Problems at the Cumene Production Facility, Unit 800

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.

Cumene Production Reactions

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

$$\underset{propylene}{C_3H_6} + \underset{benzene}{C_6H_6} \rightarrow \underset{cumene}{C_9H_{12}}$$

$$\underset{propylene}{C_3H_6} + \underset{cumene}{C_9H_{12}} \rightarrow \underset{p-diisopropyl\ benzene}{C_{12}H_{18}}$$

Process Description

The PFD for the cumene production process, Unit 800, is given in Figure 1. 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 to the temperature required by the catalyst in the fired heater. The shell-and-tube reactor converts the reactants to desired and undesired products as per the 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 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, i.e., there are no pressure reduction valves downstream of the flash drum.

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 be within specifications given in Table 1.

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

2. 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, while previously it was controlling the flow.

3. 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.

4. Production of steam in the reactor has fallen by about 6%.

5. Catalyst in the reactor was changed 6 months ago; and, previous operating history (over last 10 years) indicates that no significant drop in catalyst activity should have occurred over this time period.

6. DIPB production, Stream 14, has dropped by about 20%.

We are very concerned about this loss in production since 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 O.K. The ambient temperature has now returned to a mild 70°F, and both pumps seem to be working fine.

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 since other producers in the area are beginning to under-cut our prices. Management wants to find out if any significant savings in operating costs can be found for Unit 800.

Other Information

Other pertinent information is appended, including, a flowtable for the process streams at design conditions, i.e., prior to the current operating problem; Table 2, a utility summary table at design conditions; Table 3, pump curves, Figures 2 and 3, a set of design calculations, and an equipment list, Table 4.

Assignment

Specifically, you are to prepare the following by .... (2 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

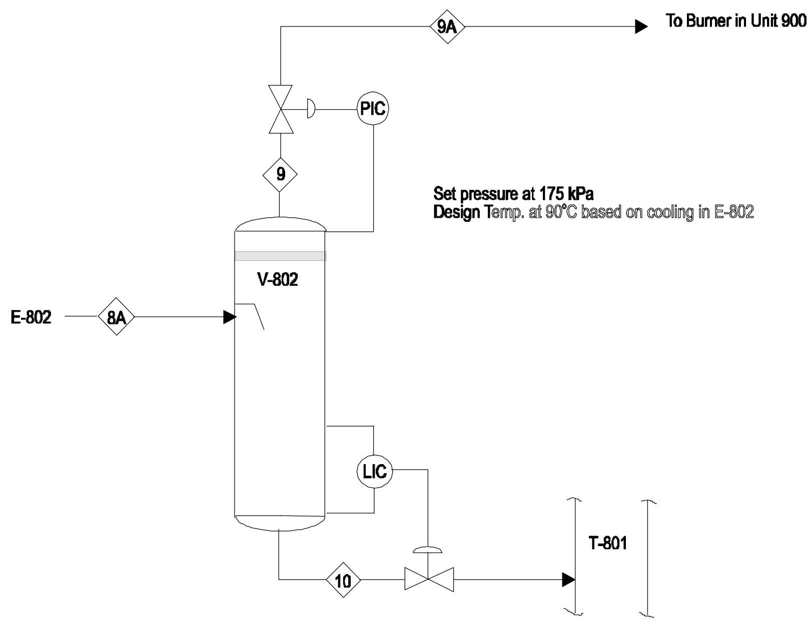
Report Format

This report should be brief. Most of the report should be an executive summary, not to exceed 5 double-spaced, typed pages, which summarizes your diagnosis, recommendations, and rationale. Figures and tables may be included (do not count against page limit) in the executive summary. An appendix should be attached which includes items such as the requested calculations. These calculations should be easy to follow. The guidelines given in Chapter 22 of this book should be followed.

Process Design 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´ 10^{-6} kg/m.s
Gas Density = 1.18 (273) *P* / (293+90) (1.01) = 0.00876P kg/m^3 (*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
ΔP_{valve} should be @ 0.30 bar and ΔP_{line} = 0.20 bar
length of line (Stream 9A) @ 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^3
$\Delta P_{line} = 2f\, rv^2 L_e / d_{pipe}$

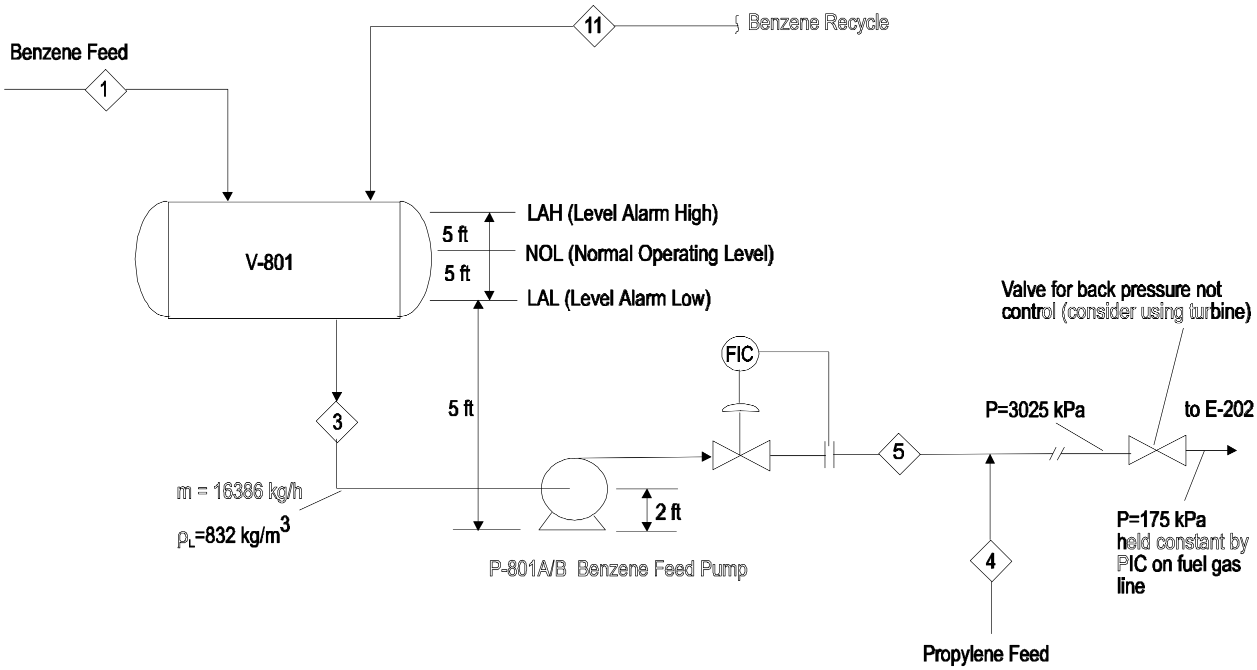
look at 3”, 4” and 6” Sch 40 pipe

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

Choose 4” sch 40 pipe

ΔP_{line} = 0.152 bar and ΔP_{valve}= 0.50 - 0.152 = 0.348 bar

Calculations for P - 801



Design Conditions (note that 1 kPa = 0.335 ft of water = 0.402 ft of benzene)
LAL (low alarm level) =5 ft from ground and pump center line is 2 ft from ground
NOL (normal operating level) = 10 ft above ground level

<u>NPSH Calculations (at LAL)</u>

static head = 5-2 = 3 ft of benzene = h_{stat}
P_{supply} = 1.01 bar = 40.7 ft of benzene = h_{supply}

$\Delta P_{friction}$ (in supply line) = 1 psi = 2.8 ft of benzene = $h_{friction}$

Vapor Pressure of Stream 3

T = 30°C	P^* = 54 kPa
T = 40°C	P^* = 72 kPa
T = 50°C	P^* = 94 kPa

Vapor Pressure of Stream 3 = 0.74 bar @ 41°C = 29.7 ft of benzene = h_{vp}

$NPSH_{available} = h_{supply} + h_{static} - h_{friction} - h_{vp}$ = 40.7 + 3 - 2.8 - 29.7 = 11.2 ft
$NPSH_{required}$ (from pump curve) = 6.1 ft @ 5.5×10^{-3} m^3/s

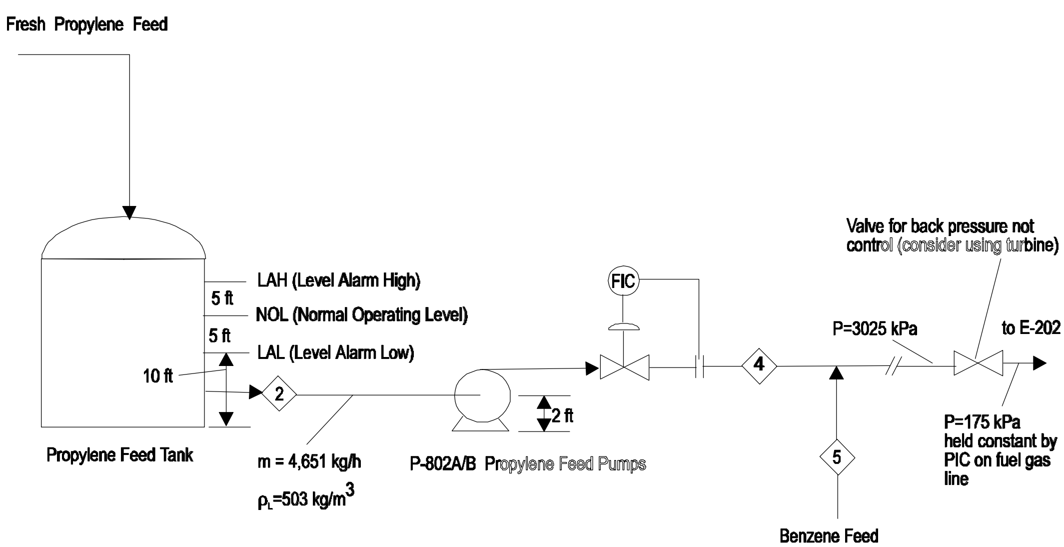
\ cavitation should not be a problem

<u>System Curve Calculations</u>

$\Delta P_{friction}$ (discharge) = 31.50 -1.75 = 29.75 bar = 1196 ft of benzene
$\Delta P_{friction}$ (suction) = 2.8 ft of benzene

$\Delta P_{discharge - tank}$ = 1.75 - 1.01 = 0.74 bar = 30 ft of benzene
ΔP_{static} = 0 (E-801 entrance @ 10 ft above ground level = NOL)
\ Required head at design flow = 1199 + 30 + ΔP_{cv} = 1230 ft of benzene + ΔP_{cv}
From pump curve this gives us ΔP_{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

<u>NPSH Calculations (at LAL)</u>

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” sch 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 2.57×10^{-3} m^3/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)

<u>System Curve Calculations</u>

$\Delta P_{friction}$ (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
ΔP_{static} = -10 feet of propylene

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

Table 1: Specifications of Products and Raw Materials

Raw Materials	
Benzene	>99.9 wt% purity
Propylene	£ 5 wt% propane impurity
Product	
Cumene	>99 wt% purity

Table 2: Flow Summary Table for Cumene Production at Design Conditions, Unit 800, Figure 1.

Stream No.	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
Flowrates (kmol/h)								
Benzene	105.00	-	205.27	-	205.27	205.27	205.27	205.27
Propylene	-	105.00	2.89	105.00	2.89	107.89	107.89	107.89
Propane	-	5.27	2.79	5.27	2.79	8.06	8.06	8.06
Cumene	-	-	0.94	-	0.94	0.94	0.94	0.94
P-Diisopropyl Benzene	-	-	-	-	-	-	-	-
Total (kmol/h)	105.00	110.27	211.89	110.27	211.89	322.16	322.16	322.16

Stream No.	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
Flowrates (kmol/h)							
Benzene	108.96	7.88	101.08	100.27	0.81	0.81	-
Propylene	8.86	5.97	2.89	2.89	-	-	-
Propane	8.06	5.27	2.79	2.79	-	-	-
Cumene	94.39	0.77	93.62	0.94	92.68	91.76	0.92
P-Diisopropyl Benzene	2.79	-	2.79	-	2.79	0.03	2.76
Total (kmol/h)	223.06	19.89	203.17	106.89	96.28	92.60	3.68

Table 3: Flow Summary Table for Utility Streams in Unit 800

Stream Name	hps to E-801	condensate from E-801	mps to E-804	condensate from E-804	hps to E-806	condensate from E-806
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

Stream Name	cw to E-802	cw from E-802	cw to E-803	cw from E-803	cw to E-805	cw from E-805
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

Table 4: 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^3
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^3

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^2 in two zones desubcooling zone: A = 13.5 m^2, U = 600 W/m^2°C, h_i = 667 W/m^2°C vaporizing zone: A = 7.3 m^2, U = 1500 W/m^2°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^2
E-803	total condenser for T-801, condensing fluid in shell A = 151 m^2, U = 450 W/m^2°C, all resistance on water side
E-804	reboiler for T-801 A = 405 m^2, U = 750 W/m^2°C, approximately equal resistances
E-805	total condenser for T-802, condensing fluid in shell A = 24.0 m^2, U = 450 W/m^2°C, all resistance on water side

E-806 reboiler for T-802
A = 64.0 m^2, U = 750 W/m^2°C, approximately equal resistances

Fired Heater

H-801 Q = 6,380 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^3, heat exchange area = 342 m^2
234 tubes, 3.0 in (7.62 cm) ID, 6 m long
U = 65 W/m^2°C, all resistance on reactor side
heat removal required = 9,780 MJ/h

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 = -5,390 MJ/h
Q_r = 7,100 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 = -5,490 MJ/h
Q_r = 5,520 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

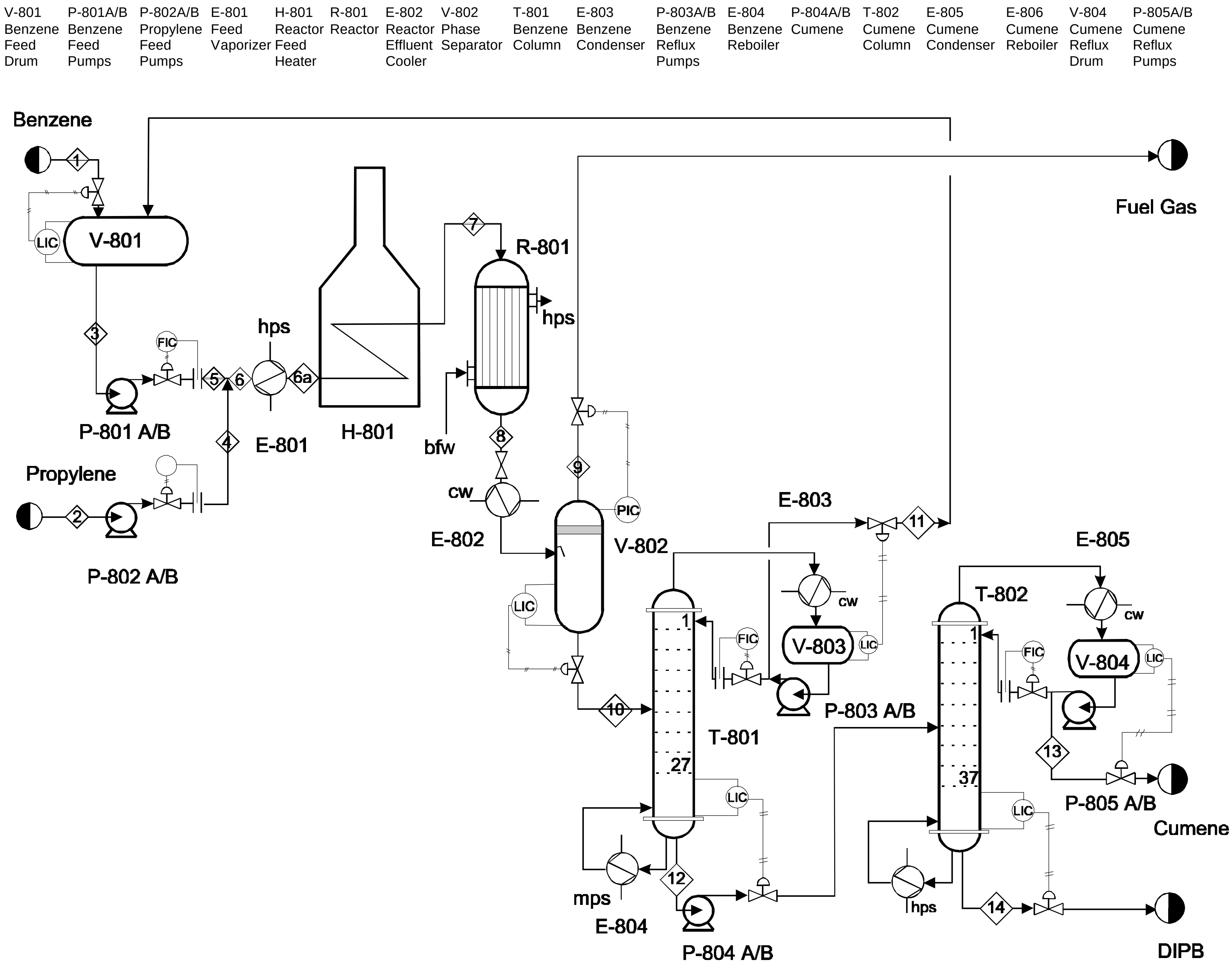
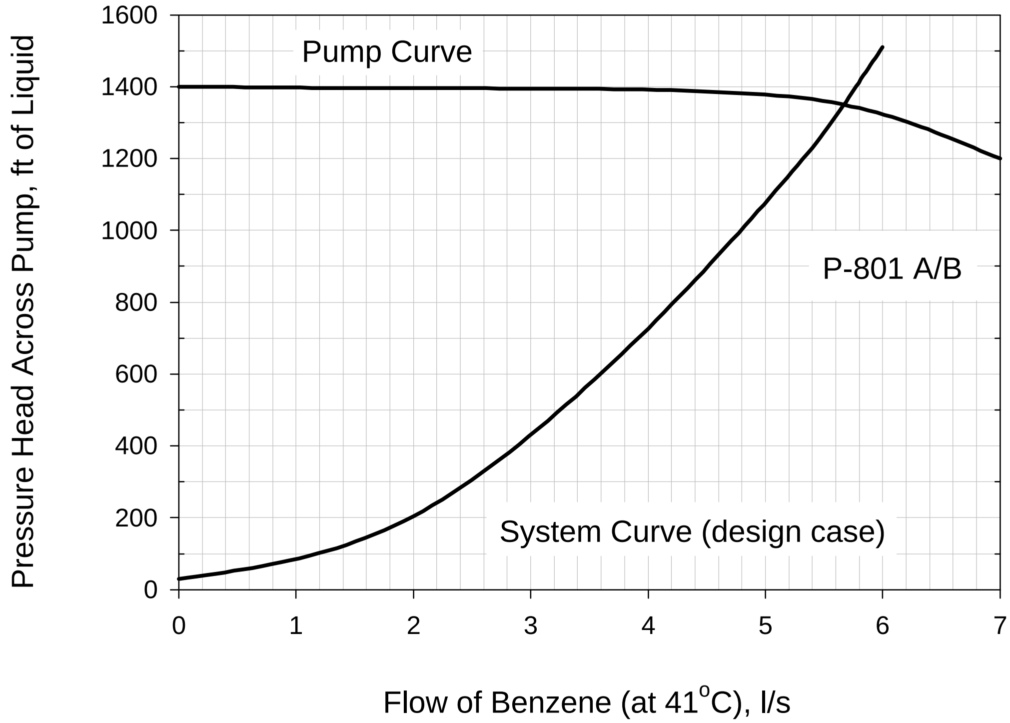


Figure 1: Process Flow Diagram for the Production of Cumene Process (Unit 800)



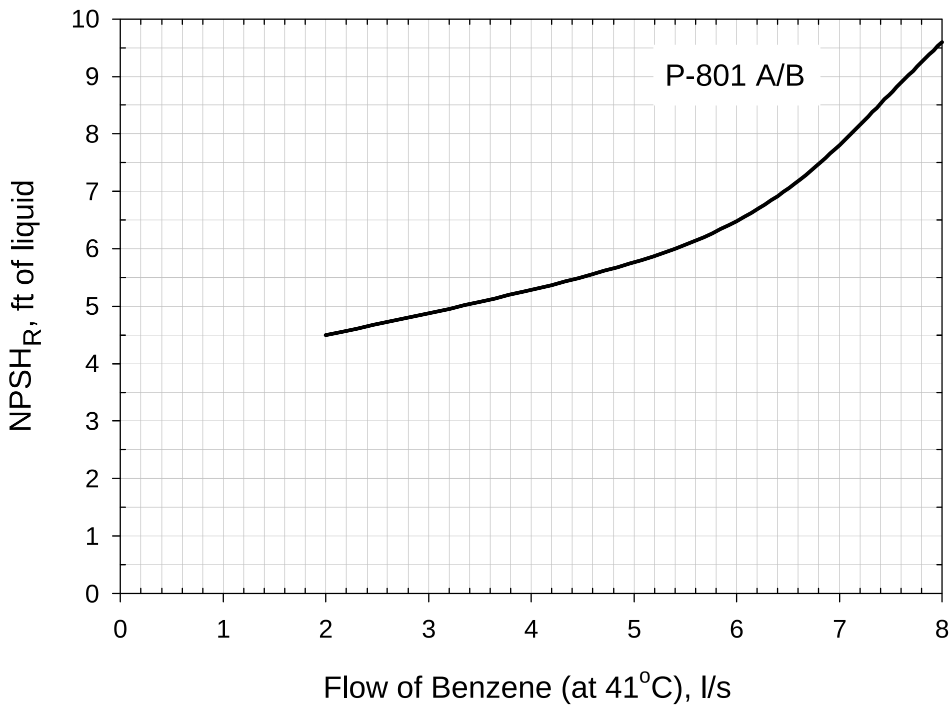


Figure 2: Pump, System and NPSH Curves for P-801 A/B

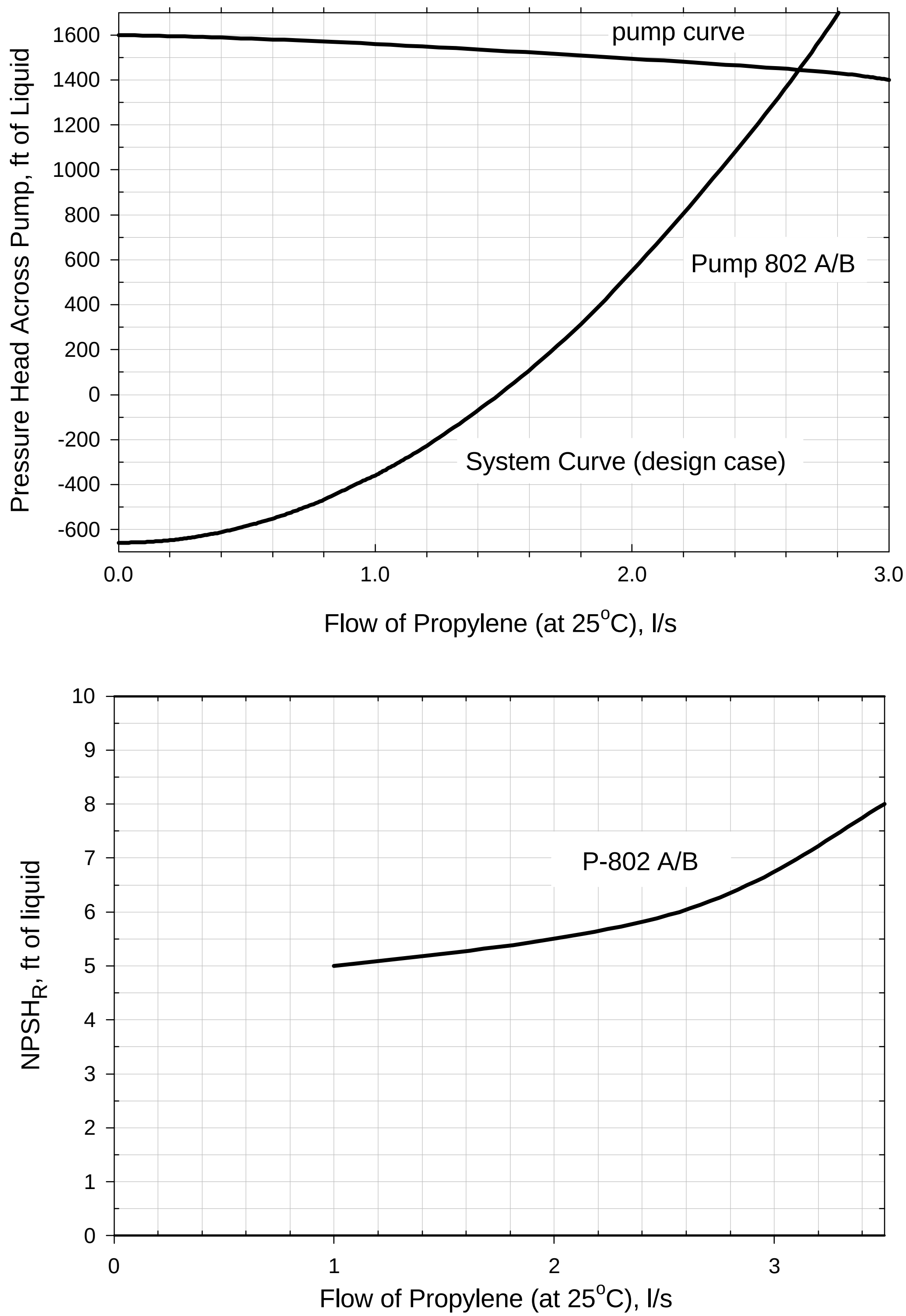


Figure 3: Pump, System, and NPSH Curves for P-802 A/B