# ChE 101.04

# MASS & ENERGY BALANCES PREPARATION & USE

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# Terminal Objective

**Upon completion of this module, you will be able to calculate mass and energy balances and utilize these balances in evaluation of operating facilities.**

# Enabling Objectives

1. Identify data required for a mass balance and sources of losses and gains.

2. Calculate mass and energy balances.

3. Calculate the amount of blowdown or purge required for a recycle system.

4. Identify the pieces of equipment that need to be investigated In order to debottleneck capacity.

# Using Mass and Energy Balances

**Basic Equations**

**Mass Balance**

**Mass In = Mass Out**

**Pounds In = Pounds Out**

**Energy Balance**

**Energy In = Energy Out**

**Btus In = Btus Out**

$$Q = mC_p\Delta t$$

$$Q = m\Delta h$$

**where:**

- **Q = heat duty, Btu/hr**
- **m = mass rate, lbs/hr**
- **Cp = average specific heat, Btu/lb °F**
- **$\Delta$h = change in enthalpy, Btu/lb**
- **$\Delta$t = change in temperature**

# Data Requirements

- Data Required
- Data Sources
- Data Checking

# Figure 1 Fractionator Simulation

FRACTIONATOR OVERHEAD AND LIGHT ENDS

| STREAM ID. ......... | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| STREAM NAME......... | OVERHEAD FROM FRACTIONATOR | SOUR WATER FROM REFLUX DRUM | REFLUX TO FRACTIONATOR | DISTILLATE LIQUID FROM REFLUX DRUM | DISTILLATE VAPOR FROM REFLUX DRUM | 1ST STAGE COMPRESSOR DISCHARGE | 1ST STAGE INTERCOOLER FEED |
| *** WET BASIS *** | | | | | | | |
| *** TOTAL STREAM *** | | | | | | | |
| TEMPERATURE, DEG F | 243.8699 | 109.9998 | 110.0000 | 110.0000 | 110.0000 | 239.9617 | 160.6182 |
| PRESSURE, PSIA | 20.3000 | 16.7000 | 16.7000 | 16.7000 | 16.7000 | 54.0574 | 54.1000 |
| MOLE FRAC LIQUID.... | 0.0000 | 1.0000 | 1.0000 | 1.0000 | 0.0000 | 0.0000 | 0.5243 |
| ENTHALPY M*BTU /HR | 447.0229 | 10.9994 | 2.7255 | 0.3162 | 44.6961 | 58.4291 | 69.4287 |
| RATE LB MOLS/HR | 24522.9375 | 7830.7969 | 6492.9961 | 753.2190 | 6925.2422 | 6925.2422 | 14756.0352 |
| RATE LB /HR | 1204360.0000 | 141071.7500 | 708331.6250 | 82169.6250 | 227375.8120 | 227375.8120 | 368447.4370 |
| STD.RATE K* FT3/DAY | 223348.94 | 71320.94 | 59136.63 | 6860.13 | 63073.42 | 63073.42 | 134394.25 |
| STD. LV RATE BBL/DAY | 116019.44 | 9683.70 | 63529.66 | 7369.75 | 32319.30 | 32319.30 | 42002.98 |
| MOLECULAR WEIGHT.... | 49.1116 | 18.0150 | 109.0916 | 109.0913 | 32.8329 | 32.8329 | 24.9693 |
| AVG. BP (MOLE) F | 129.2372 | 211.9997 | 243.9437 | 243.9434 | -114.4970 | -114.4970 | 58.7701 |
| CRIT. TEMP. F | 495.5847 | 705.5603 | 571.4163 | 571.4158 | 102.3762 | 102.3762 | 422.4744 |
| CRIT. PRES. PSIA | 1712.4731 | 3208.1313 | 452.6282 | 452.6282 | 795.0657 | 795.0657 | 2075.6382 |
| UOP K (MOLE BASIS).. | 12.7069 | 8.7615 | 11.7716 | 11.7716 | 19.5829 | 19.5829 | 13.8402 |
| *** VAPOR PHASE *** | | | | | | | |
| RATE LB MOLS/HR | 24522.9375 | 0.0000 | 0.0000 | 0.0000 | 6925.2422 | 6925.2422 | 7020.0156 |
| RATE LB /HR | 1204360.0000 | 0.0000 | 0.0000 | 0.0000 | 227375.8120 | 227375.8120 | 229082.9370 |
| ACT.RATE FT3/SEC | 2505.77 | 0.00 | 0.00 | 0.00 | 699.06 | 264.00 | 235.68 |
| ACT.DENS LB /FT3 | 0.1335 | 0.0000 | 0.0000 | 0.0000 | 0.0904 | 0.2392 | 0.2700 |
| COMPRESSIBILITY (Z). | 0.9891 | 0.0000 | 0.0000 | 0.0000 | 0.9927 | 0.9881 | 0.9823 |
| VISCOSITY, CP | 0.0108 | 0.0000 | 0.0000 | 0.0000 | 0.0103 | 0.0125 | 0.0112 |
| CP, BTU /LB F | 0.4641 | 0.0000 | 0.0000 | 0.0000 | 0.4428 | 0.5088 | 0.4724 |
| CP/(CP-R) RATIO..... | 1.0955 | 0.0000 | 0.0000 | 0.0000 | 1.1583 | 1.1350 | 1.1480 |
| *** LIQUID PHASE *** | | | | | | | |
| RATE LB MOLS/HR | 0.0000 | 7830.7969 | 6492.9961 | 753.2190 | 0.0000 | 0.0000 | 7736.0117 |
| RATE LB /HR | 0.0000 | 141071.7500 | 708331.6250 | 82169.6250 | 0.0000 | 0.0000 | 139364.1870 |
| ACT.RATE GAL/MIN | 0.00 | 284.35 | 1908.03 | 221.34 | 0.00 | 0.00 | 284.89 |
| STD.DENS(LV) LB /GAL | 0.0000 | 8.3245 | 6.3712 | 6.3712 | 0.0000 | 0.0000 | 8.3245 |
| ACT.DENS LB /GAL | 0.0000 | 8.2687 | 6.1873 | 6.1872 | 0.0000 | 0.0000 | 8.1531 |
| ACT.DENS LB /FT3 | 0.0000 | 61.8537 | 46.2839 | 46.2837 | 0.0000 | 0.0000 | 60.9895 |
| VISCOSITY, CP | 0.0000 | 0.6120 | 0.4019 | 0.4019 | 0.0000 | 0.0000 | 0.3926 |
| CP, BTU /LB F | 0.0000 | 0.9976 | 0.4924 | 0.4924 | 0.0000 | 0.0000 | 1.0007 |
| REID VAPOR PRES,PSIG | 0.0000 | 14.1081 | 6.8816 | 6.8817 | 0.0000 | 0.0000 | 14.1081 |

# Exercise 1.1

***Directions:***

**Check the data on the attached sketch and the table below. Which data appear incorrect? How would these be checked?**

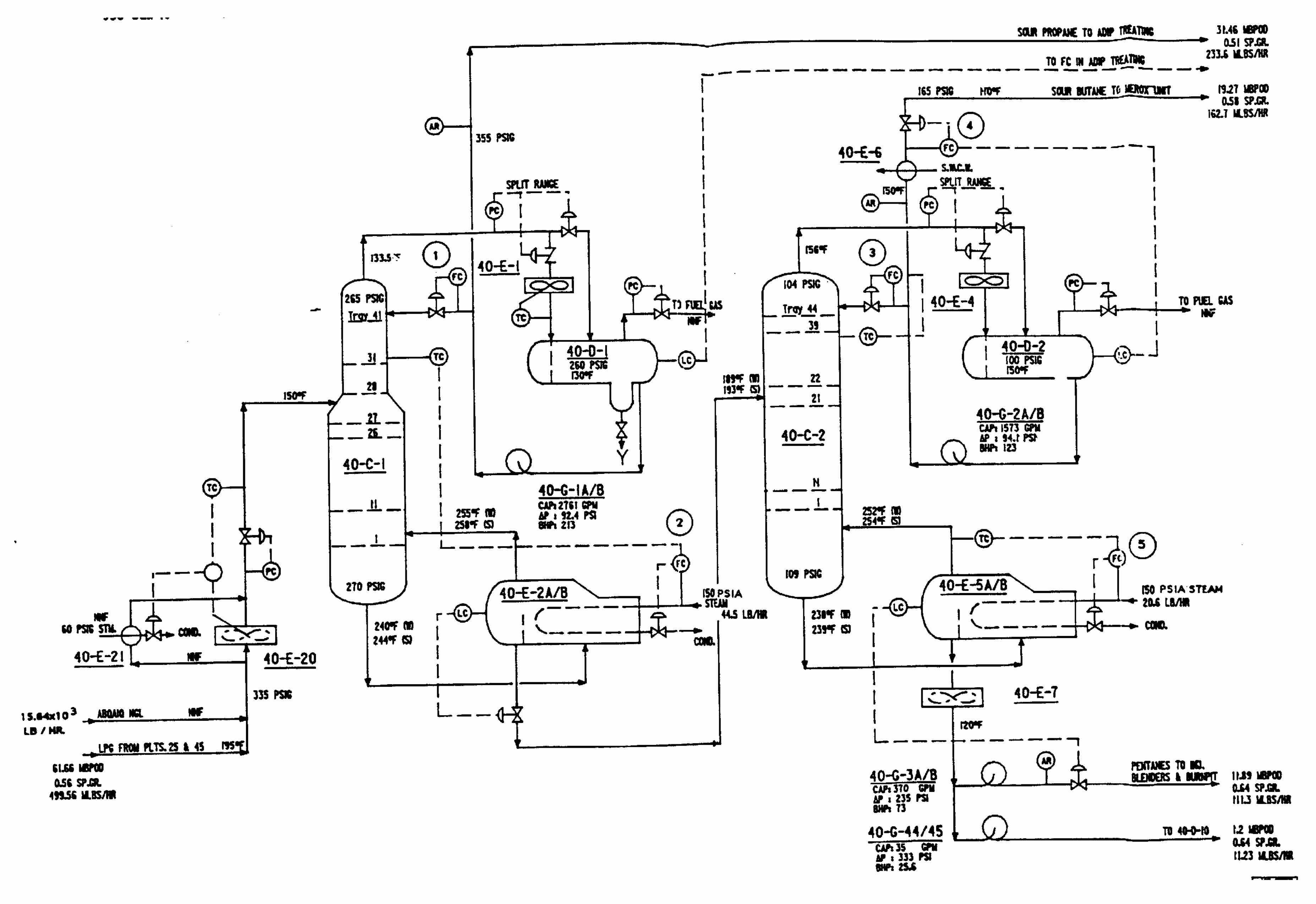
## Plant Data

| | | |
|---|---|---|
| C1 Reflux | FC-1 | 13,450B/D |
| C1 Rblr Stm | FC-2 | 44,500 lb/hr |
| C2 Reflux | FC-3 | 29,454 B/SD |
| Sour C4 Prod | FC-4 | 19,270 B/SD |
| C2 Rblr Stm | FC-5 | 20,600 lb/hr |
| Feed | NGL | 19,000 lb/hr |
| Feed | LPG | 499,560 lb/hr |

## 150 psig Steam Enthalpy Dam

$H_V$ = 1194.10 Btu/lb

$H_L$ = 330.65 Btu/lb




# Figure 5 PFD Debutanizer and Depropanizer

# Exercise 1.1, Cont'd

**Item No. 1:** Check the overall mass balance.

Inlet feed LPG : $499.56 \times 10^3$ lb/hr

Inlet NGL : $19.0 \times 10^3$ lb/hr

Propane out : $31.46 \times 10^3 \times 42 \times \dfrac{0.51 \times 8.33 \text{ lb}}{24} = 233.89 \times 10^3 \text{ lb/hr}$

Butane out : $19.27 \times 10^3 \times 42 \times \dfrac{0.58 \times 8.33 \text{ lb}}{24} = 162.93 \times 10^3 \text{ lb/hr}$

Debutanizer

Bottoms : $(11.89 + 1.2) \times 10^3 \times 42 \times \dfrac{0.64 \times 8.33\, lb}{24} = 122.12 \times 10^3 \; lb/hr$

| In | | Out | |
|---|---|---|---|
| LPG | 499.56 | Propane | 233.89 |
| NGL | 19.00 | Butane | 162.93 |
| | 518.56 | Bottoms | 122.12 |
| | | | 518.94 |

# Exercise 1.1, Cont'd

Item No. 2: Check the C-1 reflux rate.

Pump G-1 rate:

sp.gr. at 60°F = 0.51 from PFD

sp.gr. at 130°F = 0.44 Maxwell, Pg. 140 (for propane)

$$2761\ \frac{\text{gal}}{\text{min}} \times \frac{0.44 \times 8.33\ \text{lb}}{\text{gal}} \times \frac{60\ \text{min}}{\text{hr}} = 607.18 \times 10^3\ \text{lb/hr}$$

Propane product rate = $233.89 \times 10^3$ lb/hr

Reflux = 607.18 – 233.89 = $373.29 \times 10^3$ lb/hr

$$= 373.29 \times 10^3\ \frac{\text{lb}}{\text{hr}} \times \frac{\text{gal}}{0.51 \times 8.33\ \text{lb}} \times \frac{24\ \text{hr}}{\text{D}} \times \frac{\text{B}}{42\ \text{gal}} = 50{,}210\ \text{B/D @ } 60^\circ\text{F}$$

Reflux per FC-1 = 13,450 B/D

# Exercise 1.1, Cont'd

Item No. 3: Check the C-2 reflux rate.

Pump G-2 rate:

sp.gr. at 60$^o$F = 0.58

sp.gr. at 150$^o$F = 0.524 Maxwell, Pg. 140

(Note : check if 60$^o$F point falls on N-$C_4$ curve.)

$$1573\ \frac{gal}{min}\ \times\ 0.524\ \times\ 8.33\ \times\ \frac{lb}{gal}\ \times\ \frac{60\ min}{hr} = 411.96\ \times\ 10^3\ lb/hr$$

Butane rate = 162.93 x $10^3$ lb/hr

Reflux = 411.96 – 162.93 = 249.03 x $10^3$ lb/hr

$$= 249.03\ \times\ 10^3\ \frac{lb}{hr}\ \times\ \frac{gal}{0.58\ \times\ 8.33\ lb}\ \times\ \frac{B}{42\ gal}\ \times\ \frac{24\ hr}{D} = 29{,}454\ \frac{B}{D}$$

Reflux per FC-3 = 29,454 B/D

## Exercise 1.1, Cont'd

**Item No. 4: Check the C-2 bottoms rate.**

**sp.gr. at 60$^o$F = 0.64**

**sp.gr. at 120$^o$F = 0.61 Maxwell, Pg. 140**

**Note : 60$^o$F point falls just above the $C_5$ curve.**

**Maintaining the same distance, read 0.61 at 120$^o$F.**

**Pump G-3/44 rate:**

$$(370+35)\frac{gal}{\min}\ x\ 0.61\ x\ 8.33\ x\frac{lb}{gal}\ x\frac{60\min}{hr} = 123.47\ x\ 10^3\ lb/hr$$

$$= 123.47\ x\ 10^3\ x\frac{gal}{0.64\ x\ 8.33\ lb}\ x\frac{24}{42}$$

**= 13,235 B/D**

**PFD rate = 11,890 + 1,200 = 13,090 B/D**

# Exercise 1.1, Cont'd

Item No. 5: Check reboiler heat inputs.

| Exchanger | PFD Q, Btu/hr | Steam rate, lb/hr |
|---|---|---|
| E-2 | $44.5 \times 10^6$ | 44,500 |
| E-5 | $20.6 \times 10^6$ | 20,600 |

| | | |
|---|---|---|
| $H_V$ steam | = | 1194.1 Btu/lb |
| $H_L$ | = | 330.65 |
| Net Q, Btu/lb | = | 863.45 |

$$Q_{E2} = 44{,}500 \ \frac{lb}{hr} \times 863.45 \ Btu/lb = 38.4 \times 10^6 \ Btu/hr$$

$$Q_{E5} = 20{,}600 \times 863.45 = 17.8 \times 10^6 \ Btu/hr$$

# Exercise 1.1, Cont'd

1. Overall Mass Balance – OK (Check Gas to Fuel)
2. FC-1 13, 450 B/D, Pump 50, 210 B/D – Field Check Required
3. FC-3 & Pump Check – OK
4. PFD & Pump Check – OK
5. PFD & Calc Q – Calc Q Lower – Field Check

# Mass Balance Preparation

- Define Data Required
  - New Unit
  - Revised Unit
  - Operating unit

- Correcting Meter Readings

# Balances Around an Operating Unit

## New

- Product Specifications Govern
- Designer Responsible for Economical Process Design

## Changed

- Equipment Configuration Established
- Run Programs
  - Distillation
  - Heat Exchanger
- Determine Equipment Limitations

# Balances Around an Operating Unit

- Determine How Unit is Operating
- Determine What is Being Produced
- Analysis Made on Fuels and
- Calculate Heat Duties, etc.
- Check Data for Consistency and Reasonableness
- Determine Scope of the Balance

# Correcting Meter Readings

- Ensure Meter Factors Are Accurate for Test
- Constants Include All Variables
- For Liquids

$$Q_{vol/time} = \text{Constant}\sqrt{\frac{\text{sp.gr.cond.}}{\text{sp.gr.at 60}}}\sqrt{\Delta P}$$

$$W_{weight/time} = \text{Constant}\sqrt{\text{sp.gr.cond.}}\sqrt{\Delta P}$$

- For Gas

$$W_{weight/time} = \text{Constant}\sqrt{\frac{(MW)(P)}{10.73\,T_F\,Z_F}}\sqrt{\Delta P}$$

# Liquid or Gases

- Given Changes to Original Calculations, then
- For Liquids

$$\text{Actual vol/time} = \text{Flow reading} \times \sqrt{\frac{\rho_A}{\rho_{AM}}} \times \frac{\rho_{60M}}{\rho_{60A}}$$

$$\text{Actual weight/time} = \text{Flow reading} \times \sqrt{\frac{\rho_A}{\rho_{AM}}}$$

- For Gases

$$\text{Vapor density} = \rho = \frac{MW\ P}{10.73\ T\ Z}$$

## Example Problem 1

### LABORATORY ANALYSIS DATA

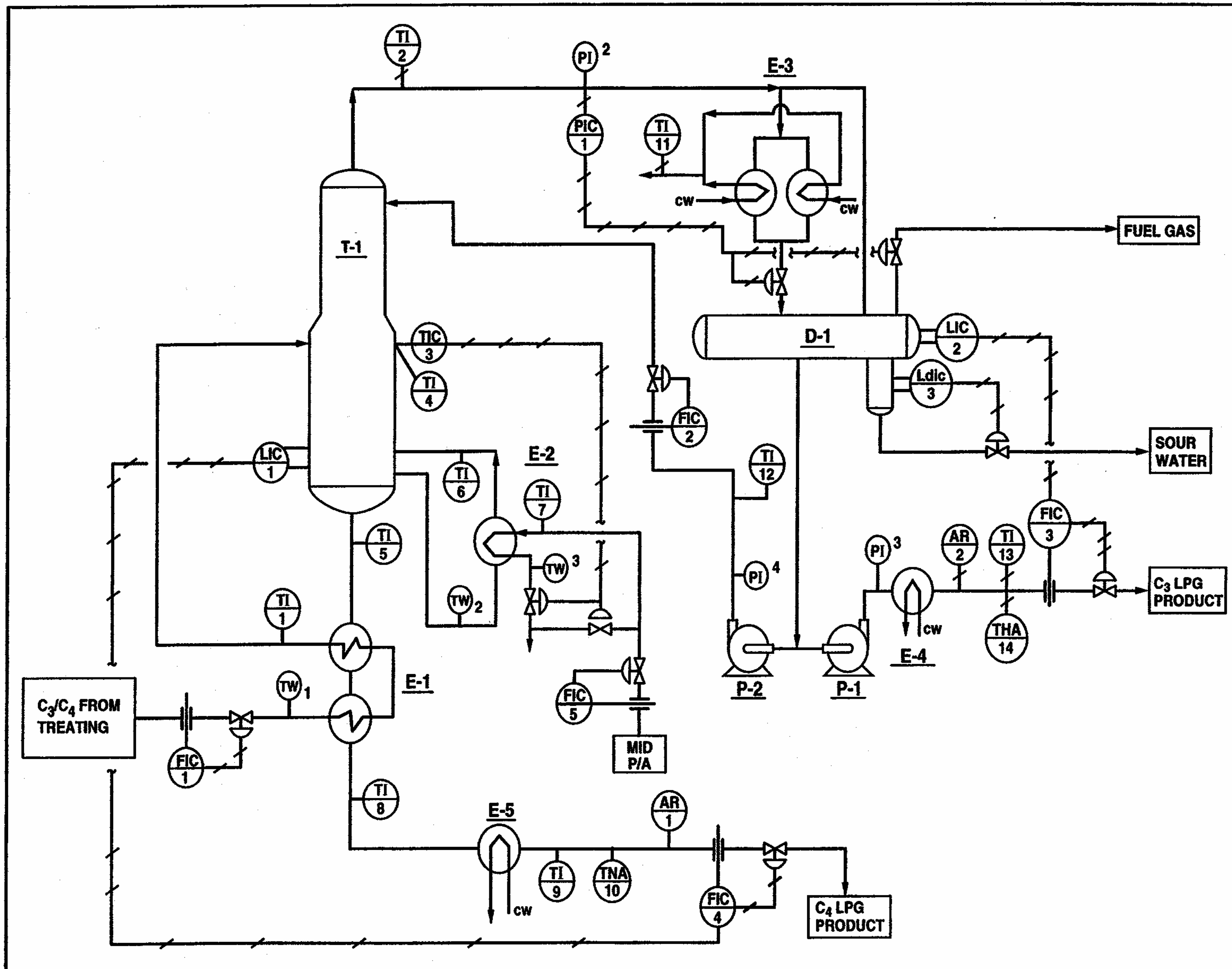
| | Feed Mole% | $C_3$ LPG Mole % | $C_4$ LPG. Mole % |
|---|---|---|---|
| MW | 50.92 | 42.8 | 57.8 |
| API | 121 | 143 | 108.5 |
| MoABP | -8.87 | -50.4 | 22.1 |
| K | 12+ | 12+ | 12+ |
| Sp. Gr. | 0.5604 | 0.5155 | 0.5896 |

# Example Problem 1, Cont'd

## PLANT DATA

| | | |
|---|---|---|
| Feed | FIC 1 | 8,237 B/D |
| Reflux | FIC-2 | 8,296 |
| $C_3$ OH Prod. | FIC-3 | 3,158 |
| $C_4$ Bottom Prod. | FIC-4 | 4,920 |
| PA | FIC-5 | 73,050 |
| Feed | TW-1 | 100°F |
| $C_4$ Bottom Prod. | TI-9 | 100°F |
| Reflux | TI-12 | 107.7°F |
| $C_3$ OH Prod. | TI-13 | 100°F |
| Tower OH | PIC-1 | 220 psig |
| $P_1$ Disch. ($C_3$ OH Prod.) | PI 3 | 357 psig |

Figure 2 C3/C4 Splitter



# Example Problem 1, Cont'd

| | FIC-1 | FIC-3 | FIC-4 |
|---|---|---|---|
| **Instrument Records** | | | |
| $Sp.Gr._{60}$ | 0.550 | 0.515 | 0.589 |
| $SP.GR._{fluid}$ | 0.509 | 0.456 | 0.538 |
| | | | |
| **Laboratory APIa** | | | |
| $Sp.\ Gr._{60}$ | 0.561 | 0.515 | 0.589 |
| Temp | 100°F | 100°F | 100°F |
| $Sp.Gr._{fluid}$ | 0.530 | 0.479 | 0.565 |

$$V_{actual} = V_{reading} \times$$

$$\sqrt{\frac{sp.gr._{A}}{sp.gr._{AM}}} \times \frac{sp.gr._{60\ M}}{sp.gr._{60\ A}}$$

# Example Problem 1, Cont'd

$$FIC\text{-}1 = 8237 \times \sqrt{\frac{0.530}{0.509}} \times \frac{0.55}{0.561} = 8279\ B/SD$$

$$FIC\text{-}3 = 3158 \times \sqrt{\frac{0.479}{0.456}} \times \frac{0.515}{0.515} = 3237\ B/D$$

$$FIC\text{-}4 = 4920 \times \sqrt{\frac{0.565}{0.538}} \times \frac{0.589}{0.589} = 5042\ B/D$$

## Example Problem 1, Cont'd

**Overall balance:**

| | | | B/D | lbs/hr |
|---|---|---|---|---|
| Feed = | 8279 B/D | Products | 3237 | 24,301 |
| | 67,705 lbs/hr | | 5042 | 43,304 |
| | | | 8279 | 67,665 (0.06%) |

**Note the results if uncorrected:**

| | | B/D | lke/hr |
|---|---|---|---|
| Feed = 8237 | Products | 3158 | 23,708 |
| = 67,361 lbs/hr | | 4920 | 42,256 |
| | | 8078 | 65,964 (2.07%) |

# Exercise 1.2

***Directions:***

**Using the following Process Flow Diagram, discuss with the instructor what plant data are required to prepare a mass balance around the unit. Assume pressure and temperature measurements can be made where required.**

***Answer:***

**Lead a discussion on the data required.**

**Liquid flows require gravity and temperature of fluid to correct meters.**

**Vapor (gas) flows require molecular weight or specific gravity, temperature and pressure of fluid to correct meters.**

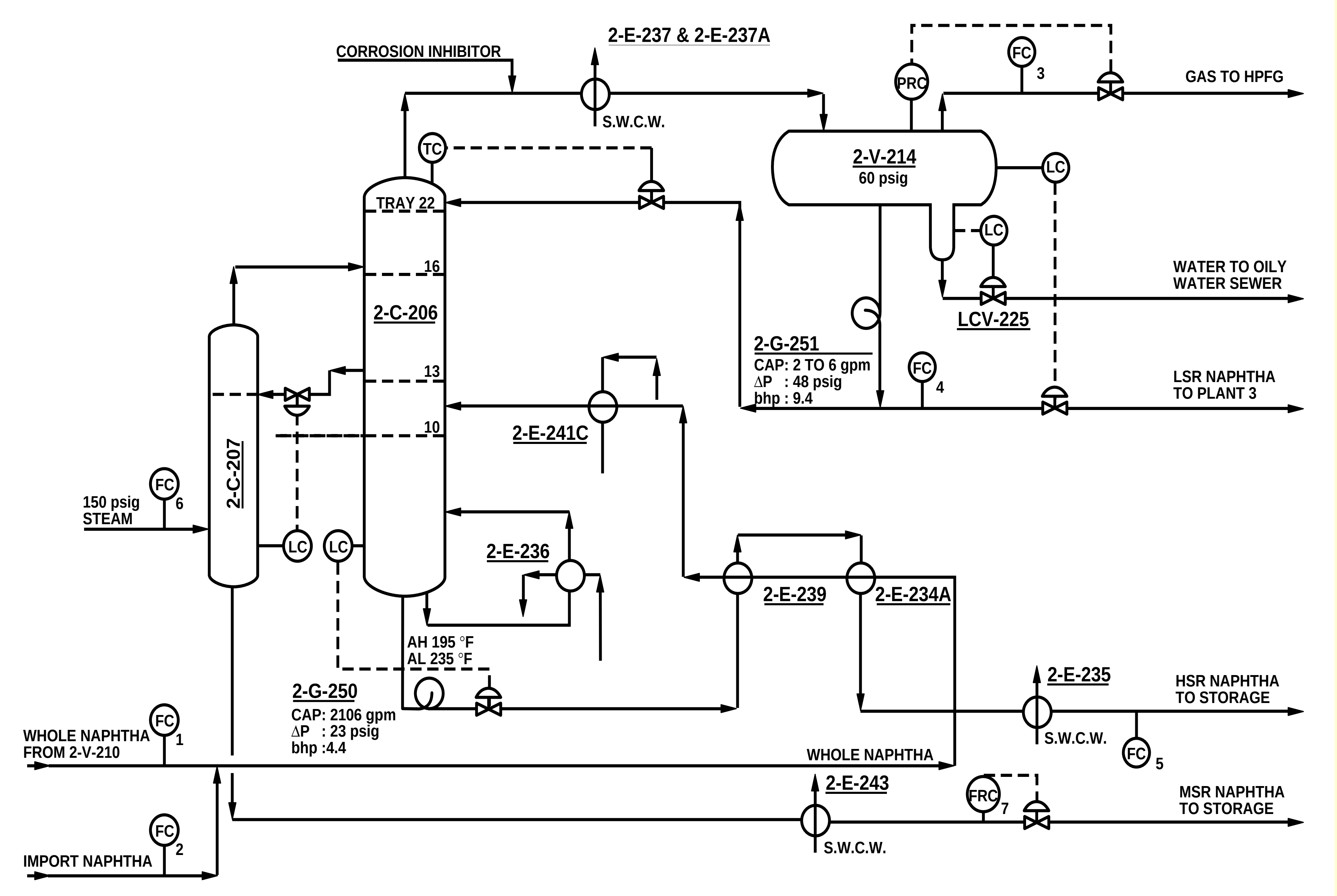
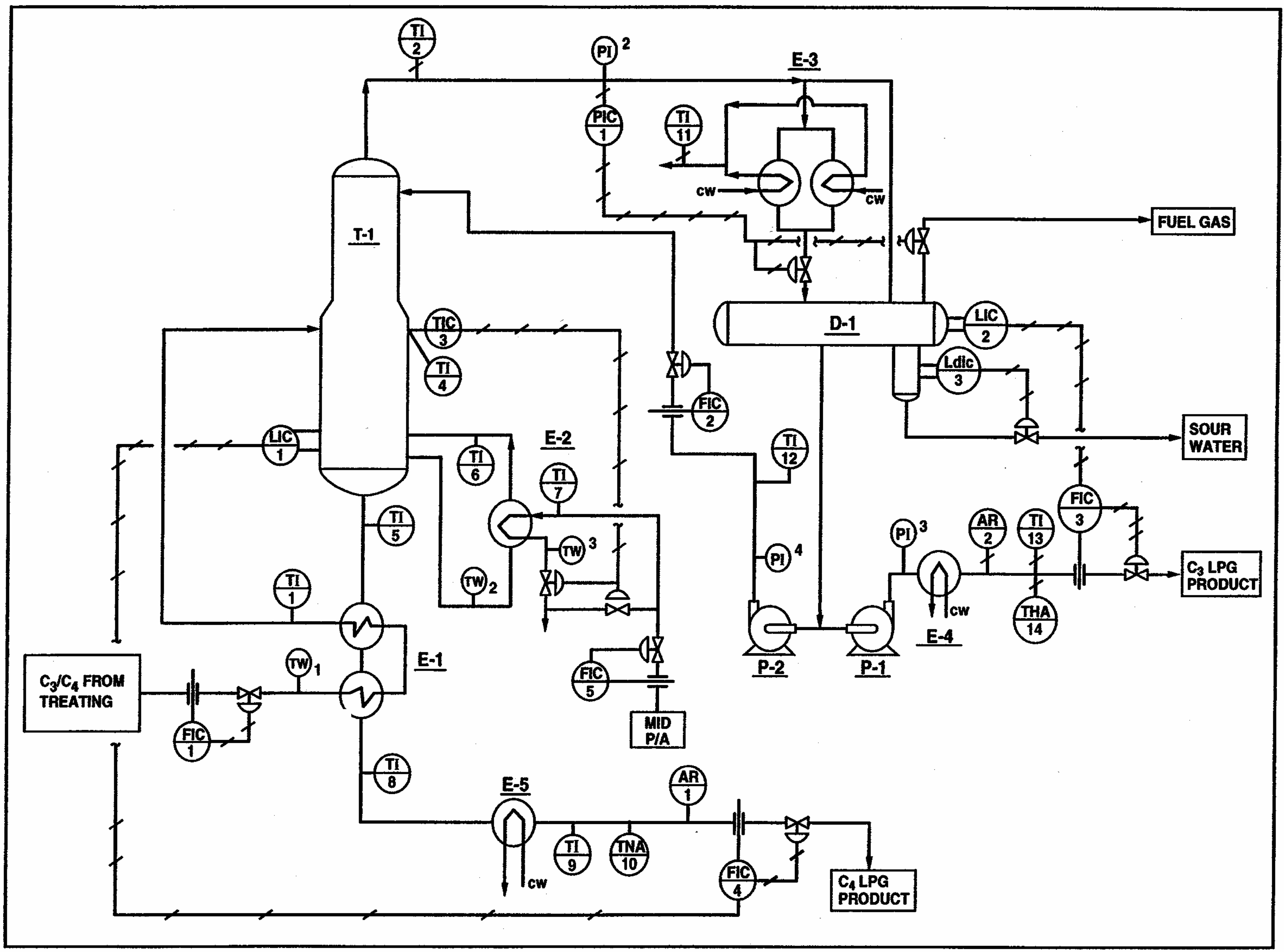



**Figure 6 PFD CDU's 1 & 2**

# Exercise 2

Figure 7 C3/C4 Splitter



# Exercise 2

***Answer:***

**Check the overall balance:**

| | | | B/D | lbs/Hr |
|---|---|---|---|---|
| FIC-1 | 8,279 B/D | FIC-3 | 3237 | 24,301 |
| | 67,705lbs/hr | FIC-4 | 5042 | 43,304 |
| | | | 8279 | 67,665 |

**Write these values on the sketch.**

# Exercise 2, Cont'd

*Answer*

| | | | sp. gr. |
|---|---|---|---|
| 2. | Feed API from analysis | = 121 | .5604 |
| | $C_3$ LPG | = 143 | .5155 |
| | $C_4$ LPG | = 108.5 | .5896 |

Write these values on the sketch.

# Exercise 2, Cont'd

Pump rates - $C_3$ LPG

60°F 143°API = 0.516 Sp.Gr. (LPG)

Temperature = 107.7°F

Maxwell, Pg. 140 propane @ 108°F = 0.462 sp.gr.

Maxwell, Pg. 2 propane @ 60°F = 0.508 sp.gr.

$$P-1\ \text{rate} = 3237 \ \text{x} \ \frac{D}{24\,\text{hr}} \ \text{x} \ \frac{\text{hr}}{60\,\text{min}} \ \text{x} \ \frac{42\,\text{gal}}{\text{bbl}} \ \text{x} \ \frac{0.508\ \text{Sp.Gr. at } 60^\circ\text{F}}{0.462\ \text{Sp.Gr. at cond.}} = 103.8\ \text{gpm}$$

$$P-2\ \text{rate} = \frac{8296}{3237} \ \text{x} \ 103.8 = 266.0$$ gpm

## Exercise 2, Cont'd

**E-1 Feed/Bottoms Exchanger**

**Temperature = TI-5 in, TI-8 out**

**$205^oF$ $123^oF$**

**$C_4$ product data : 5042 B/D, $108.5^o$API, 22.1 MoABP**

**$Sp.Gr._{60}$ = 0.5896**

$$\text{Rate} = 5042\ \frac{B}{D} \times \frac{D}{24\,hr} \times \frac{42\,gal}{B} \times \frac{0.5896 \times 8.33\,lb}{gal} = 43{,}365\,lb/hr$$

**Heat capacity :**

| Temperature | $205^oF$ | $123^oF$ |
|---|---|---|
| $C_p$ + B | 0.81 | 0.75 |
| B | -0.17 | -0.17 |
| $C_p$ | 0.64 | 0.58 Ave. = 0.61 |

$$Q = mC_P\Delta T = 43{,}365 \times 0.61 \times (205-123) = 2.17 \times 10^6 Btu/hr$$

## Exercise 2, Cont'd

E-4 $C_3$ product cooler

Stream data : 3237 B/D, 143°API, 42.8 MW, -50.4 MoABP, K =12 +

At 60°F 143°API = 0.516 Sp.Gr.

$$\text{Rate} = 3237 \times \frac{B}{D} \times \frac{42}{24} \times 0.516 \times 8.33 = 24{,}349 \text{ lb/hr}$$

| | | |
|---|---|---|
| Temperature = | TI-12 | TI-13 |
| | 107.7°F | 100°F |
| Heat capacity: | 107.7°F | 100°F |
| Propane H, Btu/lb | 176 | 170 (Maxwell, Pg. 100) |

(Cannot use the API chart, since it is beyond the range for $C_p$ on Maxwell, Pg. 93.)

$$Q = (176-170) \times \frac{\text{Btu}}{\text{lb}} \times 24{,}349 \frac{\text{lb}}{\text{hr}} = 0.146 \times 10^6 \text{ Btu/hr}$$

# Exercise 2, Cont'd

E-2 Reboiler – Use the heating media side

Temperature 324.8 in 301.2 out

Data 73,050 B/D, 38.6$^{o}$API, 347.4 MoABP

Sp.Gr. at 60$^{o}$F = 0.831

$$\text{Rate} = 73{,}050 \times \frac{42}{24} \times 0.831 \times 8.33 = 884{,}920 \text{ lb/hr}$$

Heat capacity :

| Temperature | 325$^{o}$F | 301$^{o}$F |
| --- | --- | --- |
| $C_p$ + B = | 0.635 | 0.620 |
| B | -0.052 | -0.052 |
| $C_p$ | 0.583 | 0.568 Ave. = 0.575 |

Q = 884,920 x 0.575 x (325-301) = 12.2 x 10$^{6}$Btu/hr

## Exercise 2, Cont'd

E-5 $C_4$ product cooler.

Rate is same as E-1 = 43,365 lb/hr

| Temperature | 123°F | 100°F |
|---|---|---|
| $C_p$ + B = | 0.75 | 0.735 |
| B | -0.17 | -0.17 |
| $C_p$ | 0.58 | 0.565 Ave. = 0.572 |

Q = 43,365 x 0.572 x (123-100) = 0.57 x $10^6$ Btu/hr