

## P R O J E C T

## 5

# Problems at the Cumene Production Facility, Unit 800

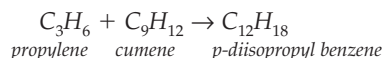
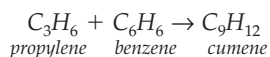
## C.5.1 BACKGROUND

Cumene (isopropyl benzene) is produced by reacting propylene with benzene. During World War II, cumene was used as an octane enhancer for piston engine aircraft fuel. Presently, most of the worldwide supply of cumene is used as a raw material for phenol production. Typically, cumene is produced at the same facility that manufactures phenol.

The plant at which you are employed currently manufactures cumene in Unit 800 by a vapor-phase alkylation process that uses a phosphoric acid catalyst supported on kieselguhr. Plant capacity is on the order of 90,000 metric tons per year of 99 wt% purity cumene. Benzene and propylene feeds are brought in by tanker trucks and stored in tanks as a liquid.

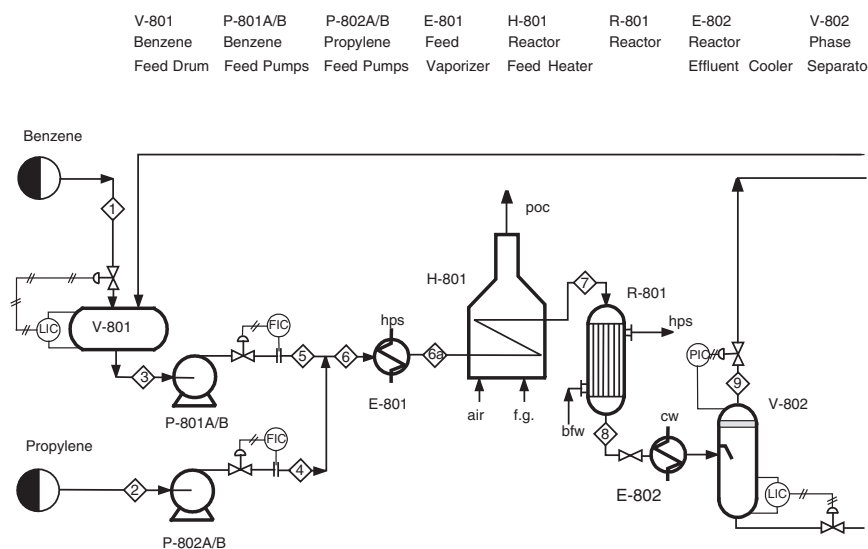
## C.5.2 CUMENE PRODUCTION REACTIONS

The reactions for cumene production from benzene and propylene are as follows:



## C.5.3 PROCESS DESCRIPTION

The PFD for the cumene production process, Unit 800, is given in Figure C.8. The reactants are fed from their respective storage tanks. After being pumped up to the required pressure (dictated by catalyst operating conditions), the reactants are mixed, vaporized, and heated in the fired heater to the temperature required by the catalyst. The shell-and-tube reactor converts the reactants to desired and undesired products as per the



**Figure C.8** Process Flow Diagram for the Production of Cumene Process (Unit 800)

above reactions. The exothermic heat of reaction is removed by producing high-pressure steam from boiler feed water in the reactor. The stream leaving the reactor enters the flash unit, which consists of a heat exchanger and a flash drum. The flash unit is used to separate the  $C_3$  impurities, which are used as fuel for a furnace in another on-site process. The liquid stream from the flash drum is sent to the first distillation column, which separates benzene for recycle. The second distillation column purifies cumene from the p-diisopropyl benzene (p-DIPB) impurity. Currently, the waste p-DIPB is used as fuel for a furnace. The pressure of both distillation columns is determined by the pressure in the flash drum; that is, there are no pressure-reduction valves downstream of the flash drum.

#### C.5.4 RECENT PROBLEMS IN UNIT 800

Recently, Unit 800 has not been operating at standard conditions. We have recently switched suppliers of propylene; however, our contract guarantees that the new propylene feed will be within specifications given in Table C.13.

Upon examining present operating conditions, we have made the following observations:

1. Production of cumene has dropped by about 8%, and the reflux in T-801 was increased by approximately 8% in order to maintain 99 wt% purity. The flows of benzene (Stream 5) and propylene (Stream 2) remained the same. Pressure in the

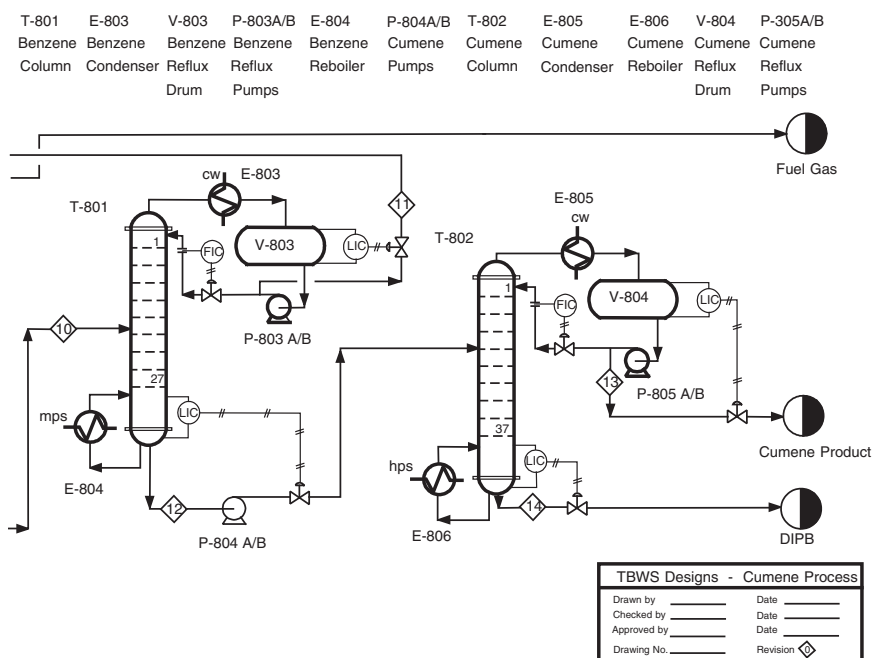


Figure C.8 (Continued)

storage tanks has not changed appreciably when measured at the same ambient temperature.

- The amount of fuel gas being produced has increased significantly and is estimated to be 78% greater than before. Additionally, it has been observed that the pressure control valve on the fuel gas line (Stream 9) coming from V-802 is now fully open, although previously it was controlling the flow.
- The benzene recycle, Stream 11, has increased by about 5%, and the temperature of Stream 3 into P-801 has increased by about 3°C.
- Production of steam in the reactor has fallen by about 6%.
- Catalyst in the reactor was changed six months ago, and previous operating history (over last ten years) indicates that no significant drop in catalyst activity should have occurred over this time period.
- p-DIPB production, Stream 14, has dropped by about 20%.

We are very concerned about this loss in production because we can currently sell all the material we produce.

Another problem that has arisen lately is the malfunction of the feed pumps. This problem arose during a very warm spell when the ambient temperature reached 110°F. A maintenance check showed that P-802 needed a new bearing, and this was taken care of, but P-801 seemed to be OK. The ambient temperature has now returned to a mild 70°F, and both pumps seem to be working fine.

**Table C.13 Specifications of Products and Raw Materials**

<b>Raw Materials</b>	
Benzene	>99.9 wt% purity
Propylene	≤ 5 wt% propane impurity
<b>Product</b>	
Cumene	>99 wt% purity

Currently, market conditions for cumene are very tight. We are in direct competition with some local companies that have recently built cumene plants. It appears that management is very concerned about our competitiveness because other producers in the area are beginning to undercut our prices. Management wants to find out whether any significant savings in operating costs can be found for Unit 800.

#### **C.5.5 OTHER INFORMATION**

Other pertinent information is appended, including a flow table for the process streams at design conditions, that is, prior to the current operating problem, Table C.14; a utility summary table at design conditions, Table C.15; pump curves, Figures C.9 and C.10; a set of design calculations; and an equipment list, Table C.16.

#### **C.5.6 ASSIGNMENT**

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

1. A written report detailing your diagnosis of the operating problems with the plant, along with your recommendations for solving these problems
2. A list of new equipment to be purchased, if any, 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.5.7 REPORT FORMAT**

This report should be brief. Most of the report should be an executive summary, not to exceed five double-spaced, typed pages, which summarizes your diagnosis, recommendations, and rationale. Figures and tables may be included (do not count these 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. The guidelines given in Chapter 29 (in this CD) should be followed.

Table C.14 Flow Summary Table for Cumene Production at Design Conditions, Unit 800 (Figure C.8)

Stream Number	1	2	3	4	5	6	6a	7
Temperature (°C)	25	25	41	28	44	41	214.0	350
Pressure (bar)	1.00	11.66	1.01	31.50	31.50	31.25	30.95	30.75
Vapor mole fraction	0	0	0	0	0.0	0.0	1.0	1.0
Flowrate (tonne/h)	8.19	4.64	16.37	4.64	16.37	21.01	21.01	21.01
<b>Flowrates (kmol/h)</b>								
Benzene	105.00	0.0	205.27	0.0	205.27	205.27	205.27	205.27
Propylene	0.0	105.00	2.89	105.00	2.89	107.89	107.89	107.89
Propane	0.0	5.27	2.79	5.27	2.79	8.06	8.06	8.06
Cumene	0.0	0.0	0.94	0.0	0.94	0.94	0.94	0.94
P-diisopropyl benzene	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total (kmol/h)	105.00	110.27	211.89	110.27	211.89	322.16	322.16	322.16

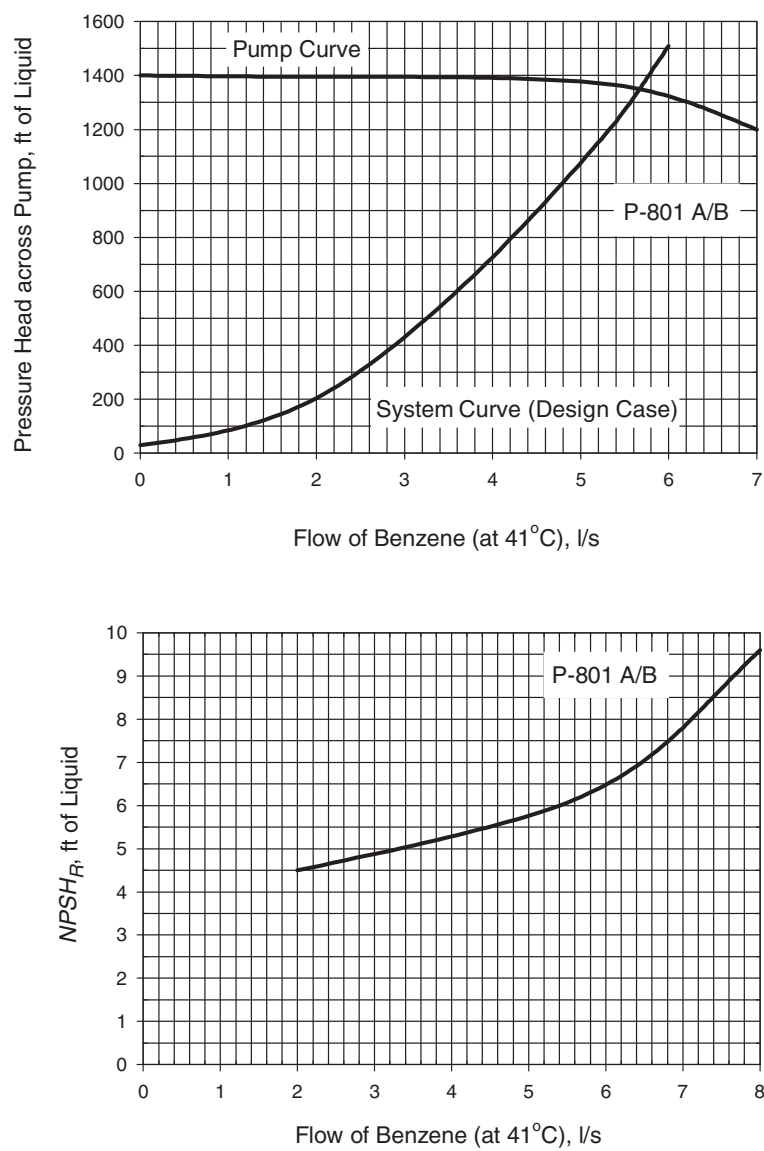
  

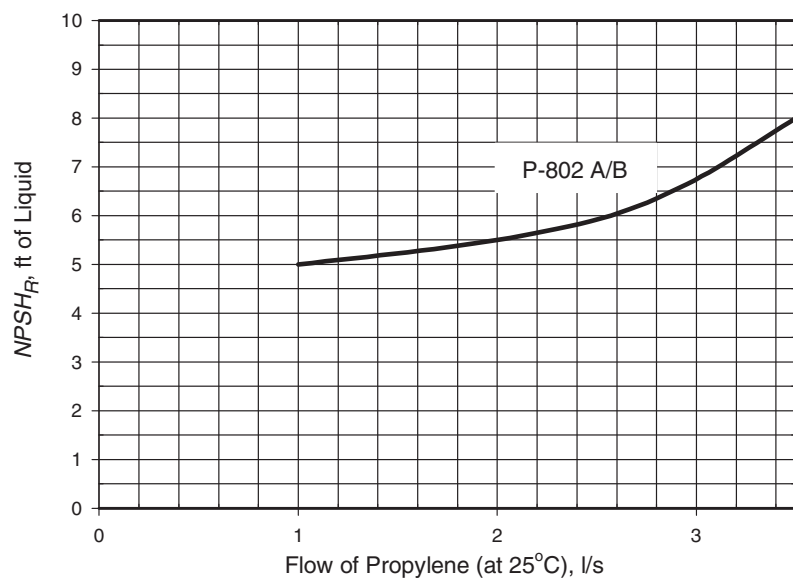
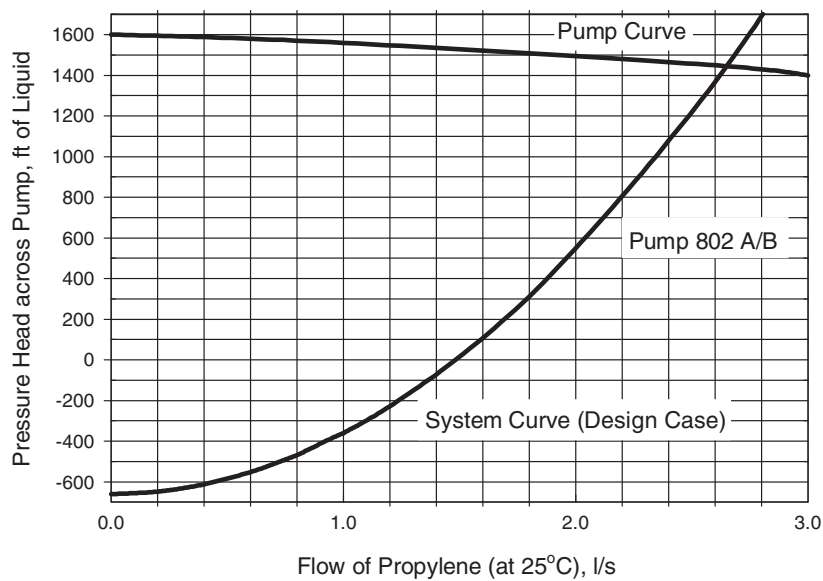
Stream Number	8	9	10	11	12	13	14
Temperature (°C)	350	90	90	57	179	178	222
Pressure (bar)	30.25	1.75	1.75	1.75	1.90	1.90	2.10
Vapor mole fraction	1.0	1.0	0.0	0.0	0.0	0.0	0.0
Flowrate (tonne/h)	21.01	1.19	19.82	8.18	11.64	11.08	0.56
<b>Flowrates (kmol/h)</b>							
Benzene	108.96	7.88	101.08	100.27	0.81	0.81	0.0
Propylene	8.86	5.97	2.89	2.89	0.0	0.0	0.0
Propane	8.06	5.27	2.79	2.79	0.0	0.0	0.0
Cumene	94.39	0.77	93.62	0.94	92.68	91.76	0.92
P-diisopropyl benzene	2.79	0.0	2.79	0.0	2.79	0.03	2.76
Total (kmol/h)	223.06	19.89	203.17	106.89	96.28	92.60	3.68

**Table C.15 Flow Summary Table for Utility Streams in Unit 800**

<b>Stream Name</b>	<b>hps to E-801</b>	<b>Condensate from E-801</b>	<b>mps to E-804</b>	<b>Condensate from E-804</b>	<b>hps to E-806</b>	<b>Condensate from E-806</b>
Temperature (°C)	254	254	185.5	185.5	254	254
Pressure (bar)	42.37	42.37	11.35	11.35	42.37	42.37
Flowrate (tonne/h)	7.60	7.60	3.56	3.56	3.25	3.25

<b>Stream Name</b>	<b>cw to E-802</b>	<b>cw from E-802</b>	<b>cw to E-803</b>	<b>cw from E-803</b>	<b>cw to E-805</b>	<b>cw from E-805</b>
Temperature (°C)	30	45	30	45	30	45
Pressure (bar)	5.16	4.96	5.16	4.96	5.16	4.96
Flowrate (tonne/h)	261.30	261.30	85.88	85.88	87.50	87.50

**Figure C.9** Pump, System, and NPSH Curves for P-801 A/B



**Figure C.10** Pump, System, and NPSH Curves for P-802 A/B



**Table C.16 Equipment Summary Table for Unit 800****Tanks** (not shown on flowsheet)

TK-801 storage tank for benzene

There are two tanks: one feeding Stream 1 and one in a filling mode.  
Each tank is 450 m<sup>3</sup>.

TK-802 storage tank for propylene

There are two tanks: one feeding Stream 2 and one in a filling mode.  
Each tank is 450 m<sup>3</sup>.**Pumps** (assume efficiency independent of flowrate)

P-801 centrifugal, 75% efficient, driver rated at 21.9 kW

P-802 centrifugal, 75% efficient, driver rated at 6.8 kW

P-803 centrifugal, 75% efficient, driver rated at 2.4 kW

P-804 centrifugal, 75% efficient, driver rated at 1.0 kW

P-805 centrifugal, 75% efficient, driver rated at 3.3 kW

**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-801 uses high-pressure steam, steam in shell,  $Q = 12,800$  MJ/h $A = 20.8$  m<sup>2</sup> in two zonesDesubcooling zone:  $A = 13.5$  m<sup>2</sup>,  $U = 600$  W/m<sup>2</sup>°C,  $h_i = 667$  W/m<sup>2</sup>°CVaporizing zone:  $A = 7.3$  m<sup>2</sup>,  $U = 1500$  W/m<sup>2</sup>°C, equal resistances on both sides

E-802 condenser for flash unit, process stream in shell, 1-2 configuration

 $Q = 16,400$  MJ/h,  $A = 533$  m<sup>2</sup>

E-803 total condenser for T-801, condensing fluid in shell

 $A = 151$  m<sup>2</sup>,  $U = 450$  W/m<sup>2</sup>°C, all resistance on water side

E-804 reboiler for T-801

 $A = 405$  m<sup>2</sup>,  $U = 750$  W/m<sup>2</sup>°C, approximately equal resistances

E-805 total condenser for T-802, condensing fluid in shell

 $A = 24.0$  m<sup>2</sup>,  $U = 450$  W/m<sup>2</sup>°C, all resistance on water side

E-806 reboiler for T-802

 $A = 64.0$  m<sup>2</sup>,  $U = 750$  W/m<sup>2</sup>°C, approximately equal resistances**Fired Heater**H-801  $Q = 6380$  MJ/h (heat actually added to fluid)

Capacity 10,000 MJ/h of heat added to fluid

70% efficiency

**Reactor**

R-801 shell-and-tube packed bed with phosphoric acid catalyst supported on kieselguhr

Boiler feed water in shell to produce high-pressure steam

Reactor volume = 6.50 m<sup>3</sup>, heat exchange area = 342 m<sup>2</sup>

234 tubes, 3.0-in (7.62 cm) ID, 6 m long

 $U = 65$  W/m<sup>2</sup>°C, all resistance on reactor side

Heat removal required = 9840 MJ/h

**Table C.16 Equipment Summary Table for Unit 800 (Continued)**

### Distillation Columns

T-801 removes benzene impurity overhead for recycle  
Medium-pressure steam used in reboiler  
Cooling water used in condenser, returned at maximum allowable temperature  
Reflux ratio = 0.44  
27 trays, 50% efficient  
24-in tray spacing, 3-in weirs  
Diameter = 1.13 m, active area = 75% of total area  
 $Q_c = -5390$  MJ/h  
 $Q_r = 7100$  MJ/h

T-802 removes cumene product overhead  
High-pressure steam used in reboiler  
Cooling water used in condenser, returned at maximum allowable temperature  
Reflux ratio = 0.63  
37 trays, 50% efficient  
24-in tray spacing, 3-in weirs  
Diameter = 1.26 m, active area = 75% of total area  
 $Q_c = -5490$  MJ/h  
 $Q_r = 5520$  MJ/h

### Vessels

V-801	benzene feed drum	4.2 m length, 1.4 m diameter
V-802	flash drum	5.2 m height, 1 m diameter
V-803	T-801 reflux drum	4 m length, 1.6 m diameter
V-804	T-802 reflux drum	6.5 m length, 1.6 m diameter

**C.5.8 PROCESS CALCULATIONS****Calculations for Fuel Gas Exit Line for V-802**

Design flow of fuel gas = 1192 kg/h

Molecular weight of fuel gas = 59.9

Gas viscosity =  $9.5 \times 10^{-6}$  kg/m.s

Gas density =  $1.18 (273) P / (293 + 90) (1.01) = 0.00876P$  kg/m<sup>3</sup> ( $P$  in bar)

Destination pressure (in burner in unit 900) = 1.25 bar

$\Delta P_{line} + \Delta P_{valve} = 1.75 - 1.25 = 0.50$  bar

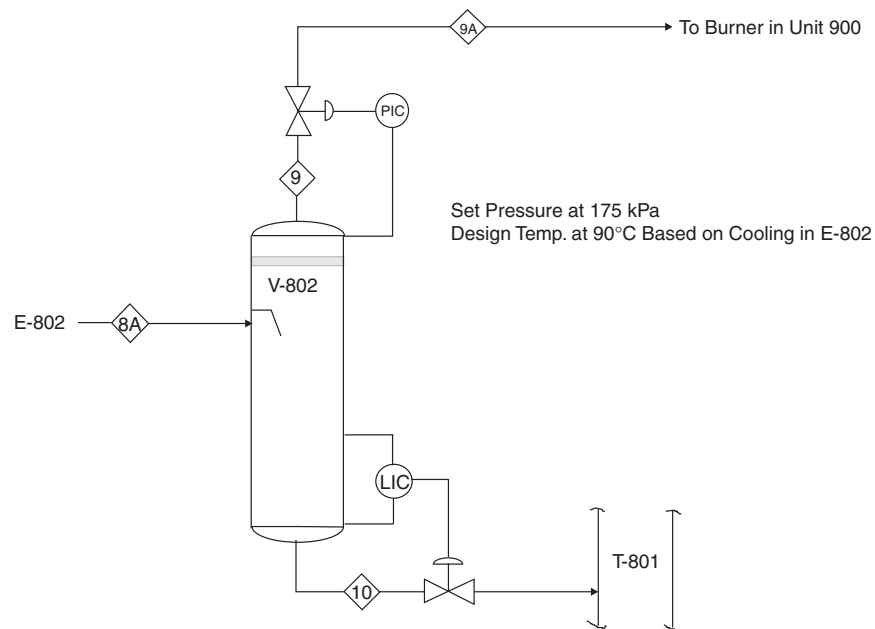
$\Delta P_{valve}$  should be  $\cong 0.30$  bar and  $\Delta P_{line} = 0.20$  bar

Length of line (Stream 9A)  $\cong 125$  m (equivalent length including fittings)

Average pressure in line,  $P = (1.45 + 1.25) / 2 = 1.35$  bar

Density of gas in line =  $0.00876 P = 1.18$  kg/m<sup>3</sup>

$\Delta P_{line} = 2f \rho u^2 L_e / d_{pipe}$



Look at 3-in, 4-in, and 6-in schedule-40 pipe:

$d_{pipe}$ (nominal)	3 in.	4 in.	6 in.
$d_{pipe(inside)} = d_i$	0.0779 m	0.1022 m	0.1541 m
$u = 4Q/\pi d_i^2$	58.9 m/s	34.2 m/s	15.0 m/s
$Re = \rho u d_i / \mu$	$5.69 \times 10^5$	$4.34 \times 10^5$	$2.88 \times 10^5$
$e/d_i$	0.00059	0.00045	0.0003
$f$ (from friction factor diagram)	0.0046	0.0045	0.0042
$\Delta P_{line} = \frac{2f\rho u^2 L_{eq}}{d_i}$	0.603 bar	0.152 bar	0.018 bar

Choose 4-in schedule-40 pipe.

$$\Delta P_{line} = 0.152 \text{ bar and } \Delta P_{valve} = 0.50 - 0.152 = 0.348 \text{ bar}$$



$\therefore$  Required head at design flow =  $1199 + 30 + \Delta P_{cv} = 1230$  ft of benzene +  $\Delta P_{cv}$   
 From pump curve this gives us  $\Delta P_{cv} = 135$  ft = 3.36 bar (this is high but OK)

### Calculations for P-802

Design Conditions (note that 1 kPa = 0.335 ft of water = 0.666 ft of propylene)  
 LAL (low alarm level) = 10 ft from ground and pump center line is 2 ft from ground  
 NOL (normal operating level) = 20 ft from ground

#### NPSH Calculations (at LAL)

Static head =  $10 - 2 = 8$  ft of propylene =  $h_{stat}$   
 $P_{supply} = P_{sat}$  (@25°C) = 11.66 bar = 777 ft of propylene =  $h_{supply}$   
 $\Delta P_{friction}$  (in supply line) = 0.2 psi = 1 ft of propylene =  $h_{friction}$  (3-in schedule 40 pipe  
 $L_e = 20$  ft)

Vapor Pressure of Stream 2 = 11.66 bar = 777 ft of propylene =  $h_{vp}$

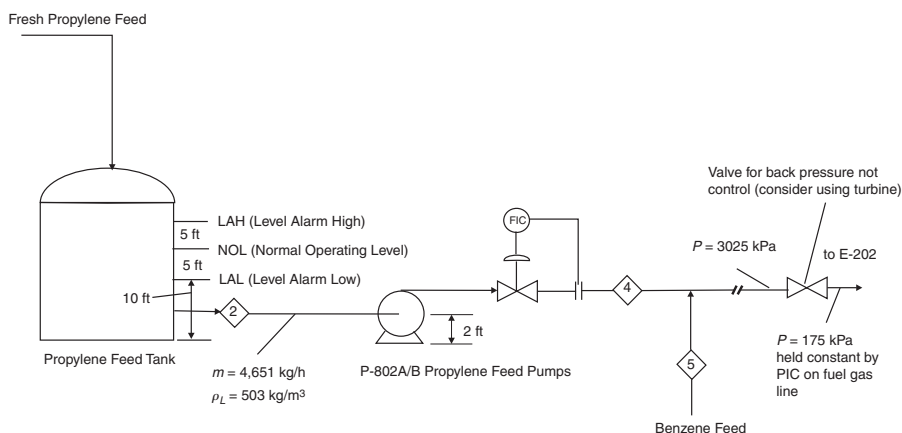
$NPSH_{available} = h_{supply} + h_{static} - h_{friction} - h_{vp} = 777 + 8 - 1 - 777 = 7$  ft of propylene  
 (@ propylene flowrate of  $2.57 \times 10^{-3} \text{ m}^3/\text{s}$ )  
 $NPSH_{required}$  (from pump curve) = 6 ft

$\therefore$  cavitation should not be a problem (put note on P&ID to increase LAL to 12 ft to be safe)

#### System Curve Calculations

$\Delta P_{friction}$  (discharge) =  $31.50 - 1.75 = 29.75$  bar = 1981 ft of propylene  
 $\Delta P_{friction}$  (suction) = 1 ft of propylene  
 $\Delta P_{discharge-tank} = 1.75 - 11.66 = -9.91$  bar = -660 ft of propylene  
 $\Delta P_{static} = -10$  ft of propylene

$\therefore$  Required head at design flow =  $1982 - 660 - 10 + \Delta P_{cv} = 1312$  ft of propylene +  $\Delta P_{cv}$   
 From pump curve this gives us  $\Delta P_{cv} = 140$  ft = 2.10 bar



## P R O J E C T

## 6

# Design of a New, 100,000-Metric-Tons-per-Year Cumene Production Facility

## C.6.1 BACKGROUND

In the opinion of our marketing research department, the demand for phenol-derived plasticizers is on the rise. Therefore, we are investigating the possibility of a new, grass-roots phenol plant to handle the anticipated increase. Because phenol is made from cumene, a grassroots cumene plant would also be necessary. Given your experience in troubleshooting our existing cumene process, we would like you to study the economics of a new cumene plant. Specifically, we would like a complete preliminary design of a grass-roots, 100,000 metric ton/y cumene process using benzene and propylene.

We have a new, proprietary catalyst, and the kinetics are included in Table C.17. We would also like you to consider the economics of our continuing to use propylene with 5% propane impurity at \$0.095/lb versus purer propylene feed. In preparing this preliminary design, you should assume that all steam made can be used elsewhere in the plant with the appropriate economic credit, that condensed steam can be returned as boiler feed water for the appropriate credit, and that fuel gas can be burned for credit at its LHV (lower heating value). Additional information is given in Table C.18.

## C.6.2 ASSIGNMENT

Your assignment is to provide the following:

1. An optimized preliminary design of a plant to make cumene from benzene and propylene using the new catalyst
2. An economic evaluation of your optimized process, using the following information:
  - After-tax internal hurdle rate = 9% p.a.
  - Depreciation = MACRS (6-year schedule; see Chapter 9)
  - Marginal taxation rate = 35%