Product Specifications

Product	Required Purity	Battery Limit Condition
Allyl chloride	> 99.9% by mole allyl chloride	Liq, $T < 55°C$, $P > 1.5$ bar
By-Product	**Required Purity**	**Battery Limit Condition**
Mixed chlorides	> 95% by mole 1,2-dichloropropene	Liq, $T < 50°C$, $P > 1.2$ bar
Chloropropene	> 95% by mole chloropropene	Liq, $T < 50°C$, $P > 1.2$ bar
31.5 wt% hydrochloric acid	31.5 wt% hydrochloric acid ± 0.1 wt %	Liq, $T < 45°C$, $P > 1.2$ bar

By-product and Waste Stream Selling Prices/Costs

By-Product	Selling Price
Mixed chlorides	\$0.10 /kg*
Chloropropene	\$0.15 /kg*
31.5 wt% hydrochloric acid (20° Baumé)	From *Chemical Marketing Reporter*

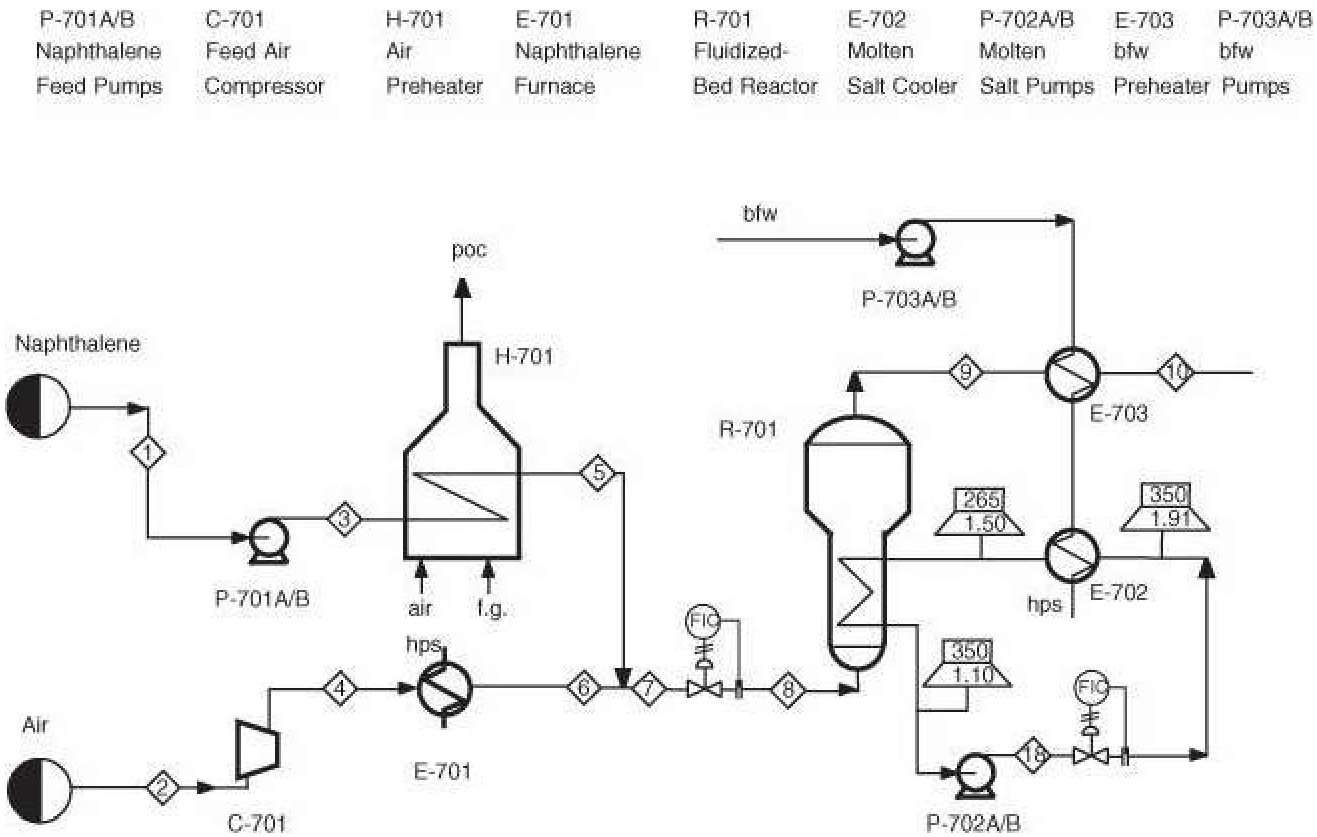
Waste Stream	Cost of Disposal
Waste acid stream (cost of regenerating carbon)	\$0.40 /kg of HCl + hydrocarbons collected on carbon

*These are credits that we will receive from our petrochemical complex for supplying these chemicals, which must meet the specifications given above. We may alternatively pay to dispose of these chemicals at a cost of \$0.25/kg. For this case, no specifications need to be met (i.e., these streams are now waste streams rather than by-products).

PROJECT 3. Scale-Down of Phthalic Anhydride Production at TBWS Unit 700

C.3.1. Background

You have recently joined the TBWS Chemical Corporation. One of TBWS's major businesses has always been production of phthalic anhydride from naphthalene. Phthalic anhydride production is integrated as part of a large chemical plant, in which naphthalene is produced and in which phthalic anhydride is immediately used to make polyester resins. In recent years, there have been some problems. Some end users have complained about the quality of the resins produced and have taken their business to other companies that produce phthalic anhydride from o-xylene. Therefore, our plant, which had been designed to produce 100,000 metric tons/year of phthalic anhydride from naphthalene, was scaled back to about 80,000 metric tons/year several years ago. We are now forced to scale down production once again due to the loss of another large customer. Marketing informs us that we may lose additional customers. Research is working on development of catalysts for the o-xylene reaction, but their results are not expected for up to a year. There is an immediate need to determine how to scale down operation of our plant to 50% of current capacity (40,000 metric tons/year). We would like to accomplish this without a shutdown, because one is not scheduled for a few months. If 50% scale-down cannot be achieved without a shutdown, we need to know how much scale-down is possible immediately. Specifically, you are to determine the maximum possible scale-down, up to 50%, under current operating conditions, and you are to define these operating conditions. Furthermore, you are to determine how the plant can be scaled down to 50% of current capacity, what operating conditions are required, and what capital expenditures, if any, are needed. Any suggestions for plant improvements that can be made during shutdown are encouraged. You must clearly define the consequences of any changes that you recommend for this process and the consequences of these changes for other processes that might be affected. It should be noted that one possible scenario is to operate the plant at design capacity for six months of the year and shut down the plant for the remaining six months. Although this solution might work, we are reluctant to lay off our operators for half the year and also to purchase additional storage in order to store enough phthalic anhydride to supply our customers for the six months that the plant is down. You should not consider this option any further.



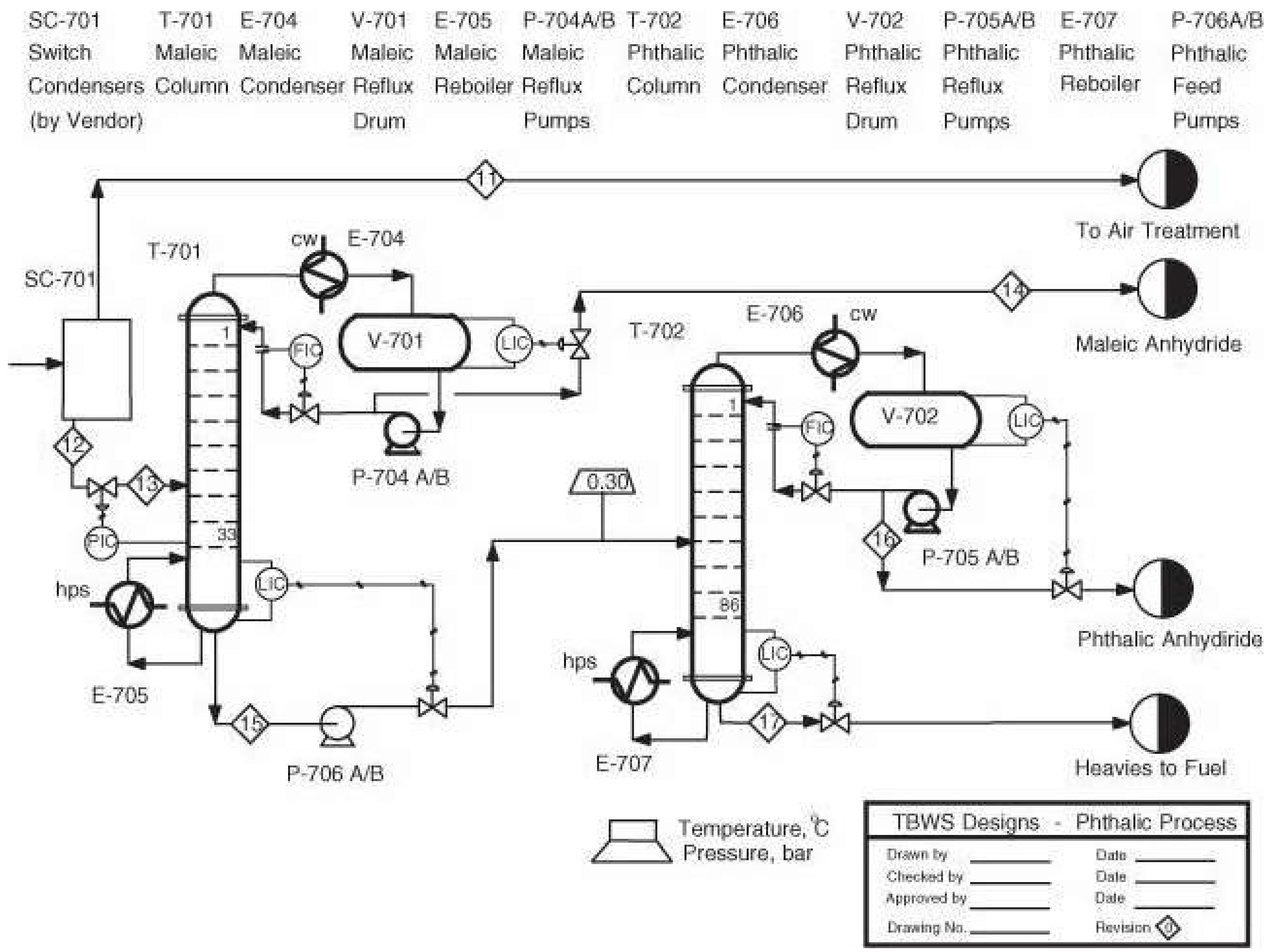


Figure C.5. Process Flow Diagram for the Production of Phthalic Anhydride from Naphthalene (Unit 700)

For your first assignment, you are to address the issues described above for the portion of the process before the switch condensers (see Figure C.5).

C.3.2. Phthalic Anhydride Production

Unit 700 now produces about 80,000 metric tons/y of phthalic anhydride. The feeds are essentially pure naphthalene and excess air. These are pressurized, heated and vaporized (naphthalene), and reacted in a fluidized bed with a vanadium oxide on silica gel catalyst. The reactions are as follows:

$$\underset{\text{naphthalene}}{C_{10}H_8} + \frac{9}{2}O_2 \rightarrow \underset{\text{phthalic anhydride}}{C_8H_4O_3} + 2H_2O + 2CO_2$$

$$C_{10}H_8 + 6O_2 \rightarrow \underset{\text{maleic anhydride}}{2C_4H_2O_3} + 2H_2O + 2CO_2$$

$$C_{10}H_8 + \frac{3}{2}O_2 \rightarrow \underset{\text{naphthoquinone}}{C_{10}H_6O_2} + H_2O$$

Additionally, the complete and incomplete combustion reactions of naphthalene also occur. The large exothermic heat of reaction is removed by molten salt circulated through coils in the reactor. The molten salt is used to produce high-pressure steam. Total conversion of naphthalene is very close to 100%. The reaction products proceed to a set of devices known as switch condensers. These are described in detail later. Design and operation of these devices are provided under contract by

CONDENSEX. They guarantee us that their condensers can operate at any capacity and provide the same separation as in current operation, as long as the pressure and the composition of the condensable portion of Stream 10 remain constant. The net result of the switch condensers is that essentially all of the light gases and water leave as vapor, with small amounts of maleic and phthalic anhydrides, and that the remaining anhydrides and naphthoquinone leave as liquid. The liquid pressure is then reduced to vacuum for distillation. The first column removes maleic anhydride impurity overhead, and the second column removes the phthalic anhydride product overhead.

Organic waste is burned for its fuel value. The dirty air, Stream 11, must be treated. The anhydrides are scrubbed using water, which is then sent to the on-site wastewater treatment facility.

C.3.3. Other Information

Other pertinent information is appended, including pump and compressor curves, Figure C.6 and Figure C.7; a flow summary table, Table C.8; and an equipment list, Table C.9.

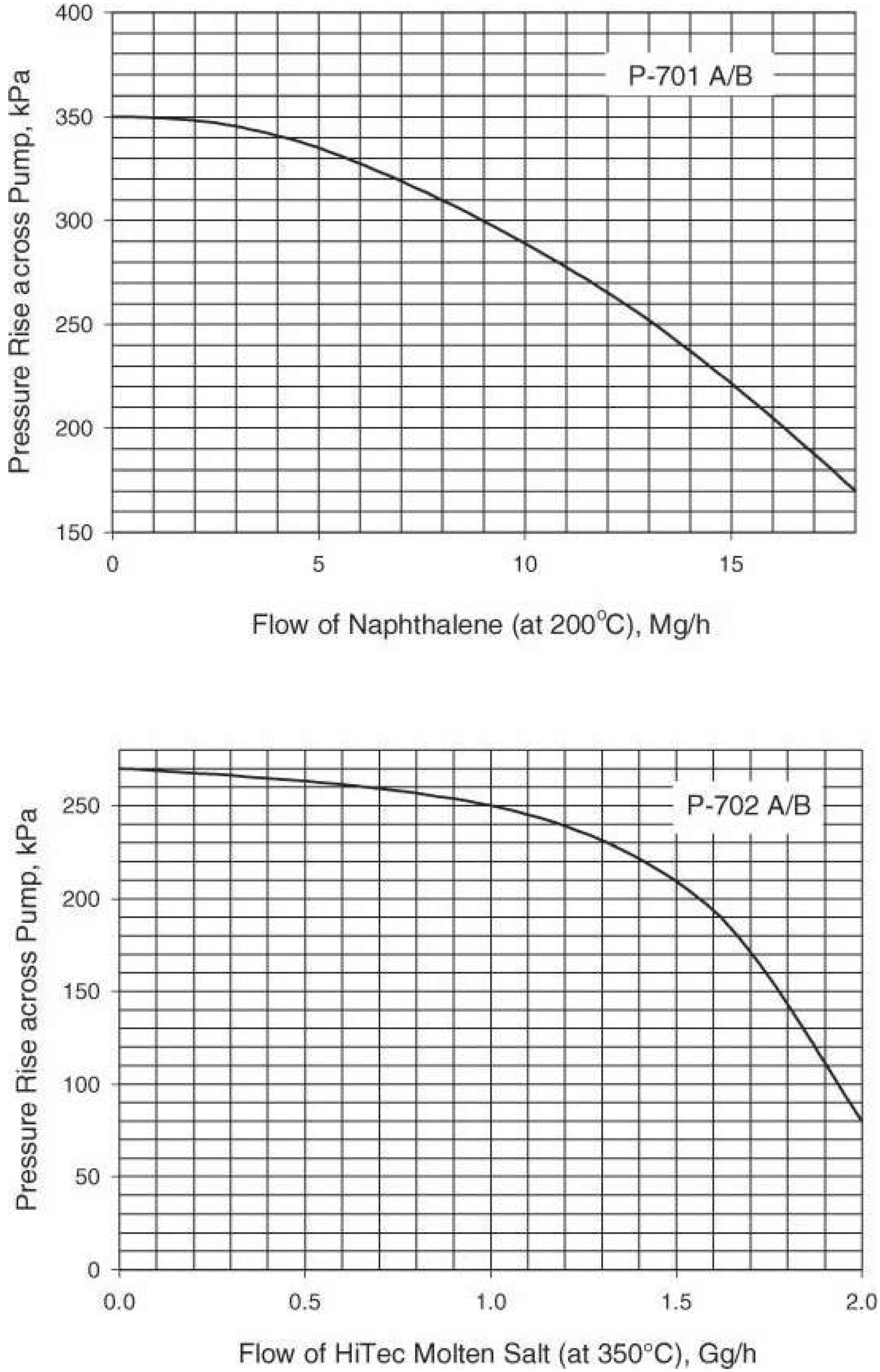
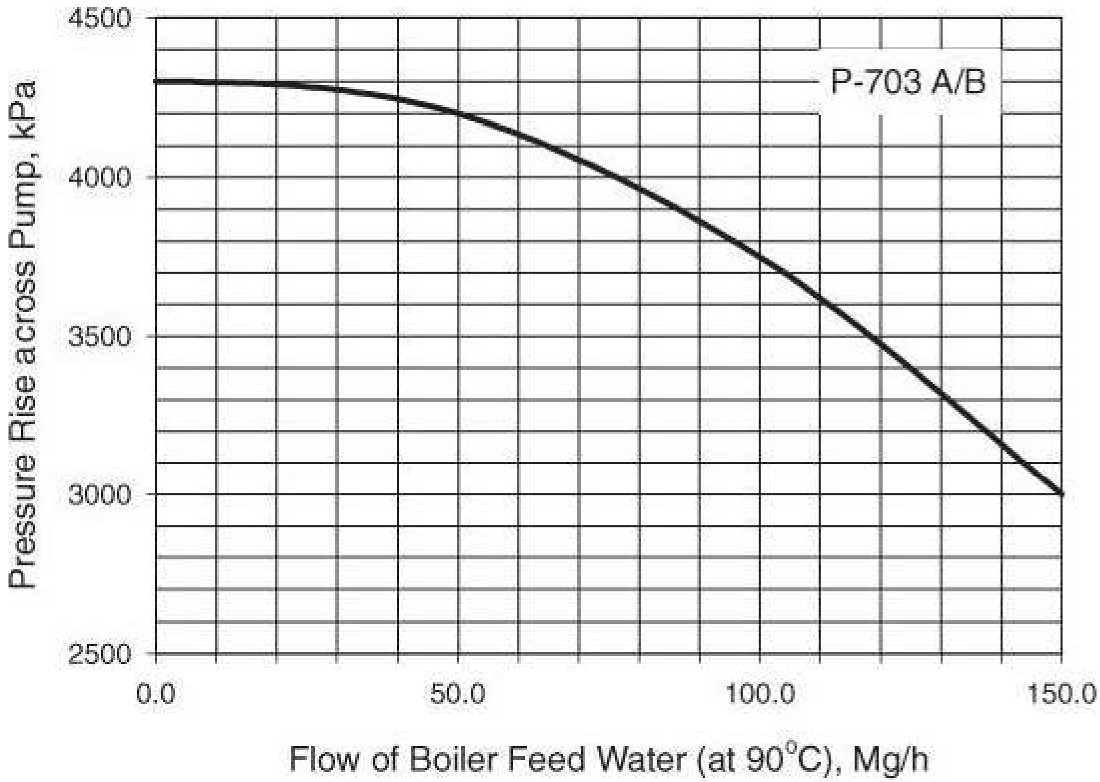


Figure C.6. Pump Curves for P-701 A/B and P-702 A/B



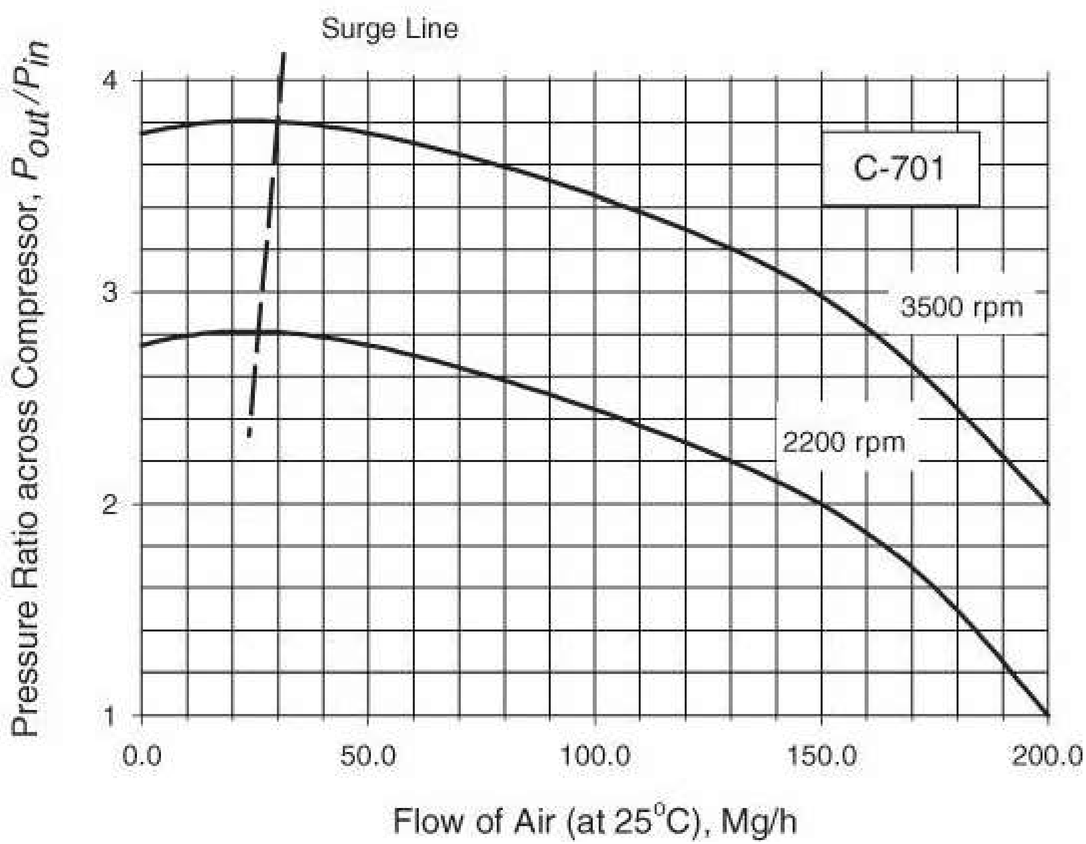


Figure C.7. Pump and Compressor Curves for P-703 A/B and C-701

Table C.8. Flow Summary Table for Current Operation of Phthalic Anhydride Production Facility, Unit 700 (see Figure C.5)

Stream Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Temperature (°C)	200	25	200	164	400	240	263	263	360	160	131	131	131	141	241	190	241	350
Pressure (bar)	0.80	1.01	3.35	3.10	2.85	2.85	2.75	2.25	2.00	1.70	1.40	1.40	0.15	0.11	0.30	0.05	0.20	3.00
Vapor mole fraction	0.0	1.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Flowrate (tonne/h)	12.82	144.25	12.82	144.25	12.82	144.25	157.07	157.07	157.07	157.07	145.00	12.07	12.07	1.61	10.47	10.06	0.40	1624.72
Flowrate (kmol/h)																		HiTec molten salt
Naphthalene	100.0	0.0	100.0	0.0	100.0	0.0	100.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oxygen	0.0	1050.0	0.0	1050.0	0.0	1050.0	1050.0	1050. 0	469.0	469.0	469.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phthalic anhydride	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	70.0	70.0	0.7	69.0	69.0	0.69	69.0	68.0	0.69	0.0
Maleic anhydride	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0-	16.0	16.0	0.8	15.0	15.0	15.0	0.015	0.015	0.0	0.0
Naphthoquinone	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	2.0	0.0	2.0	2.0	0.08	1.9	0.002	1.91	0.0
Carbon dioxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	306.0	306.0	306.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Carbon monoxide	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.0	50.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nitrogen	0.0	3950.0	0.0	3950.0	0.0	3950.0	3950.0	3950.0	3950.0	3950.0	3950.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	238.0	238.0	238.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total (kmol/h)	100.0	5000.0	100.0	5000.0	100.0	5000.0	5100.0	5100.0	5101.0	5101.0	5014.0	86.0	86.0	16.0	71.0	68.0	2.60	17,660

Stream Number	hps to E-701	Conden. from E-701	hps to E-707	Conden. from E-707	hps to E-705	Conden. from E-705	cw to E-706	cwr from E-706	cw to E-704	cwr from E-704	bfw to E-703	bfw to E-702	hps from E-702
Temperature (°C)	254	254	254	254	254	254	30	45	30	45	91	173	254
Pressure (bar)	42.4	42.4	42.4	42.4	42.4	42.4	5.16	4.86	5.16	4.86	42.4	42.4	42.4
Vapor mole fraction	1.0	0.0	1.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
Total tonnes/h	6.73	6.73	9.36	9.36	1.89	1.89	267.84	267.84	19.62	19.62	104.98	104.98	104.98

Table C.9. Equipment Summaries (Unit 700)

Compressor (assume efficiency independent of flowrate)

C-701 centrifugal, 5670 kW, 80% efficient @ design flowrate and 3500 rpm; can operate at two discrete rpm values, as shown on compressor curve; surge line also shown on compressor curve

Pumps (assume efficiency independent of flowrate)

P-701 A/B	centrifugal, 1.3 kW, 50% efficient
P-702 A/B	centrifugal, 54 kW, 70% efficient
P-703 A/B	centrifugal, 140 kW, 80% efficient
P-704 A/B	centrifugal, 0.5 kW, 40% efficient
P-705 A/B	centrifugal, 4.4 kW, 50% efficient
P-706 A/B	centrifugal, 0.8 kW, 40% efficient

Fired Heater (process fluid flows through a set of tubes with a natural gas or liquid fuel fired flame, providing the radiant and convective heat transfer necessary to heat the fluid to the desired temperature)

H-701 fired heater, $Q = 9{,}350$ MJ/h
Consists of four identical banks of tubes—currently these are all in operation and are operating in parallel—piping and valving exist to run any or all tube banks in any configuration (i.e., series, parallel, etc.)—there is a control system that maintains the temperature of Stream 5 by measuring the temperature of Stream 5 and altering the natural gas and air feed rate.

Heat Exchangers (all one pass on each side, unless otherwise noted; h_i refers to tube side; tube wall resistance negligible, unless otherwise noted)

E-701 Uses high-pressure steam, steam in shell, $Q = 11{,}370$ MJ/h
$A = 695\ m^2$, $U = 112\ W/m^2°C$, $h_i = 114\ W/m^2°C$

E-702 Makes high-pressure steam, steam in shell, $Q = 215{,}407$ MJ/h
$A = 539\ m^2$, $U = 2{,}840\ W/m^2°C$, $h_i = 3960\ W/m^2°C$
hps supplies Unit 700 needs, excess steam used in Unit 300

E-703 Preheats high-pressure bfw, bfw in shell, $Q = 36{,}900$ MJ/h
$A = 1519\ m^2$, $U = 57\ W/m^2°C$, $h_i = 63\ W/m^2°C$

E-704 Total condenser for T-701, condensing fluid in shell
$A = 5.52\ m^2$, $U = 600\ W/m^2°C$, all resistance on water side

E-705 Reboiler for T-701
$A = 50\ m^2$, $U = 1400\ W/m^2°C$, approximately equal resistances

E-706 Total condenser for T-702, condensing fluid in shell
$A = 51\ m^2$, $U = 600\ W/m^2°C$, all resistance on water side

E-707 Reboiler for T-702
$A = 243\ m^2$, $U = 1400\ W/m^2°C$, approximately equal resistances

Reactor

The reactor is a fluidized bed, which means that the bed temperature is essentially constant and equal to the exit temperature of the gas.

R-701 Fluidized bed with vanadium oxide catalyst coated on silica gel
Molten salt circulated in tubes to remove heat of reaction
Heat-exchange area = 15,850 m^2 (parallel tube banks within reactor)
$U = 100\ W/m^2{}^\circ C$, all resistance on reactor side
Heat removal required = 2.154×10^5 MJ/h
Reactor pressure drop unaffected by flowrate

Molten Salt Loop

Molten salt is used to remove the heat generated in the reactor. It circulates in a closed loop and is thermally regenerated by making high-pressure steam in E-702. The properties of this molten salt, known as HiTec, may be found in the 6th edition of Perry's, pp. 9–77.

Switch Condenser

SC-701 There are three sets of condensers. Due to the low partial pressure of phthalic anhydride in the stream, it desublimates rather than condenses. Therefore, the process stream is cooled using a low-temperature oil in tubes to promote desublimation. Then after solid is loaded on the heat transfer surface, higher-temperature oil is circulated in the tubes to melt the solid. There are three such devices, one operating in desublimation mode, one operating in melting mode, and one on standby. The net result is a liquid stream containing the condensables, and a vapor stream containing water and the noncondensables. These condensers are designed and maintained under contract by CONDENSEX. They indicate operation at any scale is possible as long as the pressure of Stream 10 remains within 10% of current operating conditions, and as long as the relative composition of the condensables remains approximately constant.

Distillation Columns (For both distillation columns, it may be assumed that weeping begins to occur at 35% of flooding. Both use high-pressure steam and cooling water at the maximum allowable temperature rise.)

T-701 Removes maleic anhydride impurity overhead
Reflux ratio = 0.27
33 trays, 40% efficient, 12-in tray spacing, 2-in weirs
Diameter = 0.84 m, active area = 75% of total area
$Q_c = -1230$ MJ/h
$Q_r = 3220$ MJ/h

T-702 Removes phthalic anhydride product overhead
Reflux ratio = 2.43
86 trays, 50% efficient, 18-in tray spacing, 0.75-in weirs
Diameter = 4.2 m, active area = 75% of total area
$Q_c = -16{,}810$ MJ/h
$Q_r = 15{,}890$ MJ/h

Vessels

V-701 Diameter = 0.50 m, Length = 1.50 m

V-702 Diameter = 1.25 m, Length = 3.75 m

Air Treatment

The organics in Stream 11 are removed in a scrubber, with 10,000 kg of water needed per kg of organic, at the current operating conditions. If the organic content of Stream 11 becomes more concentrated, then the amount of water needed increases by 100 kg per 0.001 mass fraction of organic. The water is sent to the on-site wastewater treatment facility.

C.3.4. Assignment

Your assignment is to provide recommendations as to how much immediate scale-down is possible and what, if any, modifications would be needed to scale down by 50%. For now, you are to consider only the portion of the process prior to the switch condensers. You should also recommend any other changes that you feel should be made to improve performance in Unit 700. Because our plant is due for annual shutdown in a few months, we want specific recommendations as to what should be done at that time and the cost of these alterations and/or modifications.

Specifically, you are to prepare the following by two weeks from now:

1. A written report detailing the maximum scale-down possible, how to achieve 50% scale-down, recommendations, and costs associated with scaling down production in Unit 700.
2. A list of new equipment to be purchased, including size, cost, and materials of construction.
3. An analysis of any change in the annual operating cost created by your recommended modifications.
4. A legible, organized set of calculations justifying your recommendations, including any assumptions made.

C.3.5. Report Format

This report should be brief. Most of the report should be an executive summary, not to exceed five double-spaced, typed pages, that summarizes your diagnosis, recommendations, and rationale. Figures and tables may be included (and do not count against the page limit) in the executive summary. An appendix should be attached that includes items such as the requested calculations. These calculations should be easy to follow. In general, the written report should follow the guidelines given in Chapter 29 (in this CD).

PROJECT 4. The Design of a New 100,000-Metric-Tons-per-Year Phthalic Anhydride Production Facility

C.4.1. Background

The operation of Unit 700, our phthalic anhydride facility, has been successfully scaled down by 50%. Over the long term, we are still considering changing to o-xylene as the raw material. The catalysis and reaction engineering group has finished preliminary research and is very optimistic about its new catalyst. They promise that it will be superior to other versions of o-xylene to phthalic anhydride catalysts in that most side products are minimized. At this point we are uncertain as to whether Unit 700 will be retrofitted to accommodate the new catalyst or whether we will build a new, grassroots facility at another site, nearer to an o-xylene producer.

In order for us to have enough information to make an informed decision, we need a preliminary process design for a grassroots facility to produce phthalic anhydride from what may be assumed to be pure o-xylene. Your job is to prepare a preliminary design for the new 100,000 metric tons/y phthalic anhydride from o-xylene plant, and it must be completed within the next month. You may assume that the o-xylene feed is available at 100°C and 1.1 bar and that the required purity for phthalic and maleic anhydride products is 99.9 wt% and 95.0 wt%, respectively.

C.4.2. Other Information

Concentrated organic waste streams may be burned instead of natural gas only if a fired heater is included in the design. Dilute organic waste streams must be sent to a treatment facility, with the