.92290	0.92524	0.92751	0.92973	0.93190
1.3	0.93401	0.93606	0.93807	0.94002	0.94191	0.94376	0.94556	0.94731	0.94902	0.95067
1.4	0.95229	0.95385	0.95538	0.95686	0.95830	0.95970	0.96105	0.96237	0.96365	0.96490
1.5	0.96611	0.96728	0.96841	0.96952	0.97059	0.97162	0.97263	0.97360	0.97455	0.97546
1.6	0.97635	0.97721	0.97804	0.97884	0.97962	0.98038	0.98110	0.98181	0.98249	0.98315
1.7	0.98379	0.98441	0.98500	0.98558	0.98613	0.98667	0.98719	0.98769	0.98817	0.98864
1.8	0.98909	0.98952	0.98994	0.99035	0.99074	0.99111	0.99147	0.99182	0.99216	0.99248
1.9	0.99279	0.99309	0.99338	0.99366	0.99392	0.99418	0.99443	0.99466	0.99489	0.99511
2.0	0.99532	0.99552	0.99572	0.99591	0.99609	0.99626	0.99642	0.99658	0.99673	0.99688
2.1	0.99702	0.99715	0.99728	0.99741	0.99753	0.99764	0.99775	0.99785	0.99795	0.99805
2.2	0.99814	0.99822	0.99831	0.99839	0.99846	0.99854	0.99861	0.99867	0.99874	0.99880
2.3	0.99886	0.99891	0.99897	0.99902	0.99906	0.99911	0.99915	0.99920	0.99924	0.99928
2.4	0.99931	0.99935	0.99938	0.99941	0.99944	0.99947	0.99950	0.99952	0.99955	0.99957
2.5	0.99959	0.99961	0.99963	0.99965	0.99967	0.99969	0.99971	0.99972	0.99974	0.99975
2.6	0.99976	0.99978	0.99979	0.99980	0.99981	0.99982	0.99983	0.99984	0.99985	0.99986
2.7	0.99987	0.99987	0.99988	0.99989	0.99989	0.99990	0.99991	0.99991	0.99992	0.99992
2.8	0.99992	0.99993	0.99993	0.99994	0.99994	0.99994	0.99995	0.99995	0.99995	0.99996
2.9	0.99996	0.99996	0.99996	0.99997	0.99997	0.99997	0.99997	0.99997	0.99997	0.99998
3.0	0.99998	0.99998	0.99998	0.99998	0.99998	0.99998	0.99998	0.99999	0.99999	0.99999
3.1	0.99999	0.99999	0.99999	0.99999	0.99999	0.99999	0.99999	0.99999	0.99999	0.99999
3.2	0.99999	0.99999	0.99999	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000

...4/-

Controlling step in kinetic analysis of chromatography

Controlling step	The quantity σ'^2 is Proportional to
Internal diffusion and reaction	$\frac{d^2 \upsilon}{l}$
External mass transfer	$\frac{\upsilon^{1/2} d^{3/2}}{l}$
External(Taylor) dispersion	$\frac{d^2 \upsilon}{Dl}$
Axial diffusion	$\frac{D}{l\upsilon}$
Column of actual equilibrium stages	$\frac{1}{l}$