ChE 455
Fall 2001
Major 1

Ethylene Oxide Production

Ethylene oxide is a chemical used to make ethylene glycol (the primary ingredient in antifreeze). It is also used to make poly(ethylene oxide), and both the low molecular weight and high molecular weight polymers have many applications including as detergent additives. Because ethylene oxide is so reactive, it has many other uses as a reactant.

Your company has just purchased a struggling company that, among other things, manufactures ethylene oxide. You now provide technical support for several similar ethylene oxide plants in the pacific basin. These are among the first chemical plants constructed in that region; hence, they are aging.

Problems in One Ethylene Oxide Plant

In one of the ethylene oxide plants for which you now provide technical support, the output of ethylene oxide, though still at concentration specification, has periodically been below design capacity. Recently, the reduced production rate has been occurring more frequently. An engineer on site reports the following observations:

1. The ethylene oxide mass flowrate in Stream 32 is reduced by 4.2% from design conditions during process upsets (when the reduced production rate is observed).

2. An assay of Stream 26 shows that, during process upsets, the total mass flowrate is unchanged within measurement limits, the mass flowrate of ethylene oxide is increased by 3.3%, the mass flowrate of CO_2 is decreased by 10%, the mass flowrate of oxygen is increased by 0.3%, and the mass flowrate of nitrogen appears unchanged.

3. The mass flowrate of water in Stream 33 is reduced by 10% during process upsets.

4. An assay of Stream 34 shows that, during process upsets, the total mass flowrate is reduced by 11%, the mass flowrate of ethylene is decreased by 9%, the mass flowrate of CO_2 is decreased by about 20%, the mass flowrate of oxygen is decreased by 11%, and the mass flowrate of nitrogen is decreased by 11%.

5. Periodically, the pressure-relief valve on the shell for reactor R-702 has been opening to vent steam; however, this does not appear to correspond to the times at which the other process upsets are observed.

6. The reflux pump for T-703 has been whining periodically.

7. There has been some vibration observed in compressor C-702.

The first part of your assignment is to suggest causes for this periodic problem, identify the most likely cause, and suggest potential remedies for this problem. We need your answer quickly, since a scheduled plant shut down occurs next month when minor process modifications can be implemented.

Possible Need for Scale-up in Other Ethylene Oxide Plants

Management is concerned that the plant with production problems discussed above may need to be shut down for an extended period of time. Therefore, it is desired to determine by how much ethylene oxide production in the other identical plants can be scaled-up to make up for the possible loss of production in the plant with problems. The second part of your assignment is to determine the maximum scale-up possible for ethylene oxide production. You should identify the bottlenecks to scale-up and determine which can be debottlenecked quickly and inexpensively. Each plant is scheduled for its annual, two-week shut-down over the next several months. Therefore, you can propose modifications that can be made within that two-week period.

Other Process Improvements

We are also concerned with the long-term profitability of this process. Therefore, you should also suggest any process improvements that can improve the long-term profitability. If you suggest process changes (no new equipment), you must demonstrate both profitability and feasibility. If you suggest new equipment, you must demonstrate profitability, feasibility, and estimate the time it will take to accomplish installation and implementation.

Process Description

The process flow diagram is shown in Figure 1. Ethylene feed (via pipeline from a neighboring plant) is mixed with recycled ethylene and mixed with compressed and dried air (drying step not shown), heated, and then fed to the first reactor. The reaction is exothermic, and high-pressure steam is made in the reactor shell. Conversion in the reactor is kept low to enhance selectivity for the desired product. The reactor effluent is cooled, compressed, and sent to a scrubber where ethylene oxide is absorbed by water. The vapor from the scrubber is heated, throttled, and sent to a second reactor, followed by a second series of cooling, compression, and scrubbing. A fraction of the unreacted vapor stream is purged with the remainder recycled. The combined aqueous product streams are mixed, cooled, throttled, and distilled to produce the desired product. The required purity specification is 99.5 wt% ethylene oxide.

Tables 1 and 2 contain the stream and utility flows for the process as normally operated. Table 3 contains an equipment list. Other pertinent information and calculations are contained in the appendix.

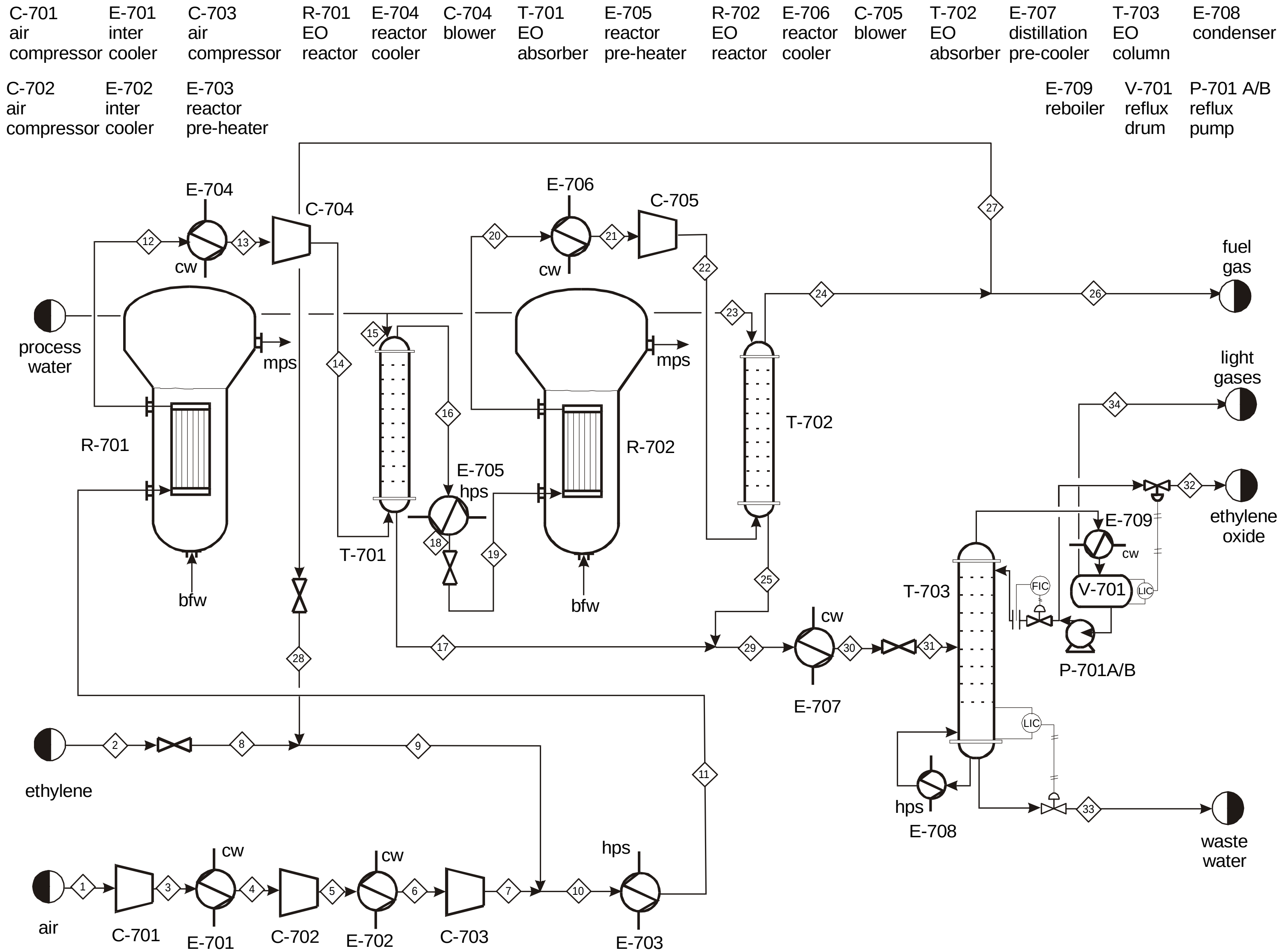


Figure 1: Process Flow Diagram for Ethylene Oxide Production

Table 1
Stream Tables for Unit 700

Stream	**1**	**2**	**3**	**4**
Temp (°C)	25.00	25.00	159.19	45.00
Pres (bar)	1.01325	50.00	3.00	2.70
Vapor mole fraction	1.00	1.00	1.00	1.00
Flowrate (kg/h)	500,000.00	20,000.00	500,000.00	500,000.00
Flowrate (kmol/h)	17,381.45	712.91	17,381.45	17,381.45
Component Flowrates (kmol/h)				
Ethylene		712.91		
Ethylene Oxide				
Carbon Dioxide				
Oxygen	3281.35		3281.35	3281.35
Nitrogen	14,100.09		14,100.09	14,100.09
Water				

Stream	**5**	**6**	**7**	**8**
Temp (°C)	206.11	45.00	195.21	-6.30
Pres (bar)	9.00	8.70	27.00	27.00
Vapor mole fraction	1.00	1.00	1.00	1.00
Flowrate (kg/h)	500,000.00	500,000.00	500,000.00	20,000.00
Flowrate (kmol/h)	17,381.45	17,381.45	17,381.45	712.91
Component Flowrates (kmol/h)				
Ethylene				712.91
Ethylene Oxide				
Carbon Dioxide				
Oxygen	3281.35	3281.35	3281.35	
Nitrogen	14,100.09	14,100.09	14,100.09	
Water				

Stream	**9**	**10**	**11**	**12**
Temp (°C)	26.34	106.74	240.00	240.00
Pres (bar)	27.00	26.80	26.50	25.75
Vapor mole fraction	1.00	1.00	1.00	1.00
Flowrate (kg/h)	524,042.00	1,023,980.01	1,023,980.01	1,023,979.79
Flowrate (kmol/h)	18,260.29	35,639.59	35,639.59	35,539.42
Component Flowrates (kmol/h)				
Ethylene	1047.95	1047.91	1047.91	838.67
Ethylene Oxide	6.48	6.47	6.47	206.79
Carbon Dioxide	31.71	31.71	31.71	49.56
Oxygen	3050.14	6331.12	6331.12	6204.19
Nitrogen	14,093.02	28,191.39	28,191.39	28,191.39
Water	30.99	30.98	30.98	48.82

Table 1 (cont'd)
Stream Tables for Unit 700

Stream	**13**	**14**	**15**	**16**
Temp (°C)	45.00	63.72	25.00	30.30
Pres (bar)	25.45	30.15	30.00	30.00
Vapor mole fraction	1.00	1.00	0.00	1.00
Flowrate (kg/h)	1,023,979.79	1,023,979.79	360,300.00	1,015,668.84
Flowrate (kmol/h)	35,539.42	35,539.42	20,000.00	35,357.65
Component Flowrates (kmol/h)				
Ethylene	838.67	838.67		837.96
Ethylene Oxide	206.79	206.79		15.45
Carbon Dioxide	49.56	49.56		49.56
Oxygen	6204.19	6204.19		6202.74
Nitrogen	28,191.39	28,191.39		28,188.72
Water	48.82	48.82	20,000.00	63.24

Stream	**17**	**18**	**19**	**20**
Temp (°C)	51.92	240.0000	239.9476	240.0000
Pres (bar)	30.00	29.7000	26.5000	25.7500
Vapor mole fraction	0.00	1.0000	1.0000	1.0000
Flowrate (kg/h)	368,611.02	1,015,668.84	1,015,668.84	1,015,668.84
Flowrate (kmol/h)	20,181.77	35,357.65	35357.66	35,277.47
Component Flowrates (kmol/h)				
Ethylene	0.70	837.96	837.96	670.64
Ethylene Oxide	191.34	15.45	15.45	175.83
Carbon Dioxide	0.01	49.55	49.55	63.44
Oxygen	1.45	6202.74	6202.74	6101.72
Nitrogen	2.68	28,188.72	28,188.72	28,188.72
Water	19,985.58	63.24	63.24	77.13

Stream	**21**	**22**	**23**	**24**
Temp C	45.00	63.78	25.00	30.0851
Pres bar	25.45	30.15	30.00	30.00
Vapor mole fraction	1.00	1.00	0.00	1.00
Total kg/h	1,015,668.84	1,015,668.84	360,300.00	1,008,083.53
Total kmol/h	35,277.47	35,277.47	20,000.00	35094.76
Flowrates in kmol/h				
Ethylene	670.64	670.64		670.08
Ethylene Oxide	175.83	175.83		12.96
Carbon Dioxide	63.44	63.44		63.43
Oxygen	6101.72	6101.72		6100.28
Nitrogen	28,188.72	28,188.72		28,186.04
Water	77.13	77.13	20,000.00	61.96

Table 1 (cont'd)
Stream Tables for Unit 700

Stream	**25**	**26**	**27**	**28**
Temp (°C)	52.26	30.09	30.09	29.48
Pres (bar)	30.00	30.00	30.00	27.00
Vapor mole fraction	0.00	1.00	1.00	1.00
Flowrate (kg/h)	367,885.27	504,042.00	504,042.00	504,042.00
Flowrate (kmol/h)	20,182.72	17,547.38	17,547.38	17,547.38
Component Flowrates (kmol/h)				
Ethylene	0.57	335.04	335.04	335.04
Ethylene Oxide	162.88	6.48	6.48	6.48
Carbon Dioxide	0.01	31.71	31.71	31.71
Oxygen	1.43	3050.14	3050.14	3050.14
Nitrogen	2.68	14,093.02	14,093.02	14,093.02
Water	20,015.15	30.99	30.99	30.99

Stream	**29**	**30**	**31**	**32**
Temp (°C)	52.08	45.00	45.02	86.40
Pres (bar)	30.00	29.70	10.00	10.00
Vapor mole fraction	0.00	0.00	0.00	0.00
Flowrate (kg/h)	73,6497.00	736,497.00	736,218.00	15,514.72
Flowrate (kmol/h)	40,364.48	40,364.48	40,354.95	352.39
Component Flowrates (kmol/h)				
Ethylene	1.27	1.27	1.27	
Ethylene Oxide	354.22	354.22	354.22	352.04
Carbon Dioxide	0.02	0.02	0.02	
Oxygen	2.89	2.89	2.89	
Nitrogen	5.35	5.35	5.35	
Water	40,000.74	40,000.74	40,000.74	0.35

Stream	**33**	**34**
Temp (°C)	182.30	182.30
Pres (bar)	10.50	10.50
Vapor mole fraction	0.00	1.00
Flowrate (kg/h)	720,703.00	278.78
Flowrate (kmol/h)	40,002.57	9.53
Component Flowrates (kmol/h)		
Ethylene		1.27
Ethylene Oxide	2.18	
Carbon Dioxide		0.02
Oxygen		2.88
Nitrogen		5.35
Water	40,000.39	

Table 2
Utility Stream Flow Summary for Unit 700

E-701 cw 1,397,870 kg/h	**E-702** cw 1,988,578 kg/h	**E-703** hps 87,162 kg/h
E-704 cw 5,009,727 kg/h	**E-705** hps 135,789 kg/h	**E-706** cw 4,950,860 kg/h
E-707 cw 513,697 kg/h	**E-708** hps 258,975 kg/h	**E-709** cw 29,609 kg/h
R-701 bfw→hps 13,673 kg/h	**R-702** bfw→hps 10,813 kg/h	

Table 3
Partial Equipment Summary

Heat Exchangers

E-701 A = 5553 m^2 1-2 exchanger, floating head, carbon steel process stream in tubes Q = 58,487 MJ/h	**E-706** A = 13,945 m^2 1-2 exchanger, floating head, carbon steel process stream in tubes Q = 207,144 MJ/h
E-702 A = 6255 m^2 1-2 exchanger, floating head, carbon steel process stream in tubes Q = 83,202 MJ/h	**E-707** A = 1478 m^2 1-2 exchanger, floating head, carbon steel process stream in tubes Q = 21,493 MJ/h
E-703 A = 12,062 m^2 1-2 exchanger, floating head, carbon steel process stream in tubes Q = 147,566 MJ/h	**E-708** A = 566 m^2 1-2 exchanger, floating head, stainless steel process stream condenses in shell Q = 43,844 MJ/h
E-704 A = 14,110 m^2 1-2 exchanger, floating head, carbon steel process stream in tubes Q = 209,607 MJ/h	**E-709** A = 154 m^2 1-2 exchanger, floating head, stainless steel process stream boils in shell Q = 14,212 MJ/h
E-705 A = 14,052 m^2 1-2 exchanger, floating head, carbon steel process stream in tubes Q = 229,890 MJ/h	

Towers

T-701 carbon steel 20 sieve trays 25% efficient trays feeds on tray 1 and 20 24 in tray spacing, 3 in weirs column height = 12.2 m diameter = 5.6 m	**T-703** stainless steel 70 sieve trays plus reboiler and condenser 33% efficient trays total condenser (E-709) feed on tray 36 reflux ratio = 0.89 12 in tray spacing, 3 in weirs column height = 43 m diameter = 8.0 m
T-702 carbon steel 20 sieve trays 25% efficient trays feeds on tray 1 and 20 24 in tray spacing, 3 in weirs column height = 12.2 m diameter = 5.6 m	

Table 3 (cont'd)
Partial Equipment Summary

Compressors

C-701 carbon steel *power* = 19 MW 80% adiabatic efficiency	**C-704** carbon steel *power* = 5.5 MW 80% adiabatic efficiency
C-702 carbon steel *power* = 23 MW 80% adiabatic efficiency	**C-705** carbon steel *power* = 5.5 MW 80% adiabatic efficiency
C-703 carbon steel *power* = 21.5 MW 80% adiabatic efficiency	

Reactors

R-701 carbon steel, shell-and-tube packed bed spherical catalyst pellet, 9 mm diameter void fraction = 0.4 V = 202 m^3 10 m tall, 7.38 cm diameter tubes 4722 tubes 100% filled with active catalyst Q = 33,101 MJ/h mps made in shell	**R-702** carbon steel, shell-and-tube packed bed spherical catalyst pellet, 9 mm diameter void fraction = 0.4 V = 202 m^3 10 m tall, 9.33 cm diameter tubes 2954 tubes 100% filled with active catalyst Q = 26,179 MJ/h mps made in shell

Other Equipment

P-701 A/B stainless steel *power* = 4 kW (actual) 73% efficient	**V-701** stainless steel V = 12.7 m^3

Economics

For process modifications, use a 15%, before-tax rate of return and a 5-year lifetime.

Deliverables

Specifically, you are to prepare the following by 9:00 am, Monday, November 12, 2001:

1. a diagnosis of potential causes for the operating problems with the plant, explanations of their relevance, and recommendations for solving the problems.

2. a recommendation as to how much scale-up is possible in each of the identical processes, modifications that will have to be made, and the cost of such modifications.

3. suggestions for process improvements, recommended modifications, the cost of such modifications, and the long-term profitability of the improvements.

3. a written report, conforming to the guidelines, detailing the information in items 1 and 2, above.

4. a legible, organized set of calculations justifying your recommendations, including any assumptions made.

5. a signed copy of the attached confidentiality statement.

Report Format

This report should be brief and should conform to the guidelines. It should be bound in a folder that is not oversized relative to the number of pages in the report. Figures and tables should be included as appropriate. An appendix should be attached that includes items such as the requested calculations. These calculations should be easy to follow. The confidentiality statement should be the very last page of the report.

The written report is a very important part of the assignment. Poorly written and/or organized written reports may require re-writing. Be sure to follow the format outlined in the guidelines for written reports. Failure to follow the prescribed format may be grounds for a re-write.

Oral Presentation

You will be expected to present and defend your results some time between November 12, 2001 and November 15, 2001. Your presentation should be 10-15 minutes, followed by about a 30 minute question and answer period. Make certain that you prepare for this presentation since it is an important part of your assignment. You should bring at least one hard copy of your slides to the presentation and hand it out before beginning the presentation.

Since you will be doing this assignment in pairs, the following rules will apply. When you arrive for your presentation one team member will be selected at random to present. The other team member will field questions. The team member presenting may not answer questions unless specifically requested by the audience.

The rules for evaluation of team members are explained in the course syllabus. Each team member must present his or her completed form to the instructor before the oral presentation begins.

Other Rules

You may discuss this major only with your partner. Discussion, collaboration, or any other interaction with anyone not in your group (including those in this class, not in this class, not at the University, etc.) is prohibited.

Consulting is available from the instructor. Chemcad consulting, i.e., questions on how to use Chemcad, not how to interpret results, is unlimited and free, but only from the instructor. Each group may receive two free minutes of consulting from the instructor. After two minutes of consulting, the rate is 2.5 points deducted for 15 minutes or any fraction of 15 minutes, on a cumulative basis. The initial 15-minute period includes the 2 minutes of free consulting. To receive consulting of any kind (including Chemcad questions), both team members must be present.

Late Reports

Late reports are unacceptable. The following severe penalties will apply:

- late report on due date before noon: one letter grade (10 points)
- late report after noon on due date: two letter grades (20 points)
- late report one day late: three letter grades (30 points)
- each additional day late: 10 additional points per day

Appendix 1

Because the PFD in Figure 1 is so crowded, some items that are present in the actual process have been deliberately omitted. These are:

1. the control system for the reactors. It is as illustrated in your text in Figure 13.1.

2. the direction of the process flow in the reactors. In Figure 1, it is shown as being upward to avoid too many line crosses. It is actually downward.

3. flow control systems for the feed section. There is a control system in the feed processing of each reactant to ensure that the proper mixture is fed to the reactor.

4. pumps for the boiler feed water feed to the reactors. The pumps take boiler feed water at 90°C and 550 kPa and raise the pressure to that required to make steam at 226°C. The steam is subsequently throttled before entering the mps header.

5. the pump for process water. The pump takes process water at 5 bar and 30°C and raises the pressure to the indicated feed pressure to the scrubbers.

If you want to do Chemcad simulations, the following thermodynamics packages are strongly recommended for simulation of this process:

K-values: global – PSRK; local for T-701, T-702 – Unifac
enthalpy: SRK

Appendix 2
Reaction Kinetics

The pertinent reactions are as follows:

$$C_2H_4 + 0.5\,O_2 \rightarrow C_2H_4O \tag{1}$$

$$C_2H_4 + 3\,O_2 \rightarrow 2CO_2 + 2H_2O \tag{2}$$

$$C_2H_4O + 2.5\,O_2 \rightarrow 2CO_2 + 2H_2O \tag{3}$$

The kinetic expressions are, respectively:

$$r_1 = \frac{1.96\exp(-2400/RT)\,p_{ethylene}}{1 + 0.00098\exp(11200/RT)\,p_{ethylene}} \tag{4}$$

$$r_2 = \frac{0.0936\exp(-6400/RT)\,p_{ethylene}}{1 + 0.00098\exp(11200/RT)\,p_{ethylene}} \tag{5}$$

$$r_3 = \frac{0.42768\exp(-6200/RT)\,p^2_{ethylene\ oxide}}{1 + 0.000033\exp(21200/RT)\,p^2_{ethylene\ oxide}} \tag{6}$$

The units for the reaction rates are moles/m^3 s. The pressure unit is bar. The activation energy numerator is in cal/mol.

other data:

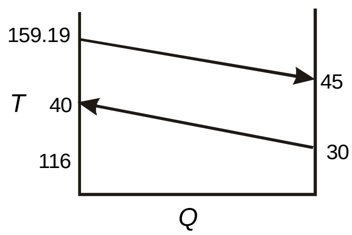
catalyst: silver on inert support, spherical catalyst support, 7.5 mm diameter
bulk catalyst density = 1250 kg/m^3
void fraction = 0.4

Appendix 3
Calculations and Other Pertinent Information

Heat Exchangers

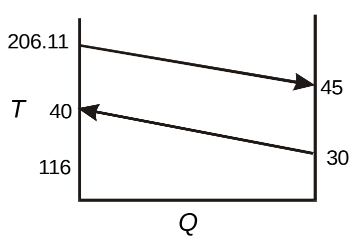
note: For all heat exchangers, the design velocity was set at 2.25 m/s for all non-phase change streams, both utility and process.

E-701



Q = 58487 MJ/h
ΔT_{lm} = 50.27°C
vapor h_i = 60 W/m^{2}K
assume vapor limiting resistance
$U \approx 1/h_i + 1/h_o$ = 60 W/m^{2}K
A = 5553 m^2
LMTD corr factor – 1-2 exchanger = 0.97
cw flow in Table 2

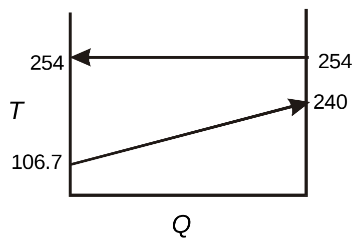
E-702



Q = 83202 MJ/h
ΔT_{lm} = 62.84°C
vapor h_i = 60 W/m^{2}K
assume vapor limiting resistance
$U \approx 1/h_i + 1/h_o$ = 60 W/m^{2}K
A = 6255 m^2

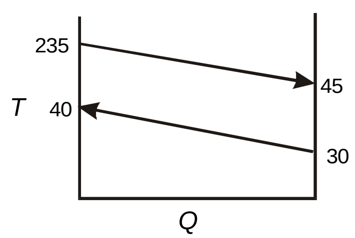
LMTD corr factor – 1-2 exchanger = 0.98
cw flow in Table 2

E-703



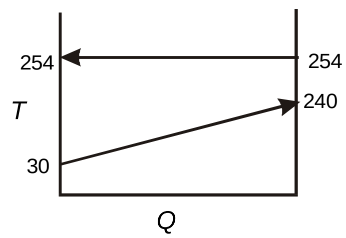
Q = 147566 MJ/h
ΔT_{lm} = 56.64°C
vapor organic h = 60 W/m^{2}K – limiting resistance compared to condensing steam
$U \approx$ 60 W/m^{2}K
A = 12,062 m^2
λ = 1693 kJ/kg
hps flow in Table 2

E-704



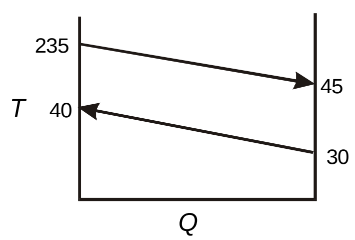
Q = 207609 MJ/h
ΔT_{lm} = 70.18°C
vapor organic h = 60 W/m^{2}K – limiting resistance
$U \approx$ 60 W/m^{2}K
$U \approx 1/h_i + 1/h_o$ = 60 W/m^{2}K
LMTD corr factor – 1-2 exchanger = 0.98
A = 14,110 m^2
cw flow in Table 2

E-705



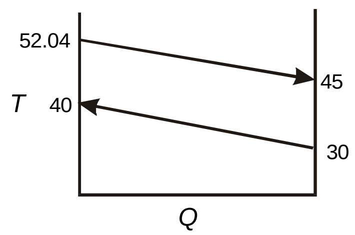
Q = 229890 MJ/h
ΔT_{lm} = 75.74°C
organic h = 60 W/m^{2}K
$U \approx$ 60 W/m^{2}K
A = 14,052 m^2
λ = 1693 kJ/kg
hps flow in Table 2

E-706



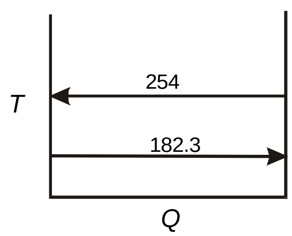
Q = 207144 MJ/h
ΔT_{lm} = 70.18°C
vapor organic h = 60 W/m^{2}K – limiting resistance
$U \approx$ 60 W/m^{2}K
LMTD corr factor – 1-2 exchanger = 0.98
A = 13,945 m^2
cw flow in Table 2

E-707



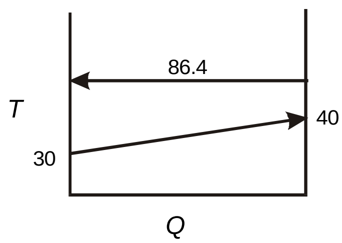
Q = 21493 MJ/h
ΔT_{lm} = 13.47°C
liquid aqueous h_i = 600 W/m^{2}K
water h_i = 600 W/m^{2}K
$U \approx 1/h_i + 1/h_o$ = 300 W/m^{2}K
LMTD corr factor – 1-2 exchanger = 1
A = 1478 m^2
cw flow in Table 2

E-708



Q = 438444 MJ/h
ΔT_{lm} = 71.7°C
boling organic h = 6000 W/m^{2}K
condensing steam h = 6000 W/m^{2}K
$U \approx$ 3000 W/m^{2}K
A = 566 m^2
hps flow in Table 2

E-709



Q = 14212 MJ/h
ΔT_{lm} = 51.23°C
water h = 600 W/m^{2}K
condensing liquid h = 3000 W/m^{2}K
$U \approx$ 500 W/m^{2}K
A = 154 m^2
λ = 48 kJ/kg
cw rate in Table 2

R-701

V = 202 m^3
Q = 33101 MJ/h
U = 60 W/m^{2}K – gas phase reaction side limiting
ΔT = 14 K
$A = Q/U\Delta T$ = 10946 m^2
use 7.38 cm diameter tubes, 10 m length
$A_{tube} = \pi(0.0738 \text{ m})(10 \text{ m}) = 2.32 \text{ m}^2$
N_A = 4722
$V_{tube} = (\pi/4)(0.0738)^2 \text{ m}^2 (10 \text{ m}) = 0.0428 \text{ m}^3$
N_V = 4722
% active catalyst 100%

R-702

V = 202 m^3
Q = 26179 MJ/h
U = 60 W/m^{2}K – gas phase reaction side limiting
ΔT = 14 K
$A = Q/U\Delta T$ = 8657 m^2
use 9.33 cm diameter tubes, 10 m length
$A_{tube} = \pi(0.0933 \text{ m})(10 \text{ m}) = 2.93 \text{ m}^2$
N_A = 2954
$V_{tube} = (\pi/4)(0.0933)^2 \text{ m}^2 (10 \text{ m}) = 0.06836 \text{ m}^3$
N_V = 2954

% active catalyst = 100%

T-501

from Chemcad, 5 ideal stages, feeds at 1 and 5
average flows:
L = 368468 kg/h, V = 1025889 kg/h
ρ_L = 982 kg/m^3
ρ_G = 31.9 kg/m^3
$(L/V)(\rho_G/\rho_L)^{0.5} = 0.064$
from flooding graph for 24 in tray spacing (P. Wankat, *Equilibrium Staged Separations*, Prentice Hall, 1988, p. 387.)
$K_v = 0.35$
u_{fl} = 1.91 ft/s = 0.58 m/s
if 75% active area and 75% of flooding
$A = (G/3600)/((0.75)(0.75)\rho_G u) = 27.27$ m^2
D = 5.9 m – reduced slightly for actual construction

25% overall column efficiency
⇒ 20 stages (so column about 40 ft tall)
$\Delta P = \rho g h N$
15000 kg m/m^{2}s^2 = (982 kg/m^3)(9.8 m/s^2)(h_{weir})(20)
h_{weir} = 0.078 m ≈ 3 in

T-702

from Chemcad, 5 ideal stages, feeds at 1 and 5
average flows:
L = 367298 kg/h, V = 1017473 kg/h
ρ_L = 982 kg/m^3
ρ_G = 31.9 kg/m^3
$(L/V)(\rho_G/\rho_L)^{0.5} = 0.065$
from flooding graph for 24 in tray spacing (P. Wankat, *Equilibrium Staged Separations*, Prentice Hall, 1988, p. 387.)
$K_v = 0.35$
u_{fl} = 1.91 ft/s = 0.58 m/s
if 75% active area and 75% of flooding
$A = (G/3600)/((0.75)(0.75)\rho_G u) = 27.27$ m^2
D = 5.9 m – reduced slightly for actual construction

25% overall column efficiency
⇒ 20 stages (so column about 40 ft tall)
$\Delta P = \rho g h N$
15000 kg m/m^{2}s^2 = (982 kg/m^3)(9.8 m/s^2)(h_{weir})(20)
h_{weir} = 0.078 m ≈ 3 in

T-703

from Chemcad, 23 ideal trays, feed at 12, plus partial reboiler and total condenser
largest flows at bottom of column:
L = 1150010 kg/h, V = 429426 kg/h
ρ_L = 833 kg/m^3
ρ_G = 12.28 kg/m^3
$(L/V)(\rho_G/\rho_L)^{0.5}$ = 0.325
from flooding graph for 12 in tray spacing (P. Wankat, *Equilibrium Staged Separations*, Prentice Hall, 1988, p. 387.)
K_v = 0.13
u_{fl} = 1.06 ft/s = 0.324 m/s
if 75% active area and 75% of flooding
$A = (G/3600)/((0.75)(0.75)\rho_G u)$ = 53.3 m^2
D = 8.24 m – reduced slightly for actual construction

33% overall column efficiency (O'Connell correlation)
$\Rightarrow$ 70 trays (so column about 70 ft tall)
$\Delta P = \rho g h N$
50000 kg m/m^{2}s^2 = (833 kg/m^3)(9.8 m/s^2)(h_{weir})(70)
h_{weir} = 0.087 m $\approx$ 3.5 in

V-701

assume 10 min residence time based on total liquid flow
$V = (1+R)D$ = 1.89(15506) = 29323 kg/h
ρ_L = 770 kg/m^3 – pure ethylene oxide
liquid at 29323 kg/h = 38.1 m^3/h
V = 38.1 m^3/h (10/60 h) = 6.35 m^3 $\Rightarrow$ 12.7 m^3

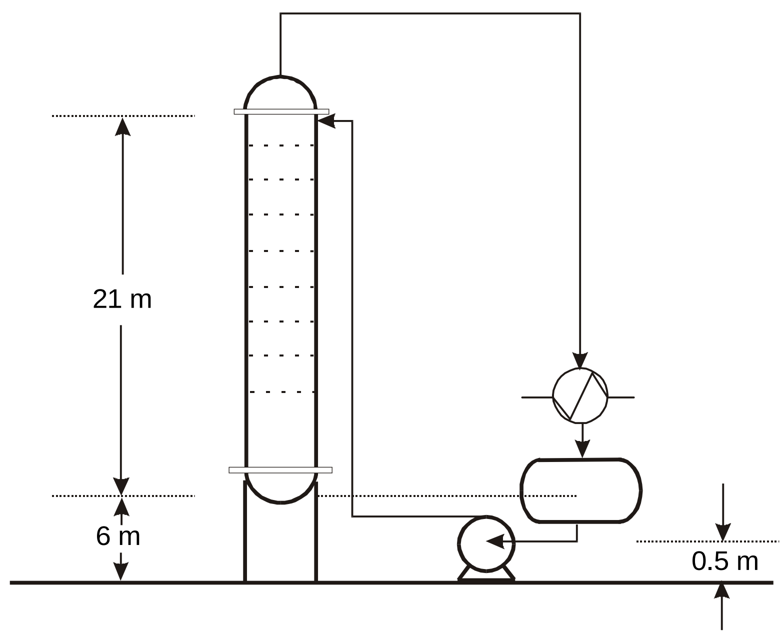
P-701

reflux pump on ground
6 m skirt elevating column
21 m column
pump inlet 0.5 m above ground
total height from top of column 26.5 m
total pipe length from pump to top of column (discharge line) = 21 + 6 – 0.5 + 5 (fittings) + 6.5 (horizontal pipe) = 38 m
reflux drum liquid level at height of top of skirt
total pipe length in suction line (from V-701 to pump only) = 6 – 0.5 +2 (fittings) + 3.5 (horizontal pipe) = 11 m (neglect vapor-phase pressure drop – before condenser)
2.5 in schedule 40 for suction and discharge
roughness factor e/d = 0.000038
ρ = 770 kg/m^3, μ = 0.0001655 kg/m s, Re = 998000, f = 0.0035
$\Delta P_{E\text{-}709}$ = 10 kPa

$\Delta P_{friction,\ discharge\ line}$ = 2(770 kg/m^3)(0.0035)(38 m)(3.42 m/s)^2/(0.06272 m) = 38.2 kPa
$\Delta P_{friction,\ suction\ line}$ = 2(770 kg/m^3)(0.0035)(11 m)(3.42 m/s)^2/(0.06272 m) = 11 kPa
$\Delta P = \Delta P_{friction,\ discharge\ line} + \Delta P_{head} + \Delta P_{friction,suction\ line} + \Delta P_{E\text{-}709}$ = 38.2 + (770 kg/m^3)(9.8 m/s^2)(26.5m)/1000 + 10 + 11 = 259.2 kPa
$\Delta P_{control\ valve}$ = 30 kPa
ΔP_{pump} = 289.2 kPa
pump power = (89200/770 J/kg)(15516(0.89)/3600) kg/s = 1.44 kW
80% efficient, actual power = 1.8 kW

NPSH
$NPSH_A = P_{V\text{-}701} + \rho gh + \Delta P_{friction,\ suction} - P^*$ = 1000 – 10 + 770(9.8)(5.5)/1000 – 11 – 1000 kPa = 20.5 kPa = 2.72 m liquid

pump and NPSH curves attached

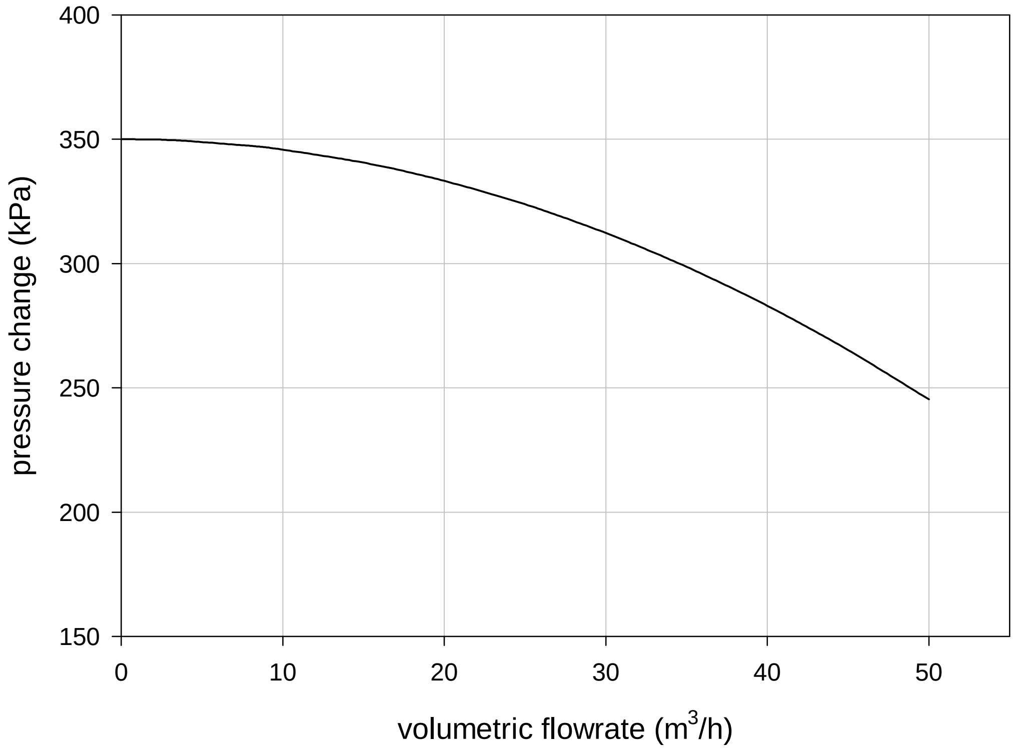


C-701 – C-703

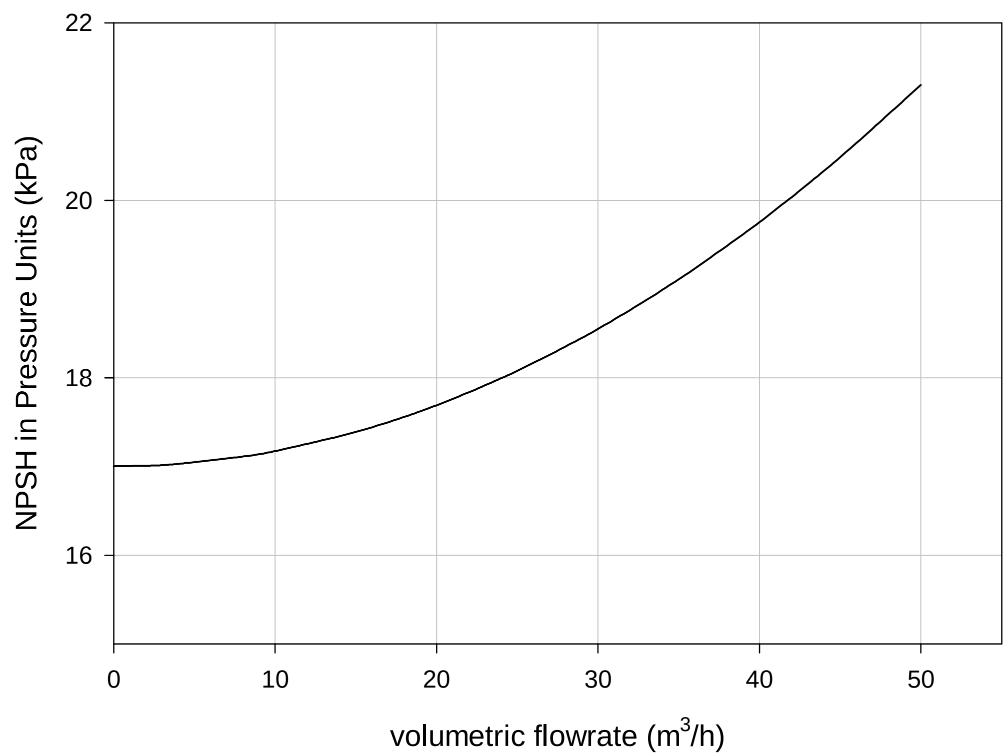
compressor curves attached
flowrate at feed conditions to first stage
variable speed compressors operating at five possible rotation speeds

C-704 – C-705

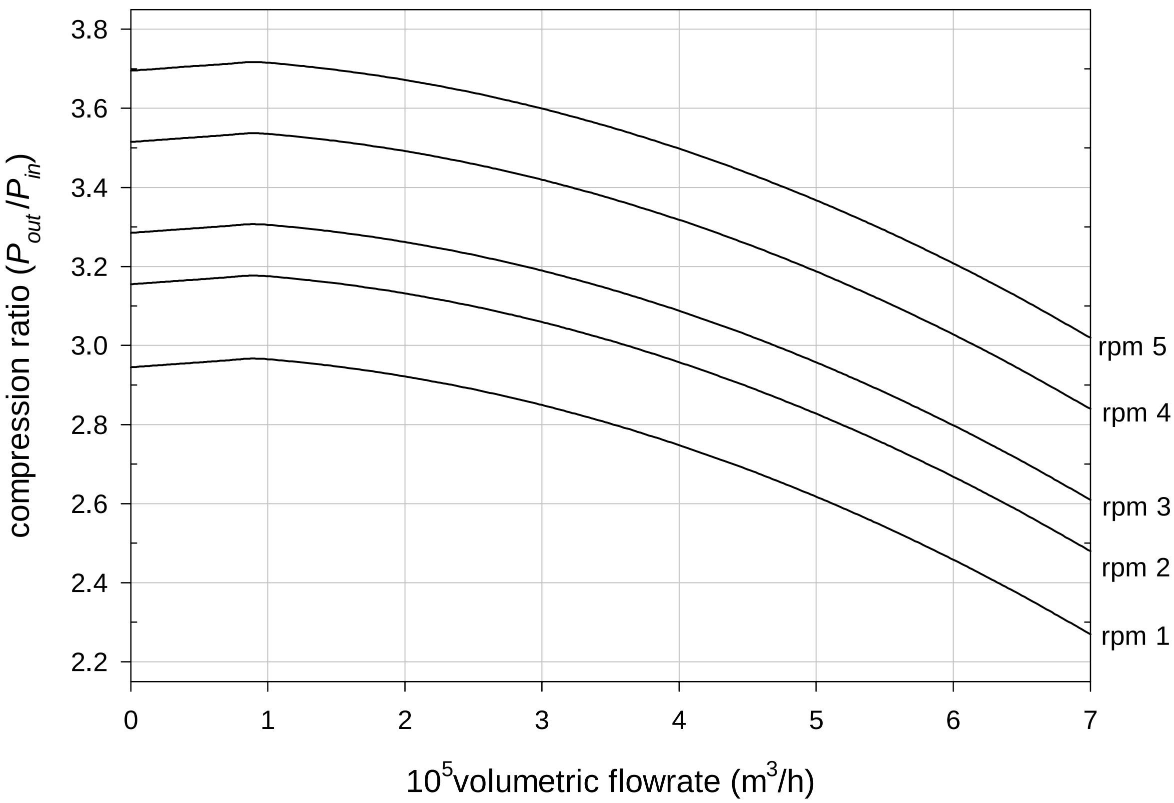
these are blowers – extensive scale-up capacity anticipated



Pump Curve for P-701



$NPSH_R$ Curve for P-701



Compressor Curves for C-701 - C-703