

Solutions Manual for
Separation Process Engineering
Includes Mass Transfer Analysis
Third Edition

Phillip C. Wankat



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SOLUTIONS MANUAL

for

SEPARATION PROCESS ENGINEERING

Third Edition

(Formerly published as *Equilibrium-Staged Separations*)

by

Phillip C. Wankat

Introduction to Solutions Manual

The material in this Solutions Manual represents my best efforts at solving all the problems in *Separation Process Engineering, Third Edition*. Note that the answers for graphical solutions can vary depending upon the accuracy of the draftsman; however, the methods shown here should be correct. Although every effort has been made to ensure that solutions are correct, there will be errors. Please inform the author of errors (wankat@purdue.edu).

The assistance of Mrs. Karen Heide in preparing this Solutions Manual is gratefully acknowledged.

This Solutions Manual is provided as a service to professors who adopt the book *Separation Process Engineering, Third Edition*, in their courses. It is copyrighted and is not to be distributed or sold. No parts of this manual should be placed on the Internet without explicit written consent from the author. Learning requires practice and feedback, not mere copying. Unfortunately, there are students and other people who do not realize that students do not learn if they copy solutions from a solutions manual. Some of these people are willing to put illegal copies of solution manuals on the Internet either for profit or for free. These illegal copies reduce student learning and make it more difficult for professors to teach courses. To aid everyone involved in teaching and learning separation processes, please help protect the integrity of the Solutions Manual.

—Phillip C. Wankat

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SAMPLE COURSE SYLLABUS

CHE 306 DESIGN SEPARATION PROCESSES

COURSE SYLLABUS

INSTRUCTOR: Professor Phillip C. Wankat
E-mail: wankat@purdue.edu (I usually answer quickly between 8 am and 5:30 pm. Use e-mail to communicate with Prof. Wankat for help.)
Office Hours: MWF 10:30-11:50 A.M. These times are reserved for 306 students.
On Wednesdays I will be in the computer lab from 1:30 to 3:20 P.M.
Other times by appointment *only*. (You are unlikely to find me if you drop in at a time other than office hours without an appointment.)

TA's – Office hours will be M 2:30 to 3:30, T 1:00 to 3:00 and W 1:00 to 2:30 (starting second week of semester).

Prerequisites: Must have passed Mass & Energy Balances and Thermodynamics

TEXTBOOK: P.C. Wankat, *Separation Process Engineering, Third Edition* (formerly published as of *Equilibrium Staged Separation Processes*), Prentice Hall, 2011.

Goals: By the end of CHE 306 you should be able to:

1. Design flash distillation by hand and computer calculations;
2. Design distillation systems by hand and computer calculations;
3. Design absorbers and strippers by hand and computer calculations;
4. Design extraction systems by hand and computer calculations;
5. Design membrane separation systems.

Importance: Separations constitute 50 to 90% of the cost (capital and operating) of chemical plants. Distillation is the most important separation method in the chemical and petroleum industries. Separations are one of the key items which delineate chemical engineering from the other engineering disciplines.

Course Structure:	The basic course outline is:	
	1. Introductory Material	(1 week)
	2. Flash Distillation	(1 week)
	3. Binary Distillation	(2 weeks)
	4. Multicomponent Distillation	(2 weeks)
	5. Complex Distillation	(2 weeks)
	6. Batch Distillation	(1 week)
	7. Distillation Design	(1 week)
	8. Absorption, Stripping, & Extraction	(2 weeks)
	9. Extraction	(1 week)
	10. Membrane separations	(2 weeks)

The detailed course outline is attached.

The *typical* weekly schedule will be:

Monday, Wednesday and Friday: 2 Lectures plus optional help.
Wednesday/Thursday: Computer Lab when scheduled
Since the schedule will sometimes deviate from this pattern, follow your detailed course outline.

Suggested Study Procedure: Read book before class. Come to class prepared. There will be short quizzes to encourage preparation. New material will be presented in class as needed. Material in the book that is a review or is easy to understand will not be lectured on. Ask questions if the book is not clear. After class, reread the book. Make extensive notes on or in the book. Before each exam summarize your notes on one page, and then reduce to 3x5 card (double-sided) you can take into the exam.
The suggested way to do homework: First, work on all problems by yourself. Then, meet with your study group to check answers and to complete solution of more difficult problems. Ask for help once these other efforts have failed. Finally, prepare your own solution to hand in if the homework will be graded. It is important to solve a lot of problems including homework that is not handed in.
You should spend 9 to 12 hours (including class & lab time) on this course every week. If you are spending less, work more problems both individually and in your study group.

Quizzes: To encourage students to prepare for and attend class, there will be a series of 10 short quizzes, which are 9% of the course grade. The lowest grade will not count, which is equivalent to one free absence. After that an absence will be a zero. Students who turn in a quiz with their name on it and who stay the entire period and pay attention will automatically earn 50%. There will be *no* quiz make-ups and no taking quizzes late (*Part of the 50% for attendance is being on time—if you want this credit make attendance a high priority. In other words, an interview at Purdue is NOT a valid excuse for missing a quiz.*) Missing 2 quizzes for plant trips will cost 1% of the course grade—a small penalty. Writing another student's name on a quiz and turning it in for a grade will be treated as a form of cheating. Graded quizzes will be passed out in labs or will be available from the TA.

Homework: There will be 8 homework assignments which are handed in. Students who solve all of the problems are very likely to see their efforts rewarded by higher test scores. The homework that is handed in will be 6% of the course grade. The professor and TAs will grade one problem selected by the professor and one problem selected by the student—*write the problem you want graded on the top of the assignment*. Graded homework assignments will be passed out in labs or will be available from the TA. Work in groups on homework is encouraged. Turn in your *own* solution (*not* Xerox copy), but please list names of group members on it.

Exams: Arrange your schedule to be available for the night exams on Sept. 30 and Nov. 4. The third exam, which is **not** a cumulative final exam, will be

during finals. Exams (including the lab test) are 70% of the course grade. Your lowest exam will be 10% and the other three exams will count as 20% each. Exams (except the lab test) are closed book, but students will be allowed and encouraged to have one 3 x 5 card (double-sided) with information on it. All electronic devices (other than a calculator) must be turned off and be buried in your back pack. Use of these devices will be considered to be cheating. Graded exams will be passed out in labs or will be available from the TA.

DO NOT MAKE TRAVEL PLANS UNTIL YOU KNOW THE FINALS SCHEDULE

Make-Up Exam: Students are strongly urged to make attendance at exams a very high personal priority and make appropriate arrangements to be present at all exams. If an exam is missed students may choose to make it their lowest exam grade and receive a zero for 10% of their course grade. Alternatively, a single *comprehensive* make-up exam (available only for students who miss a test) will be administered during finals period (after Exam 3). *This will be the only make-up exam available.* In cases of extreme duress (e.g., hospitalization) talk to Prof. Wankat for other arrangements.

Computer Lab: Computer labs are scheduled for Wednesdays and Thursdays. If you want to switch lab sections see the lab coordinator during the first week of classes to see if this is possible. Work in lab will initially be done individually and later in the semester in assigned 3- or 4-person groups. Feel free to help other students and to ask for help during lab. Laboratory will use the ASPEN Plus simulation package. Most of the lab assignments are in your textbook; thus, you will need to bring your textbook to lab.

The laboratory (not including the lab test) will be 15% of the course grade. Attendance & attention in computer lab is required, and will be 6% of the course grade. There will be a limited opportunity to do lab in advance or make-up a missed laboratory, but without help from the TA (arrange with your TA to show you have done the lab work). Because seating is limited, students *must* attend their scheduled laboratory period unless arrangements are made in advance to attend a lab session that has open seats. Group lab reports are required for two labs. Lab groups are expected to help each other for the two labs that require lab reports. Only questions from the entire group will be answered by the TA or professor for laboratory help. Lab reports will be limited to two pages of text plus one page of figures and tables. The two lab reports and the mastery lab quiz each count 3.0% of the course grade.

There will be a **lab test** worth 20% of course on November 12th and 13th during your regularly scheduled lab hours. Work will be done individually. The lab test will be open book and open notes. The use of e-

mail, the Internet, or old computer files will not be allowed during the lab test. **Plan on being present.**

Summary of Grading:	Quizzes	9%	(1/2 attendance & attention)
	Graded Homework	6%	
	Exam 1 to 3 plus lab test	70%	(lowest grade is 10% others are 20% each).
	Lab Grade (attendance, lab reports & lab quiz)	15%	(6% attendance)
	Extra Credit	0%	

Grading Scale: The class will vote if they want to use the traditional A, B, C, D scale or switch to the +/- scale. *The entire class must be graded on the same scale.*

Guaranteed Grade Scale for A, B, C, D scale:

90-100	A
80-90	B
70-80	C
60-70	D

Guaranteed Grade Scale for +/- scale:

Grade	GPA Value	Recommended Range
A+,A	4.0	93-100
A-	3.7	90.0 - 92.9
B+	3.3	87.0 - 89.9
B	3.0	83.0 - 86.9
B-	2.7	80.0 - 82.9
C+	2.3	77.0 - 79.9
C	2.0	73.0 – 76.9
C-	1.7	70.0 – 72.9
D+	1.3	67.0 – 69.9
D	1.0	63.0 – 66.9
D-	0.7 – becomes lowest passing grade	60.0 – 62.9
F	0.0	< 60.0

For both scales slightly lower cut off scores may be used at the discretion of the instructor.

Lectures: According to University regulations, it is the responsibility of students to attend all class sessions and to make up any material that is missed. To aid

students, one of the TAs will take notes of every lecture. These notes will be placed in reserve in the Potter Library.

Note: There is abundant evidence that students who regularly attend lectures tend to earn higher grades.

Optional Help

The Professor or a TA will hold a help session during the regularly scheduled class (9:30 to 10:20 a.m.) one day most weeks on Monday, Wednesday or Friday (see detailed course outline). The Wednesday class on the day of the two night exams will be an optional help session. Additional help sessions can be arranged before tests if students request them. In addition the professor and the TAs will have office hours that you are strongly encouraged to use. Since office hours are traditionally not heavily used early in the semester, this is a good time to get into the habit of attending office hours. Also, feel free to discuss questions with your laboratory instructor during laboratory.

Feedback to Prof. Wankat

With a very large class it is essentially impossible for a professor to know each student and to be aware of the difficulties they are having in learning the course material. To provide feedback to Prof. Wankat a group of student representatives will be constituted with one representative from each laboratory section. This group will meet with Prof. Wankat once per week to provide anonymous feedback from all the students in the course.

Professional Behavior:

Students in CHE 306 are continuing on a program of study to become chemical engineers. Engineers are expected to uphold the code of ethics, which includes “Being Honest,” “Engineers shall build their professional reputations on the merits of their services,” and “Engineers shall act in such a manner as to uphold and enhance the honor, integrity, and dignity of the engineering profession.” Students in CHE 306 will be expected to behave in an ethical and professional manner.

- This includes:
1. Honesty on quizzes, exams, and lab test. Cell phones, pagers, personal computers, MP3 players, personal digital assistants (e.g., Palm Pilots), & similar electronic devices must be *off* and *not in sight*—no phone calls, text messaging or use of storage available in the electronic device. Alphanumerical data or programs are not allowed in calculators. The use of head phones is not allowed. Note: Since you will be allowed the use of a 3x5 card, there is no reason to try and beat the system.
 2. No plagiarism or copying.
 3. Claim credit for homework/laboratory only if you were involved in the solution. [Do NOT turn in a copy that you do not understand.] This is common sense—not cheating. Students who copy homework (strictly speaking this is legal, but stupid) will do poorly on

exams and receive low grades because of this.

4. No disruption of class. Because cell phones are disruptive, please turn cell phones off before lectures or lab. In addition, since many students report that when students talk to neighbors during lecture it is disruptive, please do not do it.
5. Make a concerted, diligent effort to learn.

EXAMPLE Schedule A: Equilibrium Staged Plus Membranes with Computer Labs

Skip Chapter 11, 15, 16 and 18

Note: Classes are loaded towards beginning of the semester.

ChE 306, Fall 2009

				Reading
1	8/24	M	Introduction & Overview Separations	Chapt. 1
2	8/26	W	Phase equil./Flash Dist./Aspen Plus	Chapt. 2
3	26&27	W/Th	Lab 1 Intro Aspen Plus/Flash Dist. Appendix C2 <i>Bring textbook to all labs except lab test.</i>	
4	8/28	F	Quiz 1 (Phase Equilibrium/Flash). Lecture: Flash Dist.	Chapt. 2
5	8/31	M	Binary & MultiComponent Flash distillation	Chapt. 2
6	9/05	W	Quiz 2 (Binary Flash, Closed book, can have 3x5 card). Start distillation.	Chapt. 3
7	2&3	W/Th	Lab 2 (FRNY 1022) Flash Dist. Appendix	Chapt 2, Lab 2
8	9/4	F	Distillation McCabe-Thiele	Chapt. 4
	9/7	M	Labor Day – No class and no office hours	
9	9/9	W	HW 1 due. Lecture: McCabe-Thiele	Chapt. 4
10	9&10	W/Th	Lab 3. Distillation. Appendix	Chapter 4, Lab 3.
11	9/11	F	Quiz 3 (McCabe-Thiele – open book). McCabe-Thiele	C4
12	9/14	M	McCabe-Thiele	Chapt. 4
13	9/16	W	McCabe-Thiele & column design	Chapt. 10
14	16&17	W/Th	Lab 4. Distillation design. App. C6, do lab 4, and, if time, start lab 5.	
15	9/18	F	HW 2 due. Quiz 4 (McCabe-Thiele, 3x5 card) M.C. distillation profiles/calculations	Chapt. 5
	9/21	M	Optional Help	
16	9/23	W	M.C. Distillation – Short-cut	Chapt. 7
17	23&24	W/Th	Mastery lab quiz – counts same as lab report. Finish lab 5 App C6.	
18	9/25	F	Quiz 5 (M.C. Distillation, 3x5 card). M.C. Distillation – Matrix Solutions	Chapt. 6
19	9/28	M	HW 3 due. Finish M.C. Dist. Review homework	Chapt. 6
	9/30	W	Optional Class – Help Session	
20	9/30	W	Night Exam, Lilly 1105 , Scheduled for 6:30 to 7:30. (a 3x5 card with information is allowed; otherwise, closed book and closed notes)	
	9/30 & 10/01	W/Th	No Lab	
21	10/02	F	Review Exam. Start complex distillation	Chapt. 8
22	10/05	M	Complex distillation	Chapt. 8
23	10/07	W	Quiz 6 (Complex distillation, open book) Complex distillation	Chapt. 8
24	7&8	W/Th	Lab 6 Complex distillation, App. C8, lab 7 or lab 8 NOTE: Some years I do lab 6 in App. C8 or assign as a group HW.	
	10/9	F	No class & no office hours	
	10/12	M	October Break – No class and no office hours	
	10/14	W	Optional Help on HW 4 (Run by TAs)	
25	Oct 14/15	W/Th	Lab 7 Extractive distillation, in lab groups (Report Due 10/22 or 10/23 in lab) App. C8, lab 9, pp. 273-275 NOTE: In 2009 lab 10, App. C10 did not yet exist. I would add this lab.	
26	10/16	F	HW 4 due. Absorption & stripping	Chapt. 12

27	10/19	M	Absorption & Stripping	Chapt. 12
28	10/21	W	Quiz 7. Absorp. & Stripping, Start Extraction	Chapts. 12 & 13
29	21&22	W/Th	Lab 8 Absorption & Stripping (Report Due 10/29 or 10/30 in lab) App. C12, lab 11, pp. 421-423	
30	10/23	F	HW 5 due. Start extraction	Chapt. 13
	10/26	M	Optional help	
31	10/28	W	Extraction	Chapt. 13
32	28&29	W/Th	Lab 9 Extraction, App. C14, lab 12, pp. 499-500	
33	10/30	F	Quiz 8 (Extraction, 3x5 card). Extension McCabe-Thiele	Chapt. 14
34	11/02	M	HW 6 due. Review HW. Finish McCabe-Thiele	Chapt. 14
	11/04	W	Optional Help	
35	11/04	W	Night Exam 2, Lilly 1105 , Scheduled for 6:30 to 7:30. (a 3x5 card with information is allowed; otherwise, closed book and closed notes)	
	11/04 & 11/05	W/Th	No Lab	
36	11/06	F	Review exam.	
	11/09	M	No class – AIChE National	
	11/11	W	No class – AIChE National	
NOTE: Purdue's semester has 44 class periods plus the exam in Finals. The no class and optional help periods are included to comply with university regulations.				
	11/12	W/Th	No lab	
37	11/13	F	Optional help with TAs	
38	11/16	M	Batch distillation	Chapt 9
39	11/18	W	Batch distillation	Chapt. 9
40*	Nov 18&19	W/Th	Lab Exam* (FRNY 1022)	
	11/20	F	Batch Distillation Quiz 9 (batch dist, open book)	Chapt.9
	11/23	M	No class Thanksgiving Vacation	
41	11/30	M	HW 7 due. Start Membrane Separations	Chapt. 17
42	12/02	W	Membrane separations. Quiz 10 (Membranes, open book).	Chapt. 17
	Dec 2&3	W/Th	No Lab	
43	12/04	F	Membrane separations.	Chapt. 17
	12/07	M	Optional help	
	12/9	W	Optional help	
	Dec 9&10	W/Th	No lab	
44	12/11	F	HW 8 due. Membranes– Solution to HW 8. Review for exam	
	Saturday 12/19	EE 129	EXAM 3. Not cumulative, covers batch distillation & membrane separations. A 3x5 card with information is allowed; otherwise, closed book/closed notes.	

MAKE TRAVEL PLANS AFTER THE FINALS SCHEDULE IS AVAILABLE!

FINALS TBA – Makeup Exam for exam 1, 2, or 3 (Cumulative)

* Do **NOT** schedule any conflicts with lab test on Nov 18 and 19.

Readings are in *Separation Process Engineering*.

In the event of a major campus emergency, course requirements, deadlines and grading percentages are subject to changes that may be necessitated by a revised semester calendar or other circumstances. Go to Blackboard to get information about changes in this course.

EXAMPLE Schedule B: Classical Equilibrium Staged Course with Computer Lab

Skip Chapters 15, 16, 17, 18

<u>Class</u>	<u>Subject</u>	<u>Reading:</u>
1	Introduction. Phase Equilibrium	Chapt. 1
2	Phase Equilibrium, Start Flash	Chapt. 2
3	Flash – Binary & Multicomponent	Chapt. 2
4	Flash – Binary & Multicomponent	Chapt. 2
5	Lab 1 Intro to Aspen Plus. Lab 1, App. C2	
6	Flash – MultiComponent and Aspen Plus	Chapt. 2
7	Binary Distillation	Chapt. 3
8	Lab 2 – Flash Distillation. Lab 2, App C2	
9	McCabe-Thiele	Chapt. 4
10	McCabe-Thiele	Chapt. 4
11	Lab 3– Binary Distillation. Lab 3, App C4	
12	McCabe-Thiele	
13	Profiles & Intro. M. C. Distillation	Chapt. 5
14	Lab 4 – M. C. Distillation. Lab 4, App C6	
15	EXAM #1.	
16	Review Test & M. C. Dist. Mass Balances	Chapt. 5
17	Lab 5 - M.C. Distillation. Lab 5, App C6	
18	M. C. Distillation	Chapt. 6
19	Short Cut Distillation	Chapt. 7
20	Lab 6 – Complex Distillation, Lab 7, App C8	
21	Complex Distillation	Chapt. 8
22	Complex Distillation	Chapt. 8
23	Lab 7 -Complex Distillation, Lab 8, App C8	
24	Complex Distillation	Chapt. 8
25	Complex Distillation	Chapt. 8
26	Lab 8. Extractive Distillation, Lab 9, App C8	
27	Staged Col. Design.	Chapt. 10
28	Packed Cols, Distl. Costs. Energy Conservation	Chapts. 10 & 11
29	Lab 9. Tray Rating, Lab 10, App C10	
30	Exam review	
31	EXAM #2	
32	Review Exam	
33	Absorption & Stripping	Chapt. 12
34	Absorption & Stripping	Chapt. 12
35	Lab 10 – Absorption/Stripping; Lab 11, App C12	
36	Immiscible Extraction	Chapt. 13
37	Miscible Extraction	Chapt. 13
38	Lab 11 – Extraction; Lab 12, App C13	
39	Miscible Extraction	Chapt. 13
40	Extension McCabe-Thiele	Chapt. 14
41	Lab Test	
42	Batch Distillation	Chapt. 9
43	Batch Distillation	Chapt. 9
44	Exam Review	
FINALS	EXAM #3	

EXAMPLE Schedule C: Vapor-Liquid Separations Course with Computer Lab

Skip Chapters 13, 14, part 16, 17, 18

<u>Class</u>	<u>Subject</u>	<u>Reading:</u>
1	Introduction. Phase Equilibrium	Chapt. 1
2	Phase Equilibrium, Start Flash	Chapt. 2
3	Flash – Binary & Multicomponent	Chapt. 2
4	Flash – Binary & Multicomponent	Chapt. 2
5	Lab 1 Intro to Aspen Plus. Lab 1, App. C2	
6	Flash – MultiComponent and Aspen Plus	Chapt. 2
7	Binary Distillation	Chapt. 3
8	Lab 2 – Flash Distillation. Lab 2, App C2	
9	McCabe-Thiele	Chapt. 4
10	McCabe-Thiele	Chapt. 4
11	Lab 3– Binary Distillation. Lab 3, App C4	
12	McCabe-Thiele	
13	Profiles & Intro. M. C. Distillation	Chapt. 5
14	Lab 4 – M. C. Distillation. Lab 4, App C6	
15	EXAM #1.	
16	Review Test & M. C. Dist. Mass Balances	Chapt. 5
17	Lab 5 - M.C. Distillation. Lab 5, App C6	
18	M. C. Distillation	Chapt. 6
19	Short Cut Distillation	Chapt. 7
20	Lab 6 – Complex Distillation, Lab 7, App C8	
21	Complex Distillation	Chapt. 8
22	Complex Distillation	Chapt. 8
23	Lab 7 -Complex Distillation, Lab 8, App C8	
24	Complex Distillation	Chapt. 8
25	Complex Distillation	Chapt. 8
26	Lab 8. Extractive Distillation, Lab 9, App C8	
27	Staged Col. Design.	Chapt. 10
28	Packed Cols, Distl. Costs. Energy Conservation	Chapts. 10 & 11
29	Lab 9. Tray Rating, Lab 10, App C10	
30	Exam review	
31	EXAM #2	
32	Review Exam	
33	Absorption & Stripping	Chapt. 12
34	Absorption & Stripping	Chapt. 12
35	Lab 10 – Absorption/Stripping; Lab 11, App C12	
36	Mass Transfer Review Fickian Diffusion & Mass Transfer Coef. C. 15	
37	Maxwell-Stefan Diffusion & Mass Transfer	Chapter 15
38	Lab 11 – Lab Test	
39	Maxwell-Stefan Diffusion & Mass Transfer	Chapter 15
40	Rate-Based Design of Distillation	Chapter 16
41	Lab 12 – Rate-Based Design of Distillation, Lab 13, App C16	
42	Batch Distillation	Chapt. 9
43	Batch Distillation	Chapt. 9
44	Exam Review	
FINALS	EXAM #3	