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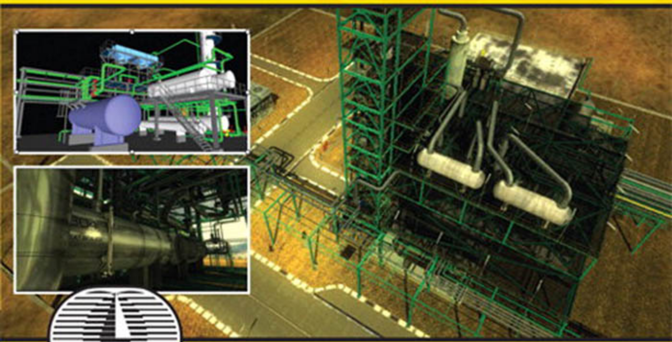
PRENTICE HALL

ANALYSIS, SYNTHESIS, AND DESIGN OF CHEMICAL PROCESSES

FOURTH EDITION

RICHARD TURTON • RICHARD C. BAILIE • WALLACE B. WHITING
JOSEPH A. SHAEIWITZ • DEBANGSU BHATTACHARYYA



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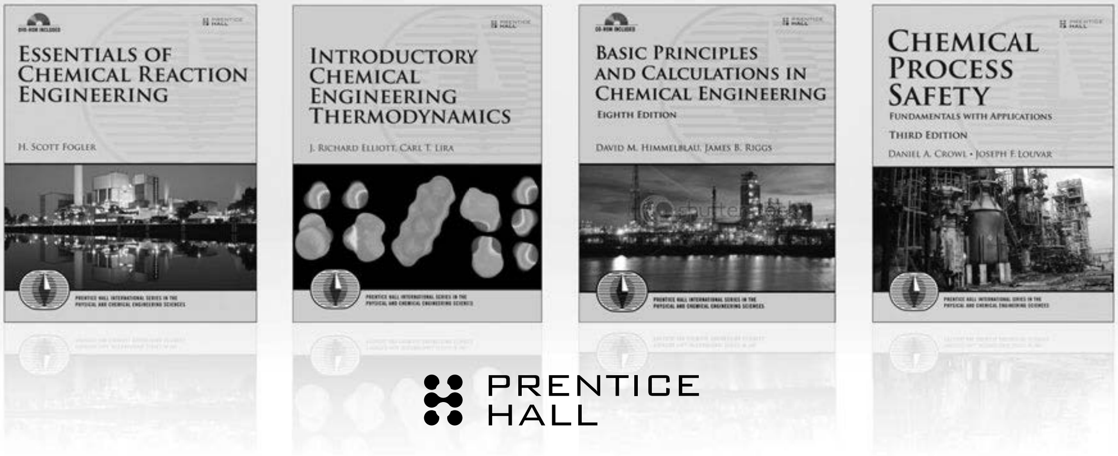

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Preface

This book represents the culmination of many years of teaching experience in the senior design course at West Virginia University (WVU) and University of Nevada, Reno. Although the program at WVU has evolved over the past 35 years and is still evolving, it is fair to say that the current program has gelled over the past 25 years as a concerted effort by the authors to integrate design throughout the undergraduate curriculum in chemical engineering.

We view design as the focal point of chemical engineering practice. Far more than the development of a set of specifications for a new chemical plant, design is the creative activity through which engineers continuously improve the operations of facilities to create products that enhance the quality of life. Whether developing the grassroots plant, proposing and guiding process modifications, or troubleshooting and implementing operational strategies for existing equipment, engineering design requires a broad spectrum of knowledge and intellectual skills to be able to analyze the big picture and the minute details and, most important, to know when to concentrate on each.

Our vehicle for helping students develop and hone their design skills is process design rather than plant design, covering synthesis of the entire chemical process through topics relating to the preliminary sizing of equipment, flowsheet optimization, economic evaluation of projects, and the operation of chemical processes. The purpose of this text is to assist chemical engineering students in making the transition from solving well-posed problems in a specific subject to integrating all the knowledge that they have gained in their undergraduate education and applying this information to solving open-ended process problems. Many of the nuts-and-bolts issues regarding plant design (for example, what schedule pipe to use for a given stream or what corrosion allowance to use for a vessel in a certain service) are not covered. Although such issues are clearly important to the practicing engineer, several excellent handbooks and textbooks are available to address such problems, and these are cited in the text where applicable.

In the fourth edition, we have rearranged some of the material from previous editions, and we have added two new chapters on advanced concepts in steady-state simulation (Chapter 16) and dynamic simulation of processes (Chapter 17). We have also added extensive material on the choice of thermodynamics package to use for modeling processes containing electrolyte solutions and solids (Chapter 13) and a brief introduction to logic control (Chapter 18). Additional pedagogical material has been added to each chapter to outline the key concepts and major lessons to be learned from each chapter.

We continue to emphasize the importance of understanding, analyzing, and synthesizing chemical processes and process flow diagrams. To this end, we have expanded Appendix B to include an additional four (making a total of 15) preliminary designs of chemical processes. All the projects have been moved to the CD accompanying the text, along with the chapters on outcomes assessment, written and oral communications, and a written report case study and the projects from Appendix C of the first edition.

The arrangement of chapters into the six sections of the book is similar to that adopted in the second edition. These sections are as follows:

- Section I—Conceptualization and Analysis of Chemical Processes
- Section II—Engineering Economic Analysis of Chemical Processes
- Section III—Synthesis and Optimization of Chemical Processes
- Section IV—Analysis of Process Performance
- Section V—The Impact of Chemical Engineering Design on Society
- Section VI—Interpersonal and Communication Skills

In Section I, the student is introduced first to the principal diagrams that are used to describe a chemical process. Next, the evolution and generation of different process configurations are covered. Key concepts used in evaluating batch processes are included in Chapter 3, and the concepts of product design are given in Chapter 4. Finally, the analysis of existing processes is covered. In Section II, the information needed to assess the economic feasibility of a process is covered. This includes the estimation of fixed capital investment and manufacturing costs, the concepts of the time value of money and financial calculations, and finally the combination of these costs into profitability measures for the process. Section III covers the synthesis of a chemical process. The minimum information required to simulate a process is given, as are the basics of using a process simulator. The choice of the appropriate thermodynamic model to use in a simulation is covered, and the choice of separation operations is covered. Process optimization (including an introduction to optimization of batch processes) and heat integration techniques are covered in this section. In addition, new material on advanced concepts using steady-state process simulators (Chapter 16) and the use of dynamic simulators (Chapter 17) has been added, and the chapter on process regulation has been expanded and rounds out Section III. In Section IV, the analysis of the performance of existing processes and equipment is covered. The material in Section 4 is substantially different from that found in most textbooks. We consider equipment that is already built and operating and analyze how the operation can be changed, how an operating problem may be solved, and how to analyze what has occurred in the process to cause an observed change. In Section V, the impact of chemical engineering design on society is covered. The role of the professional engineer in society is addressed. Separate chapters addressing ethics and professionalism, health, safety, and the environment, and green engineering are included. Finally, in Section VI, the interpersonal skills required by the engineer to function as part of a team and to communicate both orally and in written form are covered (on the CD). An entire chapter (on the CD) is devoted to addressing some of the common mistakes that students make in written reports.

Finally, three appendices are included. Appendix A gives a series of cost charts for equipment. This information is embedded in the CAPCOST program for evaluating fixed capital investments and process economics. Appendix B gives the preliminary design information for 15 chemical processes: dimethyl ether, ethylbenzene, styrene, drying oil, maleic anhydride, ethylene oxide, formalin, batch manufacture of amino acids, acrylic acid, acetone, heptenes production, shift reaction, acid-gas removal by a physical solvent, the removal of H_2S from a gas stream using the Claus process, and finally coal gasification. Appendix B is now located on the CD accompanying the book. This information is used in many of the end-of-chapter problems in the book. These processes can also be used as the starting point for more detailed analyses—for example, optimization studies. Other projects, given in Appendix C, are also included on the CD book. The reader (faculty and students) is also referred to our Web site at www.che.cemr.wvu.edu/publications/projects/, where a variety of design projects for sophomore- through senior-level chemical engineering courses is provided. There is also a link to another Web site that contains environmentally related design projects.

For a one-semester design course, we recommend including the following core:

- Section I—Chapters 1 through 6
- Section III—Chapters 11, 12, and 13
- Section V—Chapters 25 and 26

For programs in which engineering economics is not a prerequisite to the design course, Section II (Chapters 7–10) should also be included. If students have previously covered engineering economics, Chapters 14 and 15 covering optimization and pinch technology could be substituted.

For the second term of a two-term sequence, we recommend Chapters 19 through 23 (and Chapters 14 and 15 if not included in the first design course) plus a design project. Alternatively, advanced simulation techniques in Chapters 16 and 17 could be covered. If time permits, we also recommend Chapter 18 (Regulation and Control of Chemical Processes with Applications Using Commercial Software) and Chapter 24 (Process Troubleshooting and Debottlenecking) because these tend to solidify as well as extend the concepts of Chapters 19 through 23, that is, what an entry-level process engineer will encounter in the first few years of employment at a chemical process facility. For an environmental emphasis, Chapter 27 could be substituted for Chapters 18 and 24; however, it is recommended that supplementary material be included.

We have found that the most effective way both to enhance and to examine student progress is through oral presentations in addition to the submission of written reports. During these oral presentations, individual students or a student group defends its results to a faculty panel, much as a graduate student defends a thesis or dissertation.

Because design is at its essence a creative, dynamic, challenging, and iterative activity, we welcome feedback on and encourage experimentation with this design textbook. We hope that students and faculty will find the excitement in teaching and learning engineering design that has sustained us over the years.

Finally, we would like to thank those people who have been instrumental to the successful completion of this book. Many thanks are given to all undergraduate chemical engineering students at West Virginia University over the years, particularly the period 1992–2011. In particular, we would like to thank Joe Stoffa, who was responsible for developing the spreadsheet version of CAPCOST, and Mary Metzger and John Ramsey, who were responsible for collecting and correlating equipment cost information for this edition. We also acknowledge the many colleagues who have provided, both formally and informally, feedback about this text. Finally, RT would like to thank his wife, Becky; JAS would like to thank his wife, Terry; and DB would like to thank his parents, Sambhunath and Gayatri, wife Pampa, and son Swagat for their continued support, love, and patience during the preparation of this fourth edition.

R.T.
R.C.B.
W.B.W.
J.A.S.
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List of Nomenclature

Symbol	Definition	SI Units
A	Equipment Cost Attribute	
A	Area	m^2
A	Absorption Factor	
A	Annuity Value	\$/time
$A/F, i, n$	Sinking Fund Factor	
$A/P, i, n$	Capital Recovery Factor	
A_b	Bubbling Area	m^2
A_c	Cross-Sectional Area	m^2
a	Interfacial Area	m^2
a	Mean Ionic Diameter of an Electrolyte	m
a'	Interface Area per Unit Volume	m^2/m^3
BV	Book Value	\$
C	Molar Density	mol/m^3
C	Equipment Cost	\$
C or c	Molar Concentration	$kmol/m^3$
CA	Corrosion Allowance	m
CBM	Bare Module Cost	\$
COM	Cost of Manufacture	\$/time
cop	Coefficient of Performance	
C_p	Heat Capacity	kJ/kg°C or kJ/kmol°C
CCP	Cumulative Cash Position	\$
CCR	Cumulative Cash Ratio	
D	Diffusivity	m^2/s
D	Diameter	m
D	Amount Allowed for Depreciation	\$
D	Distillate Product Flowrate	kmol/time
d	Yearly Depreciation Allowance	\$/yr
$DCFROR$	Discounted Cash Flow Rate of Return	
DMC	Direct Manufacturing Cost	\$/time
$DPBP$	Discounted Payback Period	years
$\bar{D}$	Average Diffusivity	m^2/s
D_0	Diffusivity at Infinite Dilution	m^2/s
$\mathbf{d}$	Vector of Disturbance Inputs	

d_s	Average Solvent Density	kg/m^3
e	Elementary Charge	Columb
E	Money Earned	\$
E	Weld Efficiency	
E_{act} or E	Activation Energy	kJ/kmol
EAOC	Equivalent Annual Operating Cost	\$/yr
ECC	Equivalent Capitalized Cost	\$
F	Faraday's Constant	Columb/kmol
f_q	Quantity Factors for Trays	
F	Future Value	\$
F	Molar Flowrate	kmol/s
F	Equipment Module Cost Factor	
F	Correction for Multipass Heat Exchangers	
F	Future Value	\$
F_d	Drag Force	N/m^2 or kPa
f	Friction Factor	
f	Rate of Inflation	
$F/A, i, n$	Uniform Series Compound Amount Factor	
FCI	Fixed Capital Investment	\$
$F/P, i, n$	Single Payment Compound Amount Factor	
FMC	Fixed Manufacturing Costs	\$/time
F_{Lang}	Lang Factor	
f_i	Fugacity of Pure Component *i*	bar or kPa
$\hat{f}_i$	Fugacity of Component *i* in Mixture	bar or kPa
$\boldsymbol{f}$	System of Equations (vector)	
G	Gibbs Free Energy	kJ
G	Gas Flowrate	kg/s, kmol/s
GE	General Expenses	\$/time
H	Henry's Law Constant	bar or kPa in Equation (13.5), but can be different elsewhere
h	Individual Heat Transfer Coefficient	W/m^2K
H	Enthalpy or Specific Enthalpy	kJ or kJ/kg
H	Height	m
h_f	Froth Height in a Tray	m
$\boldsymbol{I}$	Identity Matrix	
I	Ionic Concentration	$kmol/m^3$
I_x	Ionic Strength on a Mole Fraction Basis	
I	Cost Index	
i	Compound Interest	
i'	Effective Interest Rate Including Inflation	
INPV	Incremental Net Present Value	\$
IPBP	Incremental Payback Period	years
$\boldsymbol{J}$	Jacobian Matrix	

k	Thermal Conductivity	W/m K
k_o	Preexponential Factor for Reaction Rate Constant	Depends on molecularity of reaction
K_p	Equilibrium Constant	Depends on reaction stoichiometry
k_{reac} or k_i	Reaction Rate Constant	Depends on molecularity of reaction
K_c	Proportional Gain	
K_{cu}	Ultimate Controller Gain	
K_{eq}	Equilibrium Constant of a Chemical Reaction	
K_i	Vapor-Liquid Equilibrium Ratio of Species i	
k_B	Boltzmann Constant	kJ/K
$\overline{k}_m$	Average Mass Transfer Coefficient	m/s
L	Lean Stream Flowrate	kg/s
L	Liquid Flowrate	kg/s or kmol/s
$\dot{m}$	Flowrate	kg/s
m	Partition Coefficient (y/x)	
M	Mass	kg
m	Molality	kmol/kg
n	Life of Equipment	years
n	Years of Investment	years
n	Number of Batches	
n_c	Number of Campaigns	
N	Number of Streams	
N	Number of Trays, Stages, or Shells	
N	Molar Flowrate	kmol/s
$NPSH$	Net Positive Suction Head	m of liquid
NPV	Net Present Value	$
N_{toG}	Number of Transfer Units	
N	Molar Hold-up	kmol
OBJ, OF	Objective Function	usually $ or $/time
p	Price	$
P	Dimensionless Temperature Approach	
P	Pressure	bar or kPa
P	Present Value	$
P^*	Vapor Pressure	bar or kPa
$P/A, i, n$	Uniform Series Present Worth Factor	
PBP	Payback Period	year
PC	Project Cost	$
$P/F, i, n$	Single Payment Present Worth Factor	
PVR	Present Value Ratio	
P(x)	Probability Density Function of x	
P_u	Ultimate Period of Oscillation	s
Q or q	Rate of Heat Transfer	W or MJ/h
Q	Quantity	
$\dot{Q}$	Heat Transfer Rate	W or MJ/h
r	Radius	m

r	Reaction Rate	kmol/m^3 or kmol/kg cat s
r	Rate of Production	kg/h
R	Gas Constant	kJ/kmol K
R	Ratio of Heat Capabilities	
R	Residual Funds Needed	$
R	Reflux Ratio	
Re	Reynolds Number	
R	Rich Stream Flowrate	kg/s
Rand	Random Number	
ROROI	Rate of Return on Investment	
ROROII	Rate of Return on Incremental Investment	
S	Entropy	kJ/K
S	Salvage Value	$
S	Maximum Allowable Working Pressure	bar
S	Salt Concentration Factor	
S	Sensitivity	
SF	Stream Factor	
T_m	Melting Temperature	K
t	Thickness of Wall	m
t	Time	s, min, h, yr
T	Total Time for a Batch	s, min, h, yr
T	Temperature	K, R, °C, or °F
U	Internal Energy	kJ
$\boldsymbol{u}$	Vector of Manipulated Inputs	
u	Flow Velocity	m/s
U	Overall Heat Transfer Coefficient	W/m^{2}K
v	Molar Volume	m^3/mol
V	Volume	m^3
V	Vapor Flow Rate	kmol/h
v_{react}	Specific Volume of Reactor	m^3/kg of product
v_p	Velocity	m/s
$\dot{v}$	Volumetric Flowrate	m^3/s
W	Weight	kg
W	Total Moles of a Component	kmol
W or *WS*	Work	kJ/kg
WC	Working Capital	$
$\boldsymbol{X}$	Matrix of Independent Variables	
$\boldsymbol{x}$	Vector of Variables	
X	Conversion	
X	Base-Case Ratio	
x	Mole or Mass Fraction	
y	Mole or Mass Fraction	
YOC	Yearly Operating Cost	$/yr
YS	Yearly Cash Flow (Savings)	$/yr
z	Valence of Ions	
z	Solids Mole Fraction	
z	Distance	m

Greek Symbols

α	Multiplication Cost Factor	
α	Relative Volatility	
α	NRTL Non-randomness Factor	
δ	Thickness of the Ion-Free Layer below	
ε	Void Fraction	
ε	Pump Efficiency	
ε	Tolerance, Error	
ε_{ij}	Lennard-Jones Energy Parameter between Species *i* and *j*	kJ/kmol
ε_r	Relative Permittivity of the Solvent	
ε_r'	Relative Permittivity of the Vapor Phase	
ε_s	Permittivity of the Solvent	Columb^2/kJ m
ϕ	Fugacity Coefficient	
$\hat{\phi}$	Fugacity Coefficient in Mixture	
ϕ^*	Fugacity Coefficient of Saturated Vapor	
γ	Activity Coefficient	
γ^∞	Activity Coefficient in the Mixture at Infinite Dilution	
$\gamma_\pm$	Mean Ionic Activity Coefficient	
κ	Inverse of Debye-Hückel length	1/m
η	Selectivity	
λ	Heat of Vaporization	kJ/kg
λ	Eigenvalue	
λ	Heat of Vaporization/Condensation	kJ/kg
$\boldsymbol{\lambda}$	Lagrangian Multiplier Vector	
λ_0	Thermal Conductivity of Pure Solvent	W/−m K
μ	Viscosity	kg/m s
μ_c	Chemical Potential	kJ
μ_0	Viscosity of Pure Solvent	kg/m s
$\boldsymbol{\theta}$	Parameter Vector	
θ	Rates of Species Concentration to that of Limiting Reactant	s\
σ	Statistical Variance	
σ	Collision Diameter	m
σ	Surface Tension	N/m
ξ	Selectivity	
ρ	Density	kg/m^3
Θ	Cycle Time	s
τ	Space Time	s
$\boldsymbol{\tau}$	NRTL Binary Interaction Energy Parameter	
τ_D	Derivative Time Constant	s
τ_I	Integral Time	s
Ω	Collision Integral	

Subscripts

1	Base Time
2	Desired Time

a	Required Attribute
ACT	Actual
Aux	Auxiliary Buildings
a, a′	Anion
b	Base Attribute
BM	Bare Module
c, c′	Cation
c	Cold
clean	Cleaning
Cont	Contingency
cycle	Cycle
d	Without Depreciation
D, d	Demand
E	Contractor Engineering Expenses
eff	Effective Interest
eq	Equivalent
el	Electrolyte(s)
eq	Metal in the Equipment
Fee	Contractor Fee
FTT	Transportation, etc.
GR	Grass Roots
h	Hot
i	Species
i	Index
in	Inlet
k	Year
L	Installation Labor
L	Lean Streams
L	Without Land Cost
LF	Long-Range Force
m	Molality Scale
m	Molecular Species
m	Heating/Cooling Medium
m	Number of Years
M	Materials for Installation
M	Material Cost Factor
max	Maximum
MC	Matching Costs
min	Minimum
n	Index for Time Instant
nom	Nominal Interest
out	Outlet
O or *OH*	Construction Overhead
Off	Offsites and Utilities
OL	Operating Labor
opt	Optimum
p	Production
P	Equipment at Manufacturer's Site (Purchased)
P	Pressure Cost Factor

P&I	Piping and Instrumentation
R	Rich Stream
RM	Raw Materials
rev	Reversible
rxn, r	Reaction
s	All Non-Water Solvents
s	Simple Interest
S	Supply
Site	Site Development
SF	Short-Range Force
TM	Total Module
UT	Utilities
WT	Waste Treatment
w	Water
+	Cation
−	Anion

Superscripts

DB	Double Declining Balance Depreciation
E or ex	Excess Property
L	Lower Limit
l	Liquid
o	Cost for Ambient Pressure Using Carbon Steel
s	Solid
SL	Straight Line Depreciation
SOYD	Sum of the Years Depreciation
U	Upper Limit
v	Vapor
∞	Aqueous Infinite Dilution
′	Includes Effect of Inflation on Interest

Additional Nomenclature

Table 1.2	Convention for Specifying Process Equipment
Table 1.3	Convention for Specifying Process Streams
Table 1.7	Abbreviations for Equipment and Materials of Construction
Table 1.10	Convention for Specifying Instrumentation and Control Systems

Note: In this book, matrices are denoted by boldface, uppercase, italicized letters and vectors are denoted by boldface, lowercase, italicized letters.

CHAPTER

1

Diagrams for Understanding Chemical Processes

WHAT YOU WILL LEARN

- Different types of chemical process diagrams
- How these diagrams represent different scales of process views
- One consistent method for drawing process flow diagrams
- The information to be included in a process flow diagram
- The purpose of operator training simulators and recent advances in 3-D representation of different chemical processes

The chemical process industry (CPI) is involved in the production of a wide variety of products that improve the quality of our lives and generate income for companies and their stockholders. In general, chemical processes are complex, and chemical engineers in industry encounter a variety of chemical process flow diagrams. These processes often involve substances of high chemical reactivity, high toxicity, and high corrosivity operating at high pressures and temperatures. These characteristics can lead to a variety of potentially serious consequences, including explosions, environmental damage, and threats to people's health. It is essential that errors or omissions resulting from missed communication between persons and/or groups involved in the design and operation do not occur when dealing with chemical processes. Visual information is the clearest way to present material and is least likely to be misinterpreted. For these reasons, it is essential that chemical engineers be able to formulate appropriate process diagrams and be skilled in analyzing and interpreting diagrams prepared by others.

The most effective way of communicating information about a process is through the use of flow diagrams.

This chapter presents and discusses the more common flow diagrams encountered in the chemical process industry. These diagrams evolve from the time a process is conceived in the laboratory through the design, construction, and the many years of plant operation. The most important of these diagrams are described and discussed in this chapter.

The following narrative is taken from Kauffman [1] and describes a representative case history related to the development of a new chemical process. It shows how teams of engineers work together to provide a plant design and introduces the types of diagrams that will be explored in this chapter.

> *The research and development group at ABC Chemicals Company worked out a way to produce alpha-beta souptol (ABS). Process engineers assigned to work with the development group have pieced together a continuous process for making ABS in commercial quantities and have tested key parts of it. This work involved hundreds of **block flow diagrams**, some more complex than others. Based on information derived from these block flow diagrams, a decision was made to proceed with this process.*
>
> *A process engineering team from ABC's central office carries out the detailed process calculations, material and energy balances, equipment sizing, etc. Working with their drafting department, they produced a series of **PFDs (Process Flow Diagrams)** for the process. As problems arise and are solved, the team may revise and redraw the PFDs. Often the work requires several rounds of drawing, checking, and revising.*
>
> *Specialists in distillation, process control, kinetics, and heat transfer are brought in to help the process team in key areas. Some are company employees and others are consultants.*
>
> *Since ABC is only a moderate-sized company, it does not have sufficient staff to prepare the 120 **P&IDs (Piping and Instrumentation Diagrams)** needed for the new ABS plant. ABC hires a well-known engineering and construction firm **(E&C Company)**, DEFCo, to do this work for them. The company assigns two of the ABC process teams to work at DEFCo to coordinate the job. DEFCo's process engineers, specialists, and drafting department prepare the P&IDs. They do much of the detailed engineering (pipe sizes, valve specifications, etc.) as well as the actual drawing. The job may take two to six months. Every drawing is reviewed by DEFCo's project team and by ABC's team. If there are disagreements, the engineers and specialists from the companies must resolve them.*
>
> *Finally, all the PFDs and the P&IDs are completed and approved. ABC can now go ahead with the construction. They may extend their contract with DEFCo to include this phase, or they may go out for construction bids from a number of sources.*

This narrative describes a typical sequence of events taking a project from its initial stages through plant construction. If DEFCo had carried out the construction, ABC could go ahead and take over the plant or DEFCo could be contracted to carry out the start-up and to commission the plant. Once satisfactory performance specifications have been met, ABC would take over the operation of the plant and commercial production would begin.

From conception of the process to the time the plant starts up, two or more years will have elapsed and millions of dollars will have been spent with no revenue from the plant. The plant must operate successfully for many years to produce sufficient income to pay for all plant operations and to repay the costs associated with designing and building the plant. During this operating period, many unforeseen changes are likely to take place. The quality of the raw materials used by the plant may change, product specifications may be raised, production rates may need to be increased, the equipment performance will decrease because of wear, the development of new and better catalysts will occur, the costs of utilities will change, new environmental regulations may be introduced, or improved equipment may appear on the market.

As a result of these unplanned changes, plant operations must be modified. Although the operating information on the original process diagrams remains informative, the actual performance taken from the operating plant will be different. The current operating conditions will appear on updated versions of the various process diagrams, which will act as a primary basis for understanding the changes taking place in the plant. These process diagrams are essential to an engineer who has been asked to diagnose operating problems, solve problems in operations, debottleneck systems for increased capacity, and predict the effects of making changes in operating conditions. All these activities are essential in order to maintain profitable plant operation.

In this chapter, the focus is on three diagrams that are important to chemical engineers: block flow, process flow, and piping and instrumentation diagrams. Of these three diagrams, the most useful to chemical engineers is the PFD. The understanding of the PFD represents a central goal of this textbook.

1.1 BLOCK FLOW DIAGRAM (BFD)

Block flow diagrams were introduced early in the chemical engineering curriculum. In the first course in material and energy balances, often an initial step was to convert a word problem into a simple block diagram. This diagram consisted of a series of blocks representing different equipment or unit operations that were connected by input and output streams. Important information such as operating temperatures, pressures, conversions, and yield was included on the diagram along with flowrates and some chemical compositions. However, the diagram did not include any details of equipment within any of the blocks.

The block flow diagram can take one of two forms. First, a block flow diagram may be drawn for a single process. Alternatively, a block flow diagram may be drawn for a complete chemical complex involving many different chemical processes. These two types of diagrams are differentiated by calling the first a block flow process diagram and the second a block flow plant diagram.

1.1.1 Block Flow Process Diagram

An example of a block flow process diagram is shown in Figure 1.1, and the process illustrated is described below.

> *Toluene and hydrogen are converted in a reactor to produce benzene and methane. The reaction does not go to completion, and excess toluene is required. The noncondensable gases are separated and discharged. The benzene product and the unreacted toluene are then separated by distillation. The toluene is then recycled back to the reactor and the benzene removed in the product stream.*

This block flow diagram gives a clear overview of the production of benzene, unobstructed by the many details related to the process. Each block in the diagram represents a process function and may, in reality, consist of several pieces of equipment. The general format and conventions used in preparing block flow process diagrams are presented in Table 1.1.

Although much information is missing from Figure 1.1, it is clear that such a diagram is very useful for "getting a feel" for the process. Block flow process diagrams often form the starting point for developing a PFD. They are also very helpful in conceptualizing new processes and explaining the main features of the process without getting bogged down in the details.

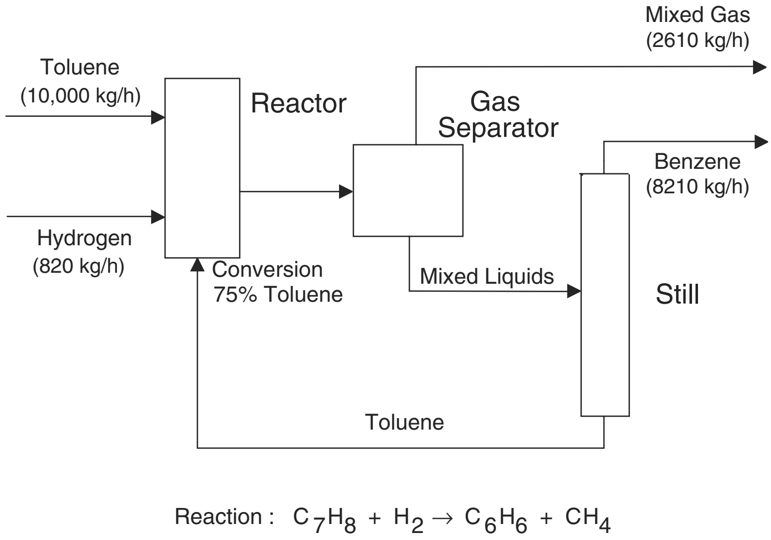

Figure 1.1 Block Flow Process Diagram for the Production of Benzene

1.1.2 Block Flow Plant Diagram

An example of a block flow plant diagram for a complete chemical complex is illustrated in Figure 1.2. This block flow plant diagram is for a coal to higher alcohol fuels plant. Clearly, this is a complicated process in which there are a number of alcohol fuel products produced from a feedstock of coal. Each block in this diagram represents a complete chemical process (compressors and turbines are also shown as trapezoids), and a block flow process diagram could be drawn for each block in Figure 1.2. The advantage of a diagram such as Figure 1.2 is that it allows a complete picture of what this plant does and how all the different processes interact to be obtained. On the other hand, in order to keep the diagram relatively uncluttered, only limited information is available about each process unit. The conventions for drawing block flow plant diagrams are similar to Table 1.1.

Both types of block flow diagrams are useful for explaining the overall operation of chemical plants. For example, consider that you have just joined a large chemical manufacturing company that produces a wide range of chemical products from the site to which you have been assigned. You would most likely be given a *block flow plant diagram*

Table 1.1 Conventions and Format Recommended for Laying Out a Block Flow Process Diagram

1. Operations shown by blocks.
2. Major flow lines shown with arrows giving direction of flow.
3. Flow goes from left to right whenever possible.
4. Light stream (gases) toward top with heavy stream (liquids and solids) toward bottom.
5. Critical information unique to process supplied.
6. If lines cross, then the horizontal line is continuous and the vertical line is broken (hierarchy for all drawings in this book).
7. Simplified material balance provided.

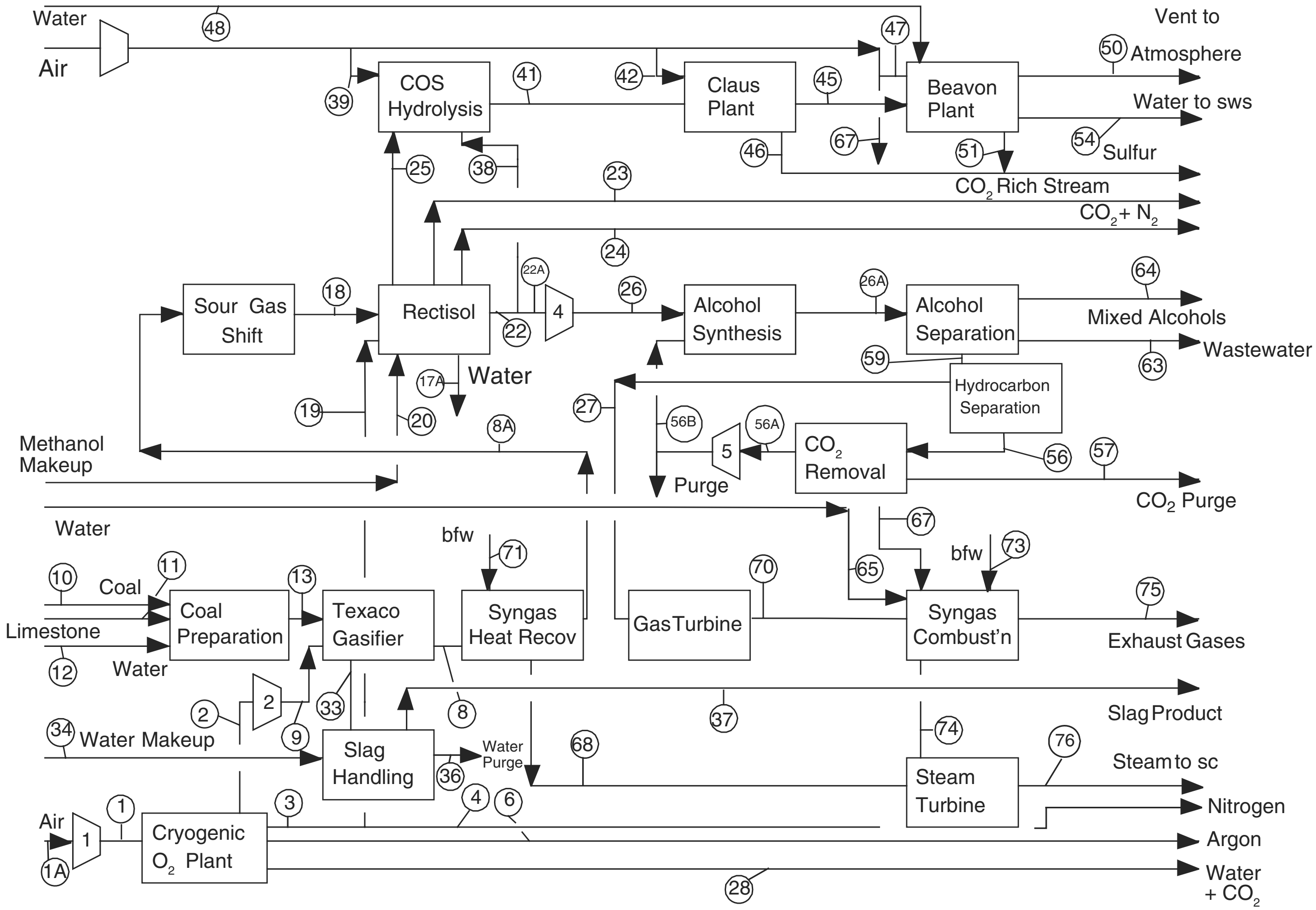

Figure 1.2 Block Flow Plant Diagram of a Coal to Higher Alcohol Fuels Process

to orient you to the products and important areas of operation. Once assigned to one of these areas, you would again likely be provided with a *block flow process diagram* describing the operations in your particular area.

In addition to the orientation function described earlier, block flow diagrams are used to sketch out and screen potential process alternatives. Thus, they are used to convey information necessary to make early comparisons and eliminate competing alternatives without having to make detailed and costly comparisons.

1.2 PROCESS FLOW DIAGRAM (PFD)

The process flow diagram (PFD) represents a quantum step up from the BFD in terms of the amount of information that it contains. The PFD contains the bulk of the chemical engineering data necessary for the design of a chemical process. For all of the diagrams discussed in this chapter, there are no universally accepted standards. The PFD from one company will probably contain slightly different information from the PFD for the same process from another company. Having made this point, it is fair to say that most PFDs convey very similar information. A typical commercial PFD will contain the following information:

1. All the major pieces of equipment in the process will be represented on the diagram along with a description of the equipment. Each piece of equipment will have assigned a unique equipment number and a descriptive name.
2. All process flow streams will be shown and identified by a number. A description of the process conditions and chemical composition of each stream will be included. These data will be either displayed directly on the PFD or included in an accompanying flow summary table.
3. All utility streams supplied to major equipment that provides a process function will be shown.
4. Basic control loops, illustrating the control strategy used to operate the process during normal operations, will be shown.

It is clear that the PFD is a complex diagram requiring a substantial effort to prepare. It is essential that it should remain uncluttered and be easy to follow, to avoid errors in presentation and interpretation. Often PFDs are drawn on large sheets of paper (for example, size D: 24 in × 36 in), and several connected sheets may be required for a complex process. Because of the page size limitations associated with this text, complete PFDs cannot be presented here. Consequently, certain liberties have been taken in the presentation of the PFDs in this text. Specifically, certain information will be presented in accompanying tables, and only the essential process information will be included on the PFD. The resulting PFDs will retain clarity of presentation, but the reader must refer to the flow summary and equipment summary tables in order to extract all the required information about the process.

Before the various aspects of the PFD are discussed, it should be noted that the PFD and the process that is described in this chapter will be used throughout the book. The process is the hydrodealkylation of toluene to produce benzene. This is a well-studied and well-understood commercial process still used today. The PFD presented in this chapter for this process is technically feasible but is in no way optimized. In fact, many improvements to the process technology and economic performance can be made. Many of these improvements will become evident when the appropriate material is presented. This allows the techniques provided throughout this text to be applied both to identify technical and economic problems in the process and to make the necessary process improvements. Therefore, throughout the text, weak spots in the design, potential improvements, and a path toward an optimized process flow diagram will be identified.

The basic information provided by a PFD can be categorized into one of the following:

1. Process topology
2. Stream information
3. Equipment information

Each aspect of the PFD will be considered separately. After each of the three topics has been addressed, all the information will be gathered and presented in the form of a PFD for the benzene process.

1.2.1 Process Topology

Figure 1.3 is a skeleton process flow diagram for the production of benzene (see also the block flow process diagram in Figure 1.1). This skeleton diagram illustrates the location of the major pieces of equipment and the connections that the process streams make between equipment. The location of and interaction between equipment and process streams are referred to as the process topology.

Equipment is represented symbolically by "icons" that identify specific unit operations. Although the American Society of Mechanical Engineers (ASME) [2] publishes a set of symbols to use in preparing flowsheets, it is not uncommon for companies to use in-house symbols. A comprehensive set of symbols is also given by Austin [3]. Whatever set of symbols is used, there is seldom a problem in identifying the operation represented by each icon. Figure 1.4 contains a list of the symbols used in process diagrams presented in this text. This list covers more than 90% of those needed in fluid (gas or liquid) processes.

Figure 1.3 shows that each major piece of process equipment is identified by a number on the diagram. A list of the equipment numbers along with a brief descriptive name for the equipment is printed along the top of the diagram. The location of these equipment numbers and names roughly corresponds to the horizontal location of the corresponding piece of equipment. The convention for formatting and identifying the process equipment is given in Table 1.2.

Table 1.2 provides the information necessary for the identification of the process equipment icons shown in a PFD. As an example of how to use this information, consider the unit operation P-101A/B and what each number or letter means.

P-101A/B identifies the equipment as a pump.

P-**1**01A/B indicates that the pump is located in area 100 of the plant.

P-1**01**A/B indicates that this specific pump is number 01 in unit 100.

P-101**A/B** indicates that a backup pump is installed. Thus, there are two identical pumps, P-101A and P-101B. One pump will be operating while the other is idle.

The 100 area designation will be used for the benzene process throughout this text. Other processes presented in the text will carry other area designations. Along the top of the PFD, each piece of process equipment is assigned a descriptive name. From Figure 1.3 it can be seen that Pump P-101 is called the "toluene feed pump." This name will be commonly used in discussions about the process and is synonymous with P-101.

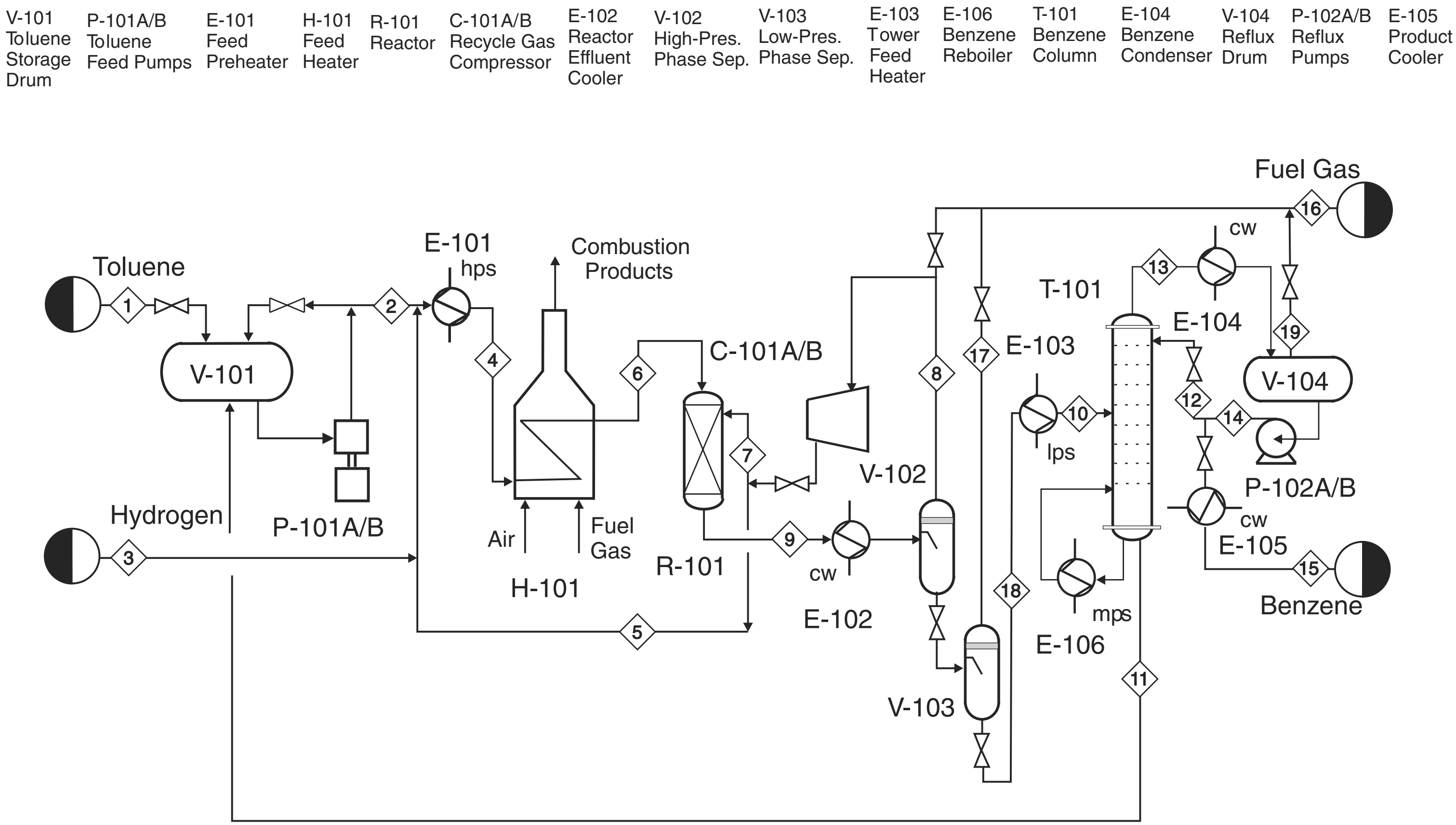

Figure 1.3 Skeleton Process Flow Diagram (PFD) for the Production of Benzene via the Hydrodealkylation of Toluene

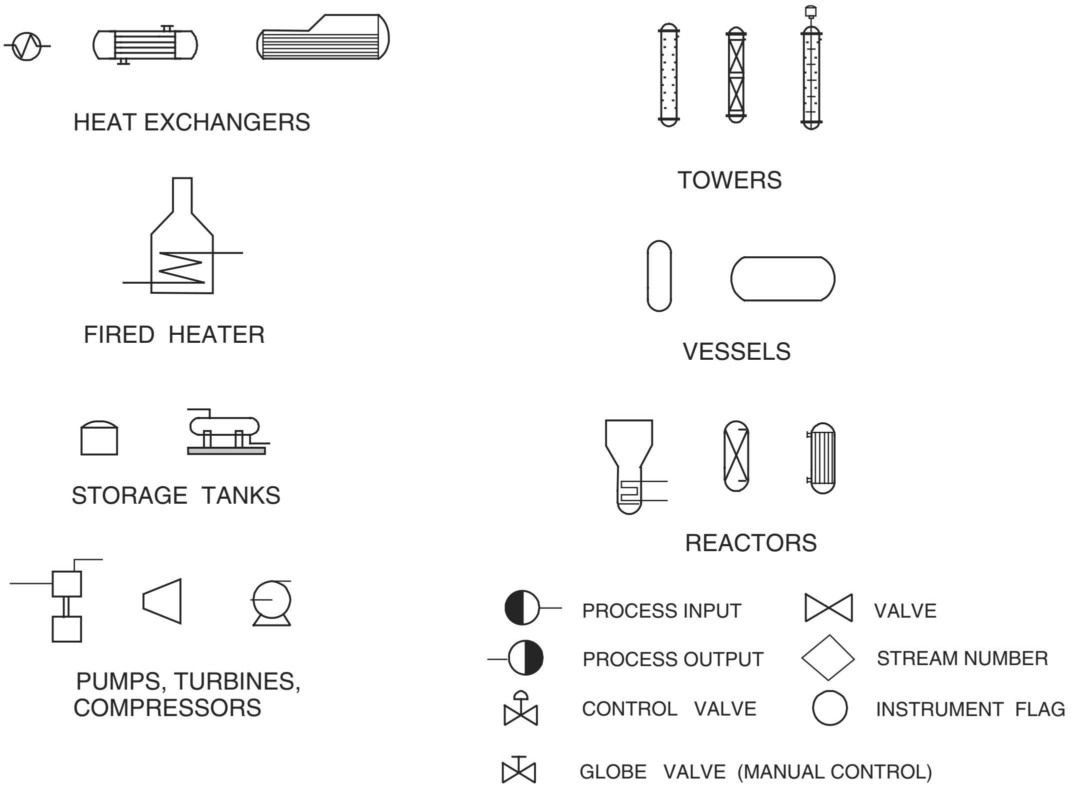

Figure 1.4 Symbols for Drawing Process Flow Diagrams

During the life of the plant, many modifications will be made to the process; often it will be necessary to replace or eliminate process equipment. When a piece of equipment wears out and is replaced by a new unit that provides essentially the same process function as the old unit, then it is not uncommon for the new piece of equipment to inherit the old equipment's name and number (often an additional letter suffix will be used, e.g., H-101 might become H-101A). On the other hand, if a significant process modification takes place, then it is usual to use new equipment numbers and names. Example 1.1, taken from Figure 1.3, illustrates this concept.

Example 1.1

Operators report frequent problems with E-102, which are to be investigated. The PFD for the plant's 100 area is reviewed, and E-102 is identified as the "Reactor Effluent Cooler." The process stream entering the cooler is a mixture of condensable and noncondensable gases at 654°C that are partially condensed to form a two-phase mixture. The coolant is water at 30°C. These conditions characterize a complex heat transfer problem. In addition, operators have noticed that the pressure drop across E-102 fluctuates wildly at certain times, making control of the process difficult. Because of the frequent problems with this exchanger, it is recommended that E-102 be replaced by two separate heat exchangers. The first exchanger cools the effluent gas and generates steam needed in the plant. The second exchanger uses cooling water to reach the desired exit temperature of 38°C. These exchangers are to be designated as E-107 (reactor effluent boiler) and E-108 (reactor effluent condenser).

Table 1.2 Conventions Used for Identifying Process Equipment

Process Equipment	General Format XX-YZZ A/B
	XX are the identification letters for the equipment classification
	C - Compressor or Turbine
	E - Heat Exchanger
	H - Fired Heater
	P - Pump
	R - Reactor
	T - Tower
	TK - Storage Tank
	V - Vessel
	Y designates an area within the plant
	ZZ is the number designation for each item in an equipment class
	A/B identifies parallel units or backup units not shown on a PFD
Supplemental Information	Additional description of equipment given on top of PFD

The E-102 designation is retired and not reassigned to the new equipment. There can be no mistake that E-107 and E-108 are new units in this process and that E-102 no longer exists.

1.2.2 Stream Information

Referring back to Figure 1.3, it can be seen that each of the process streams is identified by a number in a diamond box located on the stream. The direction of the stream is identified by one or more arrowheads. The process stream numbers are used to identify streams on the PFD, and the type of information that is typically given for each stream is discussed in the next section.

Also identified in Figure 1.3 are utility streams. Utilities are needed services that are available at the plant. Chemical plants are provided with a range of central utilities that include electricity, compressed air, cooling water, refrigerated water, steam, condensate return, inert gas for blanketing, chemical sewer, wastewater treatment, and flares. A list of the common services is given in Table 1.3, which also provides a guide for the identification of process streams.

Each utility is identified by the initials provided in Table 1.3. As an example, locate E-102 in Figure 1.3. The notation, cw, associated with the nonprocess stream flowing into E-102 indicates that cooling water is used as a coolant.

Electricity used to power motors and generators is an additional utility that is not identified directly on the PFD or in Table 1.3 but is treated separately. Most of the utilities shown are related to equipment that adds or removes heat within the process in order to control temperatures. This is common for most chemical processes.

From the PFD in Figure 1.3, the identification of the process streams is clear. For small diagrams containing only a few operations, the characteristics of the streams such

Table 1.3 Conventions for Identifying Process and Utility Streams

Process Streams	
All conventions shown in Table 1.1 apply.	
Diamond symbol located in flow lines.	
Numerical identification (unique for that stream) inserted in diamond.	
Flow direction shown by arrows on flow lines.	
Utility Streams	
lps	Low-Pressure Steam: 3–5 barg (sat)*
mps	Medium-Pressure Steam: 10–15 barg (sat)*
hps	High-Pressure Steam: 40–50 barg (sat)*
htm	Heat Transfer Media (Organic): to 400°C
cw	Cooling Water: From Cooling Tower 30°C Returned at Less than 45°C†
wr	River Water: From River 25°C Returned at Less than 35°C
rw	Refrigerated Water: In at 5°C Returned at Less than 15°C
rb	Refrigerated Brine: In at –45°C Returned at Less than 0°C
cs	Chemical Wastewater with High COD
ss	Sanitary Wastewater with High BOD, etc.
el	Electric Heat (Specify 220, 440, 660V Service)
bfw	Boiler Feed Water
ng	Natural Gas
fg	Fuel Gas
fo	Fuel Oil
fw	Fire Water

*These pressures are set during the preliminary design stages and typical values vary within the ranges shown.

†Above 45°C, significant scaling occurs.

as temperatures, pressures, compositions, and flowrates can be shown directly on the figure, adjacent to the stream. This is not practical for a more complex diagram. In this case, only the stream number is provided on the diagram. This indexes the stream to information on a flow summary or stream table, which is often provided below the process flow diagram. In this text the flow summary table is provided as a separate attachment to the PFD.

The stream information that is normally given in a flow summary table is given in Table 1.4. It is divided into two groups—required information and optional information—that may be important to specific processes. The flow summary table, for Figure 1.3, is given in Table 1.5 and contains all the required information listed in Table 1.4.

With information from the PFD (Figure 1.3) and the flow summary table (Table 1.5), problems regarding material balances and other problems are easily analyzed. Example 1.2 and Example 1.3 are provided to offer experience in working with information from the PFD.

Table 1.4 Information Provided in a Flow Summary

Required Information
Stream Number
Temperature (°C)
Pressure (bar)
Vapor Fraction
Total Mass Flowrate (kg/h)
Total Mole Flowrate (kmol/h)
Individual Component Flowrates (kmol/h)
Optional Information
Component Mole Fractions
Component Mass Fractions
Individual Component Flowrates (kg/h)
Volumetric Flowrates (m^3/h)
Significant Physical Properties Density Viscosity Other
Thermodynamic Data Heat Capacity Stream Enthalpy *K*-values
Stream Name

Table 1.5 Flow Summary Table for the Benzene Process Shown in Figure 1.3 (and Figure 1.5)

Stream Number	1	2	3	4	5	6	7	8
Temperature (°C)	25	59	25	225	41	600	41	38
Pressure (bar)	1.90	25.8	25.5	25.2	25.5	25.0	25.5	23.9
Vapor Fraction	0.0	0.0	1.00	1.0	1.0	1.0	1.0	1.0
Mass Flow (tonne/h)	10.0	13.3	0.82	20.5	6.41	20.5	0.36	9.2
Mole Flow (kmol/h)	108.7	144.2	301.0	1204.4	758.8	1204.4	42.6	1100.8
Component Flowrates (kmol/h)								
Hydrogen	0.0	0.0	286.0	735.4	449.4	735.4	25.2	651.9
Methane	0.0	0.0	15.0	317.3	302.2	317.3	16.95	438.3
Benzene	0.0	1.0	0.0	7.6	6.6	7.6	0.37	9.55
Toluene	108.7	143.2	0.0	144.0	0.7	144.0	0.04	1.05

Example 1.2

Check the overall material balance for the benzene process shown in Figure 1.3. From the figure, identify the input streams as Stream 1 (toluene feed) and Stream 3 (hydrogen feed) and the output streams as Stream 15 (product benzene) and Stream 16 (fuel gas). From the flow summary table, these flows are listed as (units are in (10^3 kg)/h):

Input:		Output:	
Stream 3	0.82	Stream 15	8.21
Stream 1	10.00	Stream 16	2.61
Total	10.82×10^3 kg/h	Total	10.82×10^3 kg/h

Balance is achieved since Output = Input.

Example 1.3

Determine the conversion per pass of toluene to benzene in R-101 in Figure 1.3. Conversion is defined as

$$\varepsilon = \text{(benzene produced)}/\text{(total toluene introduced)}$$

From the PFD, the input streams to R-101 are shown as Stream 6 (reactor feed) and Stream 7 (recycle gas quench), and the output stream is Stream 9 (reactor effluent stream). From the information in Table 1.5 (units are kmol/h):

Toluene introduced = 144 (Stream 6) + 0.04 (Stream 7) = 144.04 kmol/h

Benzene produced = 116 (Stream 9) – 7.6 (Stream 6) – 0.37 (Stream 7)
= 108.03 kmol/h

$$\varepsilon = 108.03/144.04 = 0.75$$

Alternatively, the following can be written:

Moles of benzene produced = Toluene in – Toluene out = 144.04 – 36.00
= 108.04 kmol/h

$$\varepsilon = 108.04/144.04 = 0.75$$

9	10	11	12	13	14	15	16	17	18	19
654	90	147	112	112	112	38	38	38	38	112
24.0	2.6	2.8	3.3	2.5	3.3	2.3	2.5	2.8	2.9	2.5
1.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0	1.0	0.0	1.0
20.9	11.6	3.27	14.0	22.7	22.7	8.21	2.61	0.07	11.5	0.01
1247.0	142.2	35.7	185.2	291.6	290.7	105.6	304.2	4.06	142.2	0.90
652.6	0.02	0.0	0.0	0.02	0.0	0.0	178.0	0.67	0.02	0.02
442.3	0.88	0.0	0.0	0.88	0.0	0.0	123.05	3.10	0.88	0.88
116.0	106.3	1.1	184.3	289.46	289.46	105.2	2.85	0.26	106.3	0.0
36.0	35.0	34.6	0.88	1.22	1.22	0.4	0.31	0.03	35.0	0.0

Table 1.6 Equipment Descriptions for PFD and P&IDs

Equipment Type
Description of Equipment
Towers
Size (height and diameter), Pressure, Temperature Number and Type of Trays Height and Type of Packing Materials of Construction
Heat Exchangers
Type: Gas-Gas, Gas-Liquid, Liquid-Liquid, Condenser, Vaporizer Process: Duty, Area, Temperature, and Pressure for both streams Number of Shell and Tube Passes Materials of Construction: Tubes and Shell
Tanks and Vessels
Height, Diameter, Orientation, Pressure, Temperature, Materials of Construction
Pumps
Flow, Discharge Pressure, Temperature, ΔP, Driver Type, Shaft Power, Materials of Construction
Compressors
Actual Inlet Flowrate, Temperature, Pressure, Driver Type, Shaft Power, Materials of Construction
Heaters (Fired)
Type, Tube Pressure, Tube Temperature, Duty, Fuel, Material of Construction
Other
Provide Critical Information

1.2.3 Equipment Information

The final element of the PFD is the equipment summary. This summary provides the information necessary to estimate the costs of equipment and furnish the basis for the detailed design of equipment. Table 1.6 provides the information needed for the equipment summary for most of the equipment encountered in fluid processes.

The information presented in Table 1.6 is used in preparing the equipment summary portion of the PFD for the benzene process. The equipment summary for the benzene process is presented in Table 1.7, and details of how to estimate and choose various equipment parameters are discussed in Chapter 11.

Table 1.7 Equipment Summary for Toluene Hydrodealkylation PFD

Heat Exchangers	**E-101**	**E-102**	**E-103**	**E-104**	**E-105**	**E-106**
Type	Fl.H.	Fl.H.	MDP	Fl.H.	MDP	Fl.H.
Area (m^2)	36	763	11	35	12	80
Duty (MJ/h)	15,190	46,660	1055	8335	1085	9045
Shell						
Temp. (°C)	225	654	160	112	112	185
Pres. (bar)	26	24	6	3	3	11
Phase	Vap.	Par. Cond.	Cond.	Cond.	l	Cond.
MOC	316SS	316SS	CS	CS	CS	CS
Tube						
Temp. (°C)	258	40	90	40	40	147
Pres. (bar)	42	3	3	3	3	3
Phase	Cond.	l	l	l	l	Vap.
MOC	316SS	316SS	CS	CS	CS	CS
Vessels/Tower/ Reactors	**V-101**	**V-102**	**V-103**	**V-104**	**T-101**	**R-101**
Temperature (°C)	55	38	38	112	147	660
Pressure (bar)	2.0	24	3.0	2.5	3.0	25
Orientation	Horizontal	Vertical	Vertical	Horizontal	Vertical	Vertical
MOC	CS	CS	CS	CS	CS	316SS
Size						
Height/Length (m)	5.9	3.5	3.5	3.9	29	14.2
Diameter (m)	1.9	1.1	1.1	1.3	1.5	2.3
Internals		s.p.	s.p.		42 sieve trays 316SS	Catalyst packed bed-10m
Pumps/Compressors	**P-101 (A/B)**	**P-102 (A/B)**	**C-101 (A/B)**	**Heater**		**H-101**
Flow (kg/h)	13,000	22,700	6770	Type		Fired
Fluid Density (kg/m^3)	870	880	8.02	MOC		316SS
Power (shaft) (kW)	14.2	3.2	49.1	Duty (MJ/h)		27,040
Type/Drive	Recip./ Electric	Centrf./ Electric	Centrf./ Electric	Radiant Area (m^2)		106.8
Efficiency (Fluid Power/Shaft Power)	0.75	0.50	0.75	Convective Area (m^2)		320.2

(*continued*)

Table 1.7 Equipment Summary for Toluene Hydrodealkylation PFD (*continued*)

Pumps/Compressors	P-101 (A/B)	P-102 (A/B)	C-101 (A/B)	Heater	H-101
MOC	CS	CS	CS	Tube P (bar)	26.0
Temp. (in) (°C)	55	112	38		
Pres. (in) (bar)	1.2	2.2	23.9		
Pres. (out) (bar)	27.0	4.4	25.5		

Key:

MOC	Materials of construction	Par	Partial
316SS	Stainless steel type 316	F.H.	Fixed head
CS	Carbon steel	Fl.H.	Floating head
Vap	Stream being vaporized	Rbl	Reboiler
Cond	Stream being condensed	s.p.	Splash plate
Recipr.	Reciprocating	l	Liquid
Centrf.	Centrifugal	MDP	Multiple double pipe

1.2.4 Combining Topology, Stream Data, and Control Strategy to Give a PFD

Up to this point, the amount of process information displayed on the PFD has been kept to a minimum. A more representative example of a PFD for the benzene process is shown in Figure 1.5. This diagram includes all of the elements found in Figure 1.3, some of the information found in Table 1.5, plus additional information on the major control loops used in the process.

Stream information is added to the diagram by attaching "information flags." The shape of the flags indicates the specific information provided on the flag. Figure 1.6 illustrates all the flags used in this text. These information flags play a dual role. They provide information needed in the plant design leading to plant construction and in the analysis of operating problems during the life of the plant. Flags are mounted on a staff connected to the appropriate process stream. More than one flag may be mounted on a staff. Example 1.4 illustrates the different information displayed on the PFD.

Example 1.4

Locate Stream 1 in Figure 1.5 and note that immediately following the stream identification diamond a staff is affixed. This staff carries three flags containing the following stream data:

1. Temperature of 25°C
2. Pressure of 1.9 bar
3. Mass flowrate of 10.0×10^3 kg/h

The units for each process variable are indicated in the key provided at the left-hand side of Figure 1.5.

With the addition of the process control loops and the information flags, the PFD starts to become cluttered. Therefore, in order to preserve clarity, it is necessary to limit what data are presented with these information flags. Fortunately, flags on a PFD are easy to add, remove, and change, and even temporary flags may be provided from time to time.

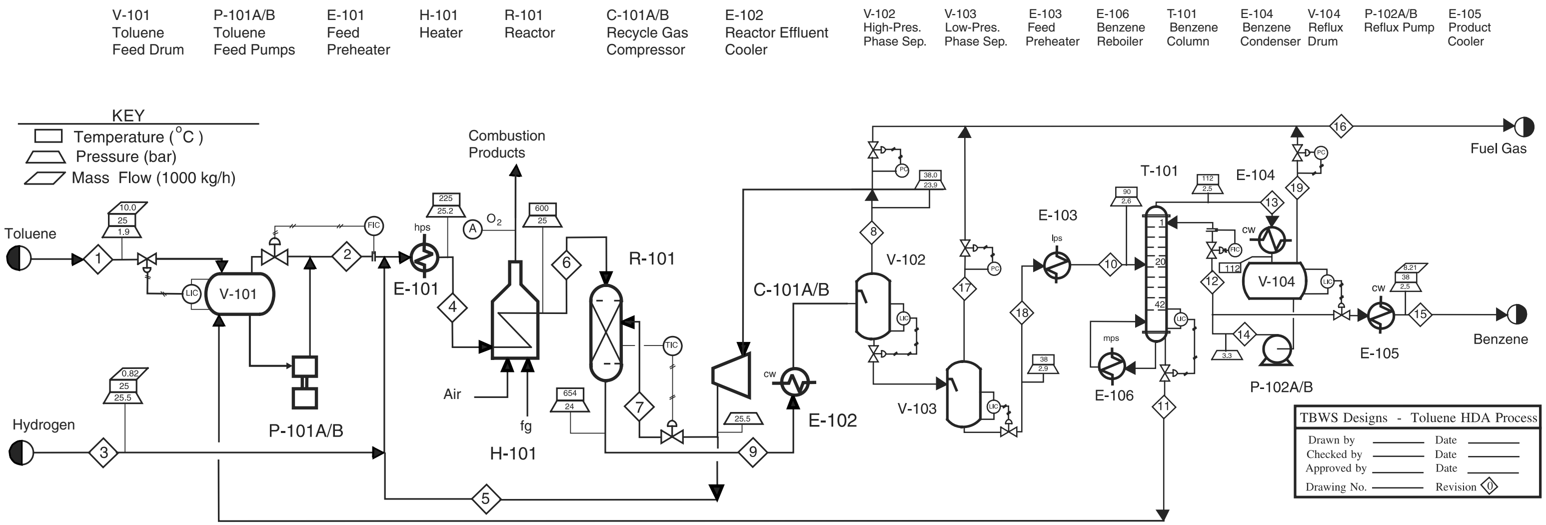

Figure 1.5 Benzene Process Flow Diagram (PFD) for the Production of Benzene via the Hydrodealkylation of Toluene

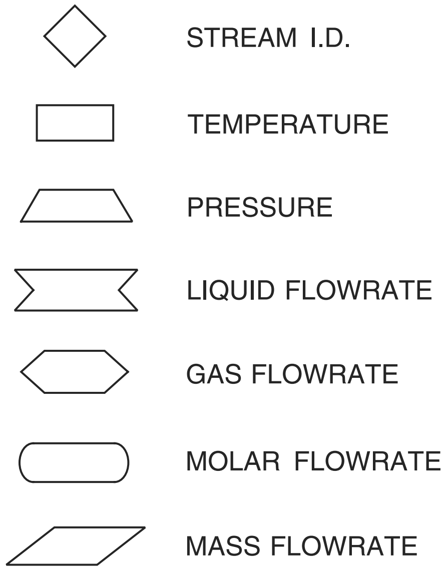

Figure 1.6 Symbols for Stream Identification

The information provided on the flags is also included in the flow summary table. However, often it is far more convenient when analyzing the PFD to have certain data directly on the diagram.

Not all process information is of equal importance. General guidelines for what data should be included in information flags on the PFD are difficult to define. However, at a minimum, information critical to the safety and operation of the plant should be given. This includes temperatures and pressures associated with the reactor, flowrates of feed and product streams, and stream pressures and temperatures that are substantially higher than the rest of the process. Additional needs are process specific. Examples 1.5–1.7 illustrate where and why information should be included directly on a PFD.

Example 1.5

Acrylic acid is temperature sensitive and polymerizes at 90°C when present in high concentration. It is separated by distillation and leaves from the bottom of the tower. In this case, a temperature and pressure flag would be provided for the stream leaving the reboiler.

Example 1.6

In the benzene process, the feed to the reactor is substantially hotter than the rest of the process and is crucial to the operation of the process. In addition, the reaction is exothermic, and the reactor effluent temperature must be carefully monitored. For this reason Stream 6 (entering) and Stream 9 (leaving) have temperature flags.

Example 1.7

The pressures of the streams to and from R-101 in the benzene process are also important. The difference in pressure between the two streams gives the pressure drop across the reactor. This, in turn, gives an indication of any maldistribution of gas through the catalyst beds. For this reason, pressure flags are also included on Streams 6 and 9.

Of secondary importance is the fact that flags are useful in reducing the size of the flow summary table. For pumps, compressors, and heat exchangers, the mass flows are the same for the input and output streams, and complete entries in the stream table are not necessary. If the input (or output) stream is included in the stream table, and a flag is added to provide the temperature (in the case of a heat exchanger) or the pressure (in the case of a pump) for the other stream, then there is no need to present this stream in the flow summary table. Example 1.8 illustrates this point.

Example 1.8

Follow Stream 13 leaving the top of the benzene column in the benzene PFD given in Figure 1.5 and in Table 1.5. This stream passes through the benzene condenser, E-104, into the reflux drum, V-104. The majority of this stream then flows into the reflux pump, P-102, and leaves as Stream 14, while the remaining noncondensables leave the reflux drum in Stream 19. The mass flowrate and component flowrates of all these streams are given in Table 1.5. The stream leaving E-104 is not included in the stream table. Instead, a flag giving the temperature (112°C) was provided on the diagram (indicating condensation without subcooling). An additional flag, showing the pressure following the pump, is also shown. In this case the entry for Stream 14 could be omitted from the stream table, because it is simply the sum of Streams 12 and 15, and no information would be lost.

More information could be included in Figure 1.5 had space for the diagram not been limited by text format. It is most important that the PFD remain uncluttered and easy to follow in order to avoid errors and misunderstandings. Adding additional material to Figure 1.5 risks sacrificing clarity.

The flow table presented in Table 1.5, the equipment summary presented in Table 1.7, and Figure 1.5 taken together constitute all the information contained on a commercially produced PFD.

The PFD is the first comprehensive diagram drawn for any new plant or process. It provides all of the information needed to understand the chemical process. In addition, sufficient information is given on the equipment, energy, and material balances to establish process control protocol and to prepare cost estimates to determine the economic viability of the process.

Many additional drawings are needed to build the plant. All the process information required can be taken from this PFD. As described in the narrative at the beginning of this chapter, the development of the PFD is most often carried out by the operating company. Subsequent activities in the design of the plant are often contracted out.

The value of the PFD does not end with the construction of the plant. It remains the document that best describes the process, and it is used in the training of operators and new engineers. It is consulted regularly to diagnose operating problems that arise and to predict the effects of changes on the process.

1.3 PIPING AND INSTRUMENTATION DIAGRAM (P&ID)

The piping and instrumentation diagram (P&ID), also known as mechanical flow diagram (MFD), provides information needed by engineers to begin planning for the construction of the plant. The P&ID includes every mechanical aspect of the plant except the information given in Table 1.8. The general conventions used in drawing P&IDs are given in Table 1.9.

Table 1.8 Exclusions from Piping and Instrumentation Diagram

1. Operating Conditions *T*, *P*
2. Stream Flows
3. Equipment Locations
4. Pipe Routing
   a. Pipe Lengths
   b. Pipe Fittings
5. Supports, Structures, and Foundations

Each PFD will require many P&IDs to provide the necessary data. Figure 1.7 is a representative P&ID for the distillation section of the benzene process shown in Figure 1.5. The P&ID presented in Figure 1.7 provides information on the piping, and this is included as part of the diagram. As an alternative, each pipe can be numbered, and the specifics of every line can be provided in a separate table accompanying this diagram. When possible, the physical size of the larger-sized unit operations is reflected by the size of the symbol in the diagram.

Utility connections are identified by a numbered box in the P&ID. The number within the box identifies the specific utility. The key identifying the utility connections is shown in a table on the P&ID.

All process information that can be measured in the plant is shown on the P&ID by circular flags. This includes the information to be recorded and used in process control

Table 1.9 Conventions in Constructing Piping and Instrumentation Diagrams

For Equipment—Show Every Piece Including
Spare Units Parallel Units Summary Details of Each Unit
For Piping—Include All Lines Including Drains and Sample Connections, and Specify
Size (Use Standard Sizes) Schedule (Thickness) Materials of Construction Insulation (Thickness and Type)
For Instruments—Identify
Indicators Recorders Controllers Show Instrument Lines
For Utilities—Identify
Entrance Utilities Exit Utilities Exit to Waste Treatment Facilities

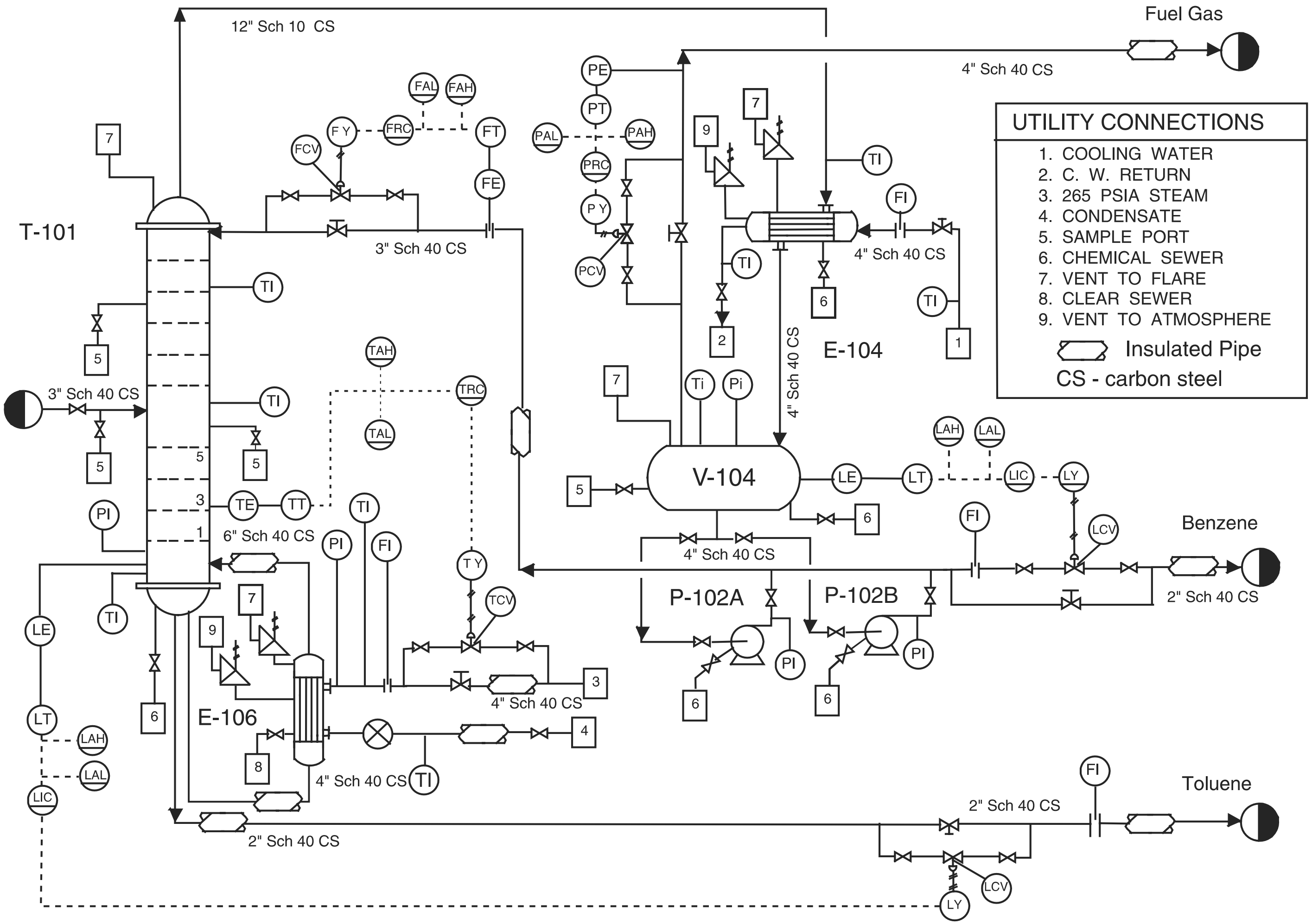

Figure 1.7 Piping and Instrumentation Diagram for Benzene Distillation (adapted from Kauffman, D., *Flow Sheets and Diagrams, AIChE Modular Instruction, Series G: Design of Equipment*, series editor J. Beckman, AIChE, New York, 1986, vol. 1, Chapter G.1.5, AIChE copyright © 1986 AIChE, all rights reserved)

loops. The circular flags on the diagram indicate where the information is obtained in the process and identify the measurements taken and how the information is dealt with. Table 1.10 summarizes the conventions used to identify information related to instrumentation and control. Example 1.9 illustrates the interpretation of instrumentation and control symbols.

Table 1.10 Conventions Used for Identifying Instrumentation on P&IDs (ISA standard ISA-S5-1, [4])

Location of Instrumentation		
○	Instrument Located in Plant	
⊖	Instrument Located on Front of Panel in Control Room	
○ (dotted)	Instrument Located on Back of Panel in Control Room	
Meanings of Identification Letters XYY		
	First Letter (X)	***Second or Third Letter (Y)***
A	Analysis	Alarm
B	Burner Flame	
C	Conductivity	Control
D	Density or Specific Gravity	
E	Voltage	Element
F	Flowrate	
H	Hand (Manually Initiated)	High
I	Current	Indicate
J	Power	
K	Time or Time Schedule	Control Station
L	Level	Light or Low
M	Moisture or Humidity	Middle or Intermediate
O		Orifice
P	Pressure or Vacuum	Point
Q	Quantity or Event	
R	Radioactivity or Ratio	Record or print
S	Speed or Frequency	Switch
T	Temperature	Transmit
V	Viscosity	Valve, Damper, or Louver
W	Weight	Well
Y		Relay or Compute
Z	Position	Drive
Identification of Instrument Connections		
———	Capillary	
—//—	Pneumatic	
········	Electrical	

Example 1.9

Consider the benzene product line leaving the right-hand side of the P&ID in Figure 1.7. The flowrate of this stream is controlled by a control valve that receives a signal from a level measuring element placed on V-104. The sequence of instrumentation is as follows:

A level sensing element (LE) is located on the reflux drum V-104. A level transmitter (LT) also located on V-104 sends an electrical signal (designated by a dashed line) to a level indicator and controller (LIC). This LIC is located in the control room on the control panel or console (as indicated by the horizontal line under LIC) and can be observed by the operators. From the LIC, an electrical signal is sent to an instrument (LY) that computes the correct valve position and in turn sends a pneumatic signal (designated by a solid line with cross hatching) to activate the control valve (LCV). In order to warn operators of potential problems, two alarms are placed in the control room. These are a high-level alarm (LAH) and a low-level alarm (LAL), and they receive the same signal from the level transmitter as does the controller.

This control loop is also indicated on the PFD of Figure 1.5. However, the details of all the instrumentation are condensed into a single symbol (LIC), which adequately describes the essential process control function being performed. The control action that takes place is not described explicitly in either drawing. However, it is a simple matter to infer that if there is an increase in the level of liquid in V-104, the control valve will open slightly and the flow of benzene product will increase, tending to lower the level in V-104. For a decrease in the level of liquid, the valve will close slightly.

The details of the other control loops in Figures 1.5 and 1.7 are left to problems at the end of this chapter. It is worth mentioning that in virtually all cases of process control in chemical processes, the final control element is a valve. Thus, all control logic is based on the effect that a change in a given flowrate has on a given variable. The key to understanding the control logic is to identify which flowrate is being manipulated to control which variable. Once this has been done, it is a relatively simple matter to see in which direction the valve should change in order to make the desired change in the control variable. The response time of the system and type of control action used—for example, proportional, integral, or differential—are left to the instrument engineers and are not covered in this text.

The final control element in nearly all chemical process control loops is a valve.

The P&ID is the last stage of process design and serves as a guide for those who will be responsible for the final design and construction. Based on this diagram,

1. Mechanical engineers and civil engineers will design and install pieces of equipment.
2. Instrument engineers will specify, install, and check control systems.
3. Piping engineers will develop plant layout and elevation drawings.
4. Project engineers will develop plant and construction schedules.

Before final acceptance, the P&IDs serve as a checklist against which each item in the plant is checked.

The P&ID is also used to train operators. Once the plant is built and is operational, there are limits to what operators can do. About all that can be done to correct or alter performance of the plant is to open, close, or change the position of a valve. Part of the training would pose situations and require the operators to be able to describe what specific valve should be changed, how it should be changed, and what to observe in order to monitor the effects of the change. Plant simulators (similar to flight simulators) are sometimes involved in operator training. These programs are sophisticated, real-time process simulators that show a trainee operator how quickly changes in controlled variables propagate through the process. It is also possible for such programs to display scenarios of process upsets so that operators can get training in recognizing and correcting such situations. These types of programs are very useful and cost-effective in initial operator training. However, the use of P&IDs is still very important in this regard.

The P&ID is particularly important for the development of start-up procedures when the plant is not under the influence of the installed process control systems. An example of a start-up procedure is given in Example 1.10.

Example 1.10

Consider the start-up of the distillation column shown in Figure 1.7. What sequence would be followed? The procedure is beyond the scope of this text, but it would be developed from a series of questions such as

a. What valve should be opened first?
b. What should be done when the temperature of . . . reaches . . . ?
c. To what value should the controller be set?
d. When can the system be put on automatic control?

These last three sections have followed the development of a process from a simple BFD through the PFD and finally to the P&ID. Each step showed additional information. This can be seen by following the progress of the distillation unit as it moves through the three diagrams described.

1. **Block Flow Diagram (BFD) (see Figure 1.1):** The column was shown as a part of one of the three process blocks.
2. **Process Flow Diagram (PFD) (see Figure 1.5):** The column was shown as the following set of individual equipment: a tower, condenser, reflux drum, reboiler, reflux pumps, and associated process controls.
3. **Piping and Instrumentation Diagram (P&ID) (see Figure 1.7):** The column was shown as a comprehensive diagram that includes additional details such as pipe sizes, utility streams, sample taps, numerous indicators, and so on. It is the only unit operation on the diagram.

The value of these diagrams does not end with the start-up of the plant. The design values on the diagram are changed to represent the actual values determined under normal operating conditions. These conditions form a “base case” and are used to compare operations throughout the life of the plant.

1.4 ADDITIONAL DIAGRAMS

During the planning and construction phases of a new project, many additional diagrams are needed. Although these diagrams do not possess additional process information, they are essential to the successful completion of the project. Computers are being used more and more to do the tedious work associated with all of these drawing details. The creative work comes in the development of the concepts provided in the BFD and the process development required to produce the PFD. The computer can help with the drawings but cannot create a new process. Computers are valuable in many aspects of the design process where the size of equipment to do a specific task is to be determined. Computers may also be used when considering performance problems that deal with the operation of existing equipment. However, they are severely limited in dealing with diagnostic problems that are required throughout the life of the plant.

The diagrams presented here are in both American Engineering and SI units. The most noticeable exception is in the sizing of piping, where pipes are specified in inches and pipe schedule. This remains the way they are produced and purchased in the United States. A process engineer today must be comfortable with SI, conventional metric, and American (formerly British, who now use SI exclusively) Engineering units.

These additional diagrams are discussed briefly below.

A **utility flowsheet** may be provided that shows all the headers for utility inputs and outputs available along with the connections needed to the process. It provides information on the flows and characteristics of the utilities used by the plant.

Vessel sketches, logic ladder diagrams, wiring diagrams, site plans, structural support diagrams, and many other drawings are routinely used but add little to our understanding of the basic chemical processes that take place.

Additional drawings are necessary to locate all of the equipment in the plant. **Plot plans** and **elevation diagrams** are provided that locate the placement and elevation of all of the major pieces of equipment such as towers, vessels, pumps, heat exchangers, and so on. When constructing these drawings, it is necessary to consider and to provide for access for repairing equipment, removing tube bundles from heat exchangers, replacement of units, and so on. What remains to be shown is the addition of the structural support and piping.

Piping isometrics are drawn for every piece of pipe required in the plant. These drawings are 3-D sketches of the pipe run, indicating the elevations and orientation of each section of pipe. In the past, it was also common for comprehensive plants to build a **scale model** so the system could be viewed in three dimensions and modified to remove any potential problems. Over the past thirty years, scale models have been replaced by three-dimensional **computer aided design (CAD)** programs that are capable of representing the plant as-built in three dimensions. They provide an opportunity to view the local equipment topology from any angle at any location inside the plant. One can actually "walk through" the plant and preview what will be seen when the plant is built. The ability to "view" the plant before construction will be made even more realistic with the help of **virtual reality** software. With this new tool, it is possible not only to walk through the plant but also to "touch" the equipment, turn valves, climb to the top of distillation columns, and so on. In the next section, the information needed to complete a preliminary plant layout design is reviewed, and the logic used to locate the process units in the plant and how the elevations of different equipment are determined are briefly explained.

1.5 THREE-DIMENSIONAL REPRESENTATION OF A PROCESS

As mentioned earlier, the major design work products, both chemical and mechanical, are recorded on two-dimensional diagrams (PFD, P&ID, etc.). However, when it comes to the construction of the plant, there are many issues that require a three-dimensional representation of the process. For example, the location of shell-and-tube exchangers must allow for tube bundle removal for cleaning and repair. Locations of pumps must allow for access for maintenance and replacement. For compressors, this access may also require that a crane be able to remove and replace a damaged drive. Control valves must be located at elevations that allow operator access. Sample ports and instrumentation must also be located conveniently. For anyone who has toured a moderate-to-large chemical facility, the complexity of the piping and equipment layout is immediately apparent. Even for experienced engineers, the review of equipment and piping topology is far easier to accomplish in 3-D than 2-D. Due to the rapid increase in computer power and advanced software, such representations are now done routinely using the computer. In order to "build" an electronic representation of the plant in 3-D, all the information in the previously mentioned diagrams must be accessed and synthesized. This in itself is a daunting task, and a complete accounting of this process is well beyond the scope of this text. However, in order to give the reader a flavor of what can now be accomplished using such software, a brief review of the principles of plant layout design will be given. A more detailed account involving a virtual plant tour of the dimethyl ether (DME) plant (Appendix B.1) is given on the CD accompanying this book.

For a complete, detailed analysis of the plant layout, all equipment sizes, piping sizes, PFDs, P&IDs, and all other information should be known. However, for this description, a preliminary plant layout based on information given in the PFD of Figure B.1.1 is considered. Using this figure and the accompanying stream tables and equipment summary table (Tables B.1.1 and B.1.3), the following steps are followed:

1. *The PFD is divided into logical subsystems.* For the DME process, there are three logical subsections, namely, the feed and reactor section, the DME purification section, and the methanol separation and recycle section. These sections are shown as dotted lines on Figure 1.8.
2. *For each subsystem, a preliminary plot plan is created.* The topology of the plot plan depends on many factors, the most important of which are discussed below.

   In general, the layout of the plot plan can take one of two basic configurations: the grade-level, horizontal, in-line arrangement and the structure-mounted vertical arrangement [5]. The grade-level, horizontal, in-line arrangement will be used for the DME facility. In this arrangement, the process equipment units are aligned on either side of a pipe rack that runs through the middle of the process unit. The purpose of the pipe rack is to carry piping for utilities, product, and feed to and from the process unit. Equipment is located on either side of the pipe rack, which allows for easy access. In addition, vertical mounting of equipment is usually limited to a single level. This arrangement generally requires a larger "footprint" and, hence, more land than does the structure-mounted vertical arrangement. The general arrangement for these layout types is shown in Figure 1.9.

   The minimum spacing between equipment should be set early on in the design. These distances are set for safety purposes and should be set with both local and national codes in mind. A comprehensive list of the recommended minimum distances between process equipment is given by Bausbacher and Hunt [5]. The values for some basic process equipment are listed in Table 1.11.

   The sizing of process equipment should be completed and the approximate location on the plot plan determined. Referring to Table B.1.3 for equipment specifications gives some idea of key equipment sizes. For example, the data given for the reflux drums V-202 and V-203, reactor R-201, and towers T-201 and T-202 are sufficient to sketch these units on the plot plan. However, pump sizes must be obtained from vendors or previous jobs, and additional calculations for heat exchangers must be done to estimate their required footprint on the plot plan. Calculations to illustrate the estimation of equipment footprints are given in Example 1.11.

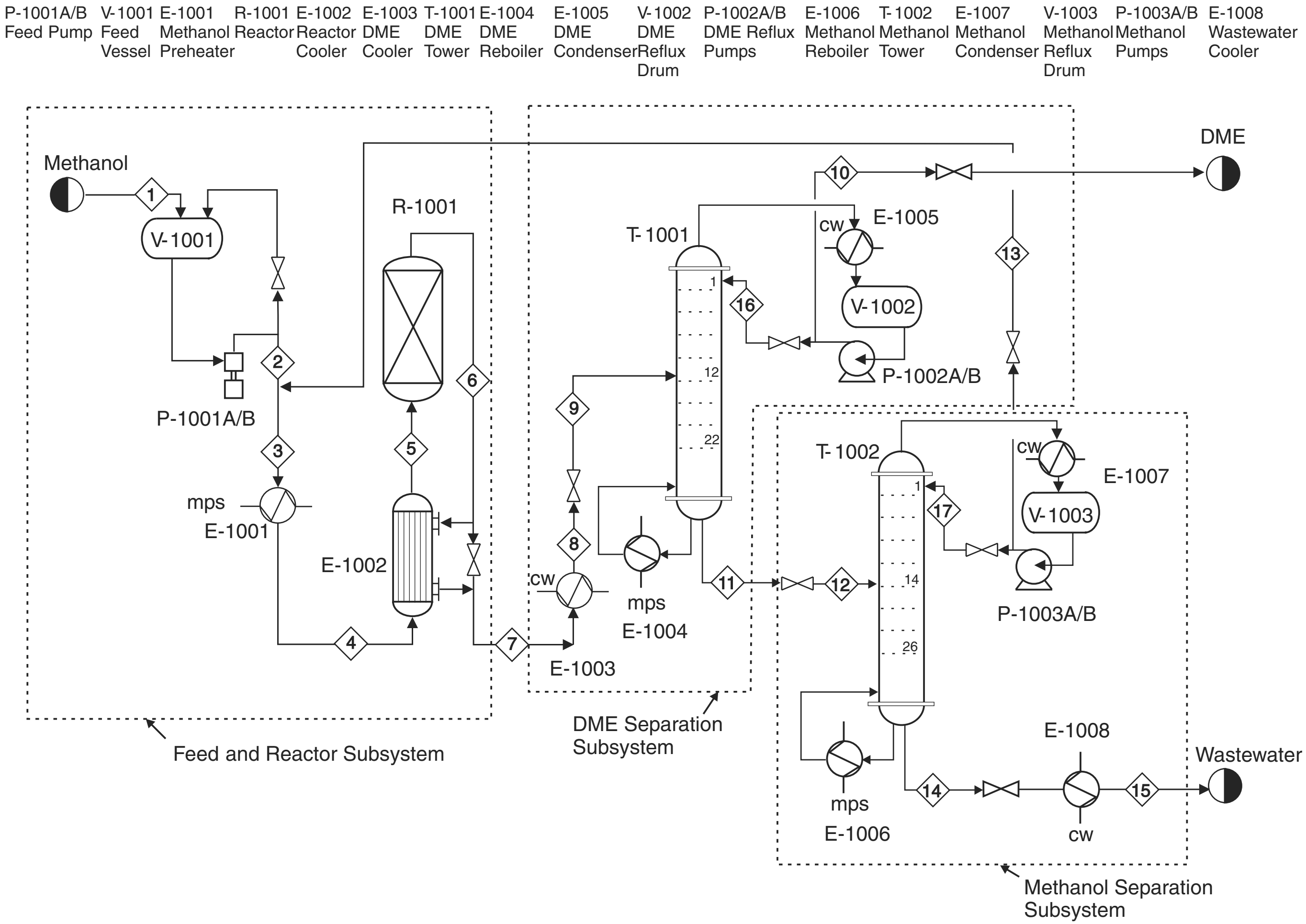

Figure 1.8 Subsystems for Preliminary Plan Layout for DME Process

(a)

(b)

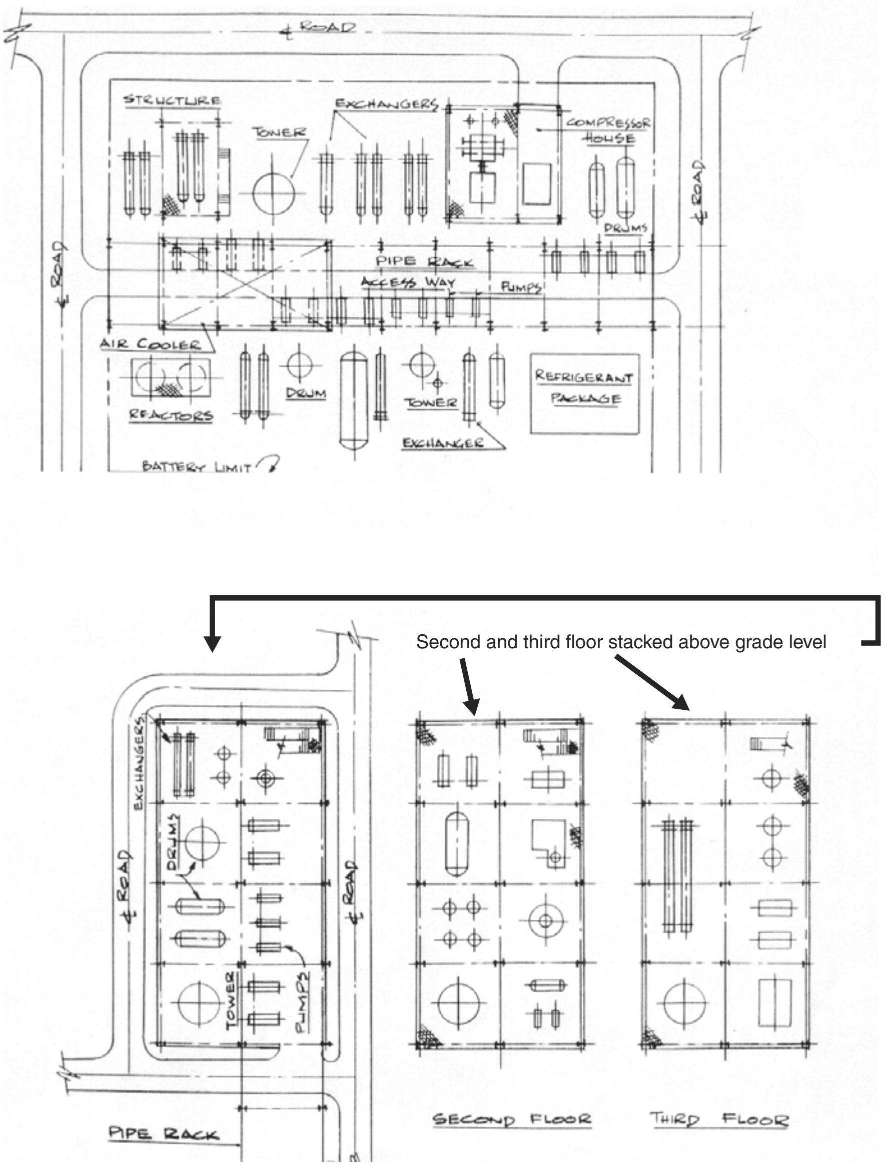

Figure 1.9 Different Types of Plant Layout: (a) Grade-Mounted, Horizontal, In-line Arrangement, and (b) Structure-Mounted Vertical Arrangement (*Source: Process Plant Layout and Piping Design,* by E. Bausbacher and R. Hunt, © 1994, reprinted by permission of Pearson Education, Inc., Upper Saddle River, NJ)

Example 1.11

Estimate the footprint for E-202 in the DME process.
From Table B.1.3 the following information can be found:

Floating-Head Shell-and-Tube design

Area = 171 m^2

Hot Side—Temperatures: in at 364°C and out at 281°C

Cold Side—Temperatures: in at 154ºC and out at 250ºC
Choose a two-shell pass and four-tube pass exchanger
Area per shell = 171/2 = 85.5 m^2
Using 12 ft, 1-in OD tubes, 293 tubes per shell are needed

Assuming the tubes are laid out on a 1¼-in square pitch, a 27-in ID shell is required.

Assume that the front and rear heads (where the tube fluid turns at the end of the exchanger) are 30 in in diameter and require 2 ft each (including flanges), and that the two shells are stacked on top of each other. The footprint of the exchanger is given in Figure E1.11.

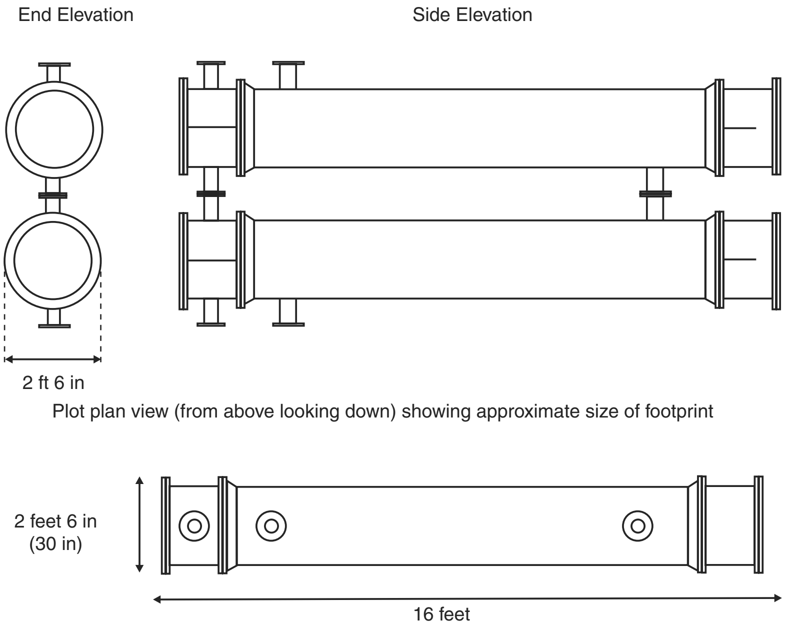

Figure E1.11 Approximate Dimensions and Footprint of Exchanger E-202

Table 1.11 Recommended Minimum Spacing (in Feet) between Process Equipment for Refinery, Chemical, and Petrochemical Plants

	Pumps	Compressors	Reactors	Towers and Vessels	Exchangers
Pumps	M	25	M	M	M
Compressors		M	30	M	M
Reactors			M	15	M
Towers				M	M
Exchangers					M

M = minimum for maintenance access

Source: Process Plant Layout and Piping Design, by E. Bausbacher and R. Hunt, © 1994, reprinted by permission of Pearson Education, Inc., Upper Saddle River, NJ

Next, the size of the major process lines must be determined. In order to estimate these pipe sizes, it is necessary to make use of some heuristics. A heuristic is a simple algorithm or hint that allows an approximate answer to be calculated. The preliminary design of a piece of equipment might well use many such heuristics, and some of these might conflict with each other. Like any simplifying procedure, the result from a heuristic must be reviewed carefully. For preliminary purposes, the heuristics from Chapter 11 can be used to estimate approximate pipe sizes. Example 1.12 illustrates the heuristic for calculating pipe size.

Example 1.12

Consider the suction line to P-202 A/B; what should be the pipe diameter?
From Table 11.8, 1(b) for liquid pump suction, the recommended liquid velocity and pipe diameter are related by $u = (1.3 + D\text{ (in)}/6)$ ft/s.

From Table B.1.1, the mass flowrate of the stream entering P-202, $\dot{m}$ = Stream 16 + Stream 10 = 2170 + 5970 = 8140 kg/h and the density is found to be 800 kg/m^3.
The volumetric flowrate is 8140/800 = 10.2 m^3/h = 0.00283 m^3/s= 0.0998 ft^3/s.

The procedure is to calculate the velocity in the suction line and compare it to the heuristic. Using this approach, the following table is constructed:

Nominal Pipe Diameter (inch)	Velocity (ft/s) = Vol Flow/Flow Area	Velocity (h/s) from $u = (1.3 + D/6)$
1.0	18.30	1.47
1.5	8.13	1.55
2.0	4.58	1.63
3.0	2.03	1.80
4.0	1.14 ⟷	1.97

Therefore, the pipe diameter that satisfies both the heuristic and the continuity equation lies between 3 and 4 in. Taking a conservative estimate, a 4-in suction line is chosen for P-202.

The next step to consider is the placement of equipment within the plot plan. This placement must be made considering the required access for maintenance of the equipment and also the initial installation. Although this step may seem elementary, there are many cases [5] where the incorrect placement of equipment subsequently led to considerable cost overruns and major problems both during the construction of the plant and during maintenance operations. Consider the example shown in Figure 1.10(a), where two vessels, a tower, and a heat exchanger are shown in the plot plan. Clearly, V-1 blocks the access to the exchanger's tube bundle, which often requires removal to change leaking tubes or to remove scale on the outside of the tubes. With this arrangement, the exchanger would have to be lifted up vertically and placed somewhere where there was enough clearance so that the tube bundle could be removed. However, the second vessel, V-2, and the tower T-1 are located such that crane access is severely limited and a very tall (and expensive) crane would be required. The relocation of these same pieces of equipment, as shown in Figure 1.10(b), alleviates both these problems. There are too many considerations of

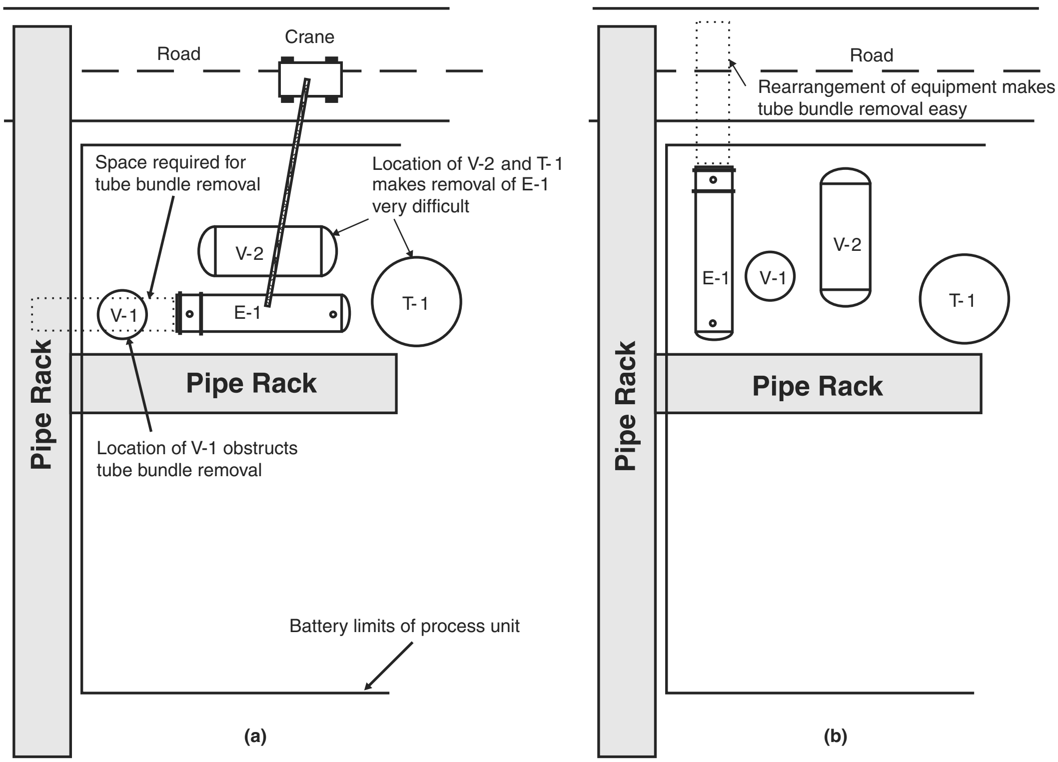

Figure 1.10 The Effect of Equipment Location on the Ease of Access for Maintenance, Installation, and Removal

this type to cover in detail in this text, and the reader is referred to Bausbacher and Hunt [5] for more in-depth coverage of these types of problems. Considering the DME facility, a possible arrangement for the feed and reactor subsection is shown in Figure 1.11.

3. *The elevation of all major equipment is established.* In general, equipment located at grade (ground) level is easier to access and maintain and is cheaper to install. However, there are circumstances that dictate that equipment be elevated in order to provide acceptable operation. For example, the bottoms product of a distillation column is a liquid at its bubble point. If this liquid is fed to a pump, then, as the pressure drops in the suction line due to friction, the liquid boils and causes the pumps to cavitate. To alleviate this problem, it is necessary to elevate the bottom of the column relative to the pump inlet, in order to increase the Net Positive Suction Head Available (for more detail about $NPSH_A$ see Chapter 21). This can be done by digging a pit below grade for the pump or by elevating the tower. Pump pits have a tendency to accumulate denser-than-air gases, and maintenance of equipment in such pits is dangerous due to the possibility of suffocation and poisoning (if the gas is poisonous). For this reason, towers are generally elevated between 3 and 5 m (10 and 15 ft) above ground level by using a "skirt." This is illustrated in Figure 1.12. Another reason for elevating a distillation column is also illustrated in Figure 1.12. Often a thermosiphon reboiler is used. These reboilers use the difference in density between the liquid fed to the reboiler and the two-phase mixture (saturated liquid-vapor) that leaves the reboiler

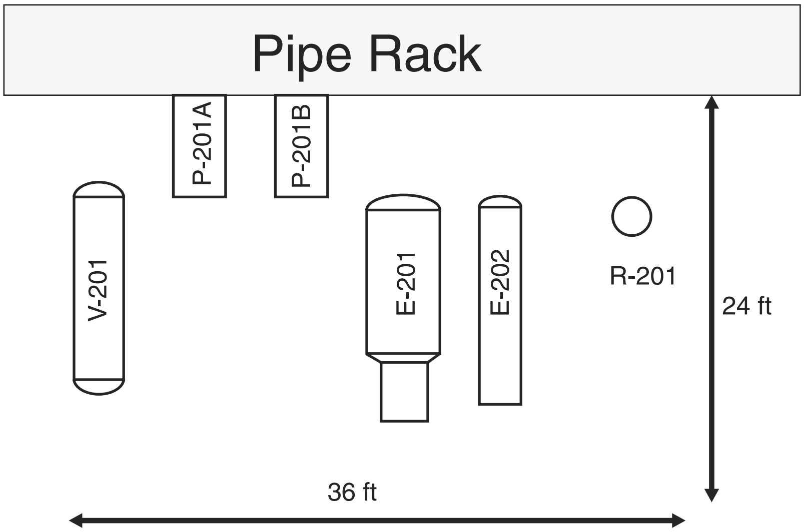

Figure 1.11 Possible Equipment Arrangement for the Reactor and Feed Section of DME Facility, Unit 200

to "drive" the circulation of bottoms liquid through the reboiler. In order to obtain an acceptable driving force for this circulation, the static head of the liquid must be substantial, and a 3–5 m height differential between the liquid level in the column and the liquid inlet to the reboiler is typically sufficient. Examples showing when equipment elevation is required are given in Table 1.12.

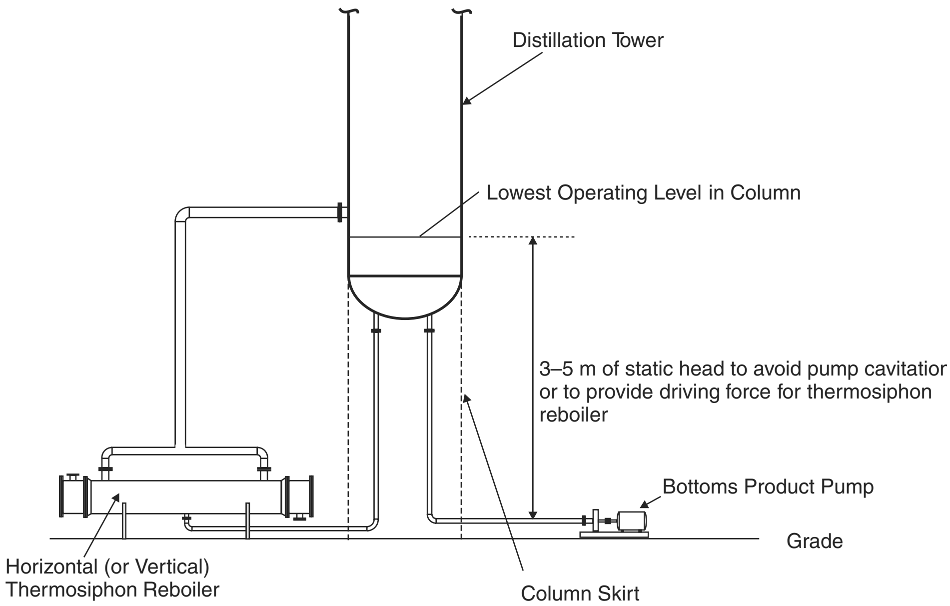

Figure 1.12 Sketch Illustrating Reasons for Elevating Distilling Column

Table 1.12 Reasons for Elevating Equipment

Equipment to Be Elevated	Reason for Elevation
Columns or vessels	When the NPSH available is too low to avoid cavitation in the discharge pump, equipment must be elevated.
Columns	To provide driving head for thermosiphon reboilers.
Any equipment containing suspended solids or slurries	To provide gravity flow of liquids containing solids that avoids the use of problematic slurry pumps.
Contact barometric condensers	This equipment is used to produce vacuum by expanding high-pressure steam through an ejector. The condensables in the vapor are removed by direct contact with a cold-water spray. The tail pipe of such a condenser is sealed with a 34-foot leg of water.
Critical fire-water tank (or cooling water holding tank)	In some instances, flow of water is absolutely critical, for example, in firefighting or critical cooling operations. The main water supply tank for these operations may be elevated to provide enough water pressure to eliminate the need for feed pumps.

4. *Major process and utility piping are sketched in.* The final step in this preliminary plant layout is to sketch in where the major process (and utility) pipes (lines) go. Again, there are no set rules to do this. However, the most direct route between equipment that avoids clashes with other equipment and piping is usually desirable. It should be noted that utility lines originate and usually terminate in headers located on the pipe rack. When process piping must be run from one side of the process to another, it may be convenient to run the pipe on the pipe rack. All control valves, sampling ports, and major instrumentation must be located conveniently for the operators. This usually means that they should be located close to grade or a steel access platform. This is also true for equipment isolation valves.

1.6 THE 3-D PLANT MODEL

The best way to see how all the above elements fit together is to view the Virtual Plant Tour AVI file on the CD that accompanies this text. The quality and level of detail that 3-D software is capable of giving depend on the system used and the level of detailed engineering that is used to produce the model. Figures 1.13–1.15 were generated for the DME facility using the PDMS software package from Cadcentre, Inc. (These figures and the Virtual_Plant_Tour.AVI file are presented here with permission of Cadcentre, Inc.) In Figure 1.13, an isometric view of the DME facility is shown. All major process equipment, major process and utility piping, and basic steel structures are shown. The

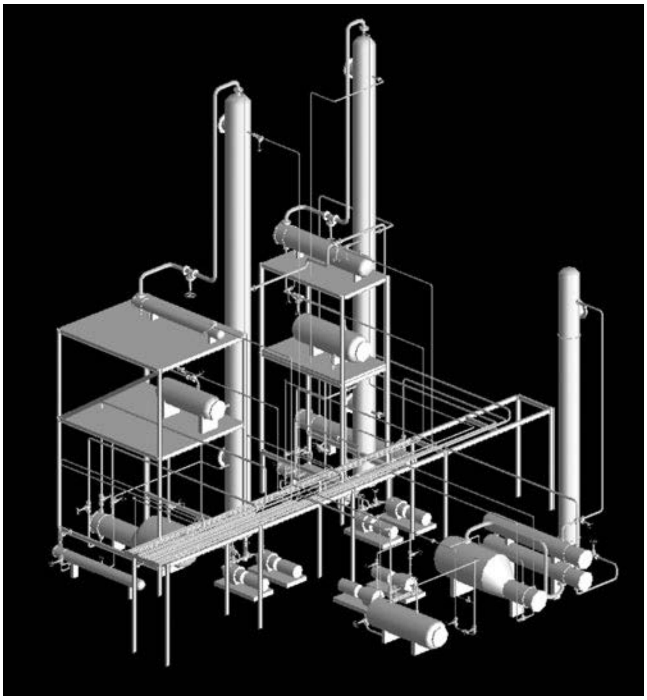

Figure 1.13 Isometric View of Preliminary 3-D Plant Layout Model for DME Process (Reproduced by Permission of Cadcentre, an Aveva Group Company, from their Vantage/ PDMS Software)

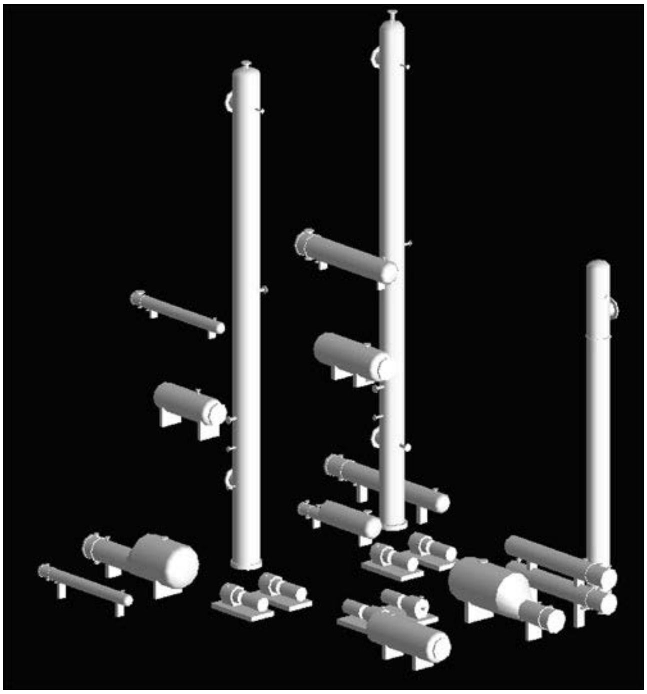

Figure 1.14 3-D Representation of Preliminary Equipment Layout for the DME Process (Reproduced by Permission of Cadcentre, an Aveva Group Company, from their Vantage/ PDMS Software)

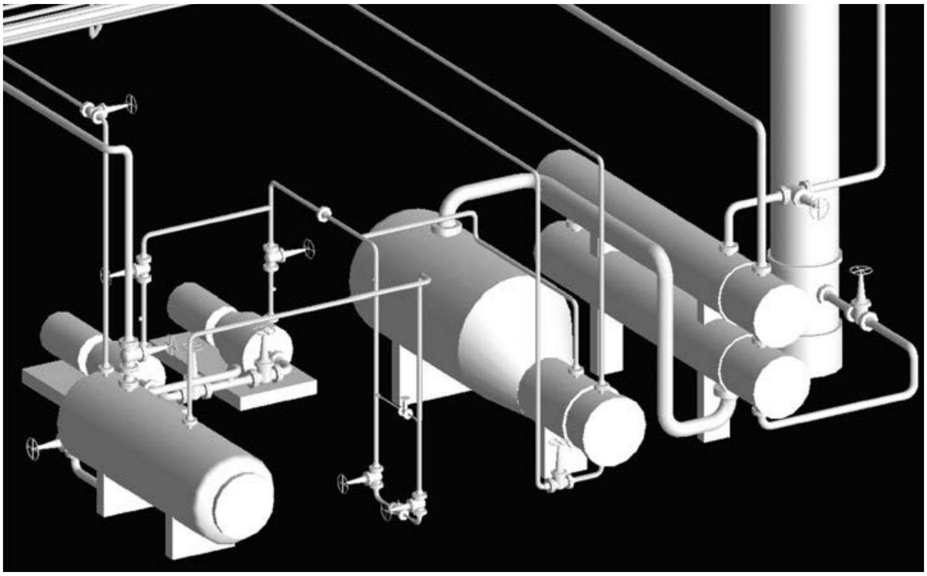

Figure 1.15 3-D Representation of the Reactor and Feed Sections of the DME Process Model (Reproduced by Permission of Cadcentre, an Aveva Group Company, from their Vantage/PDMS Software)

pipe rack is shown running through the center of the process, and steel platforms are shown where support of elevated process equipment is required. The distillation sections are shown to the rear of the figure on the far side of the pipe rack. The reactor and feed section is shown on the near side of the pipe rack. The elevation of the process equipment is better illustrated in Figure 1.14, where the piping and structural steel have been removed. The only elevated equipment apparent from this figure are the overhead condensers and reflux drums for the distillation columns. The overhead condensers are located vertically above their respective reflux drums to allow for the gravity flow of condensate from the exchangers to the drums. Figure 1.15 shows the arrangement of process equipment and piping for the feed and reactor sections. The layout of equipment corresponds to that shown in Figure 1.11. It should be noted that the control valve on the discharge of the methanol feed pumps is located close to grade level for easy access.

1.7 OPERATOR AND 3-D IMMERSIVE TRAINING SIMULATORS

1.7.1 Operator Training Simulators (OTS)

Up to this point in the chapter, the different elements and diagrams used in the specification and description of a process have been covered. The means by which the material balances, energy balances, and design calculations for the various unit operations, required to specify all the design conditions, have been carried out has not been covered. Indeed, the simulation of chemical processes using programs such as CHEMCAD, Aspen Plus, PRO/II, HYSIS, and others is not addressed until much later, in Chapter 13.

Nevertheless, it should be clear that extensive simulation of the process will be required to determine and to specify all of the conditions needed in the design. Typically, these simulations are carried out under steady-state conditions and represent a single design operating point, or possibly are made for several different operating points. The steady-state simulation of the process is clearly very important from the standpoint of defining the design conditions and specifying the equipment parameters, such as vessel sizes, heat-exchanger areas and duties, pipe sizes, and so on. However, once the plant has been built, started up, and commissioned, it is rare that the process will operate at that design condition for any given period of time. Moreover, how the process can be started up or run at, for example, 65% or 110% of design capacity is not evident from the original design. Nevertheless, the plant will be run at off-design conditions throughout its life. In order to help operators and engineers understand how to start up and shut down the process, deal with emergencies, or operate at off-design conditions, an operator training simulator (OTS) may be built.

The foundation of an OTS is a dynamic simulation (model) of the process to which a human machine interface (HMI) is connected. The HMI, in its simplest form, is a pictorial representation of the process that communicates with the dynamic model, and through it, process variables are displayed. The HMI also displays all the controls for the process; an operator can control the process by changing these controls. An example of an HMI is shown in Figure 1.16. This particular example shows a portion of an acid-gas recovery (AGR) unit for an OTS developed by the Department of Energy to simulate an IGCC (Integrated Gasification Combined Cycle) coal-fed power plant. Process variables calculated by the dynamic model are displayed in boxes throughout the HMI. Operators can monitor the change in these variables with time just as they would in a control room situation. The only difference is that the process is simulated rather than actually operating. In general terms, the OTS functions for an operator just as a flight simulator does for a pilot or astronaut. Therefore, operators and engineers can gain operational experience and understanding about a process or plant through the OTS but with the added benefit that any mistakes or errors can be identified and corrected during training sessions without exposing personnel to any risks that might occur if training were to be done on the actual plant.

The starting point for developing an OTS is the steady-state simulation, the equipment information, and instrumentation and control data. In general, the P&IDs are used as the starting point for the generation of the HMI since they contain all the necessary information for the controls and instrumentation. The dynamic model is developed so that the steady-state design condition will be simulated when all the inputs (feeds) are at their design values. Details of how dynamic simulators are used in process design are included in Chapter 17. Needless to say, the development of a fully functioning dynamic model for a process that accurately reflects all the controls and valves in the process is a substantial task that takes a team of engineers many months to accomplish.

1.7.2 3-D Immersive Training Simulators (ITS)

In Section 1.6, the concept of a 3-D plant model was introduced. Such models are "constructed" in an "electronic" environment using precise design data on the size, location and elevation (x-, y-, and z-coordinates), and orientation of each piece of equipment. In addition, the piping arrangement and location of valves, nozzles, instruments, sample ports, drains, and so forth are all specified. Such a representation allows the engineer and

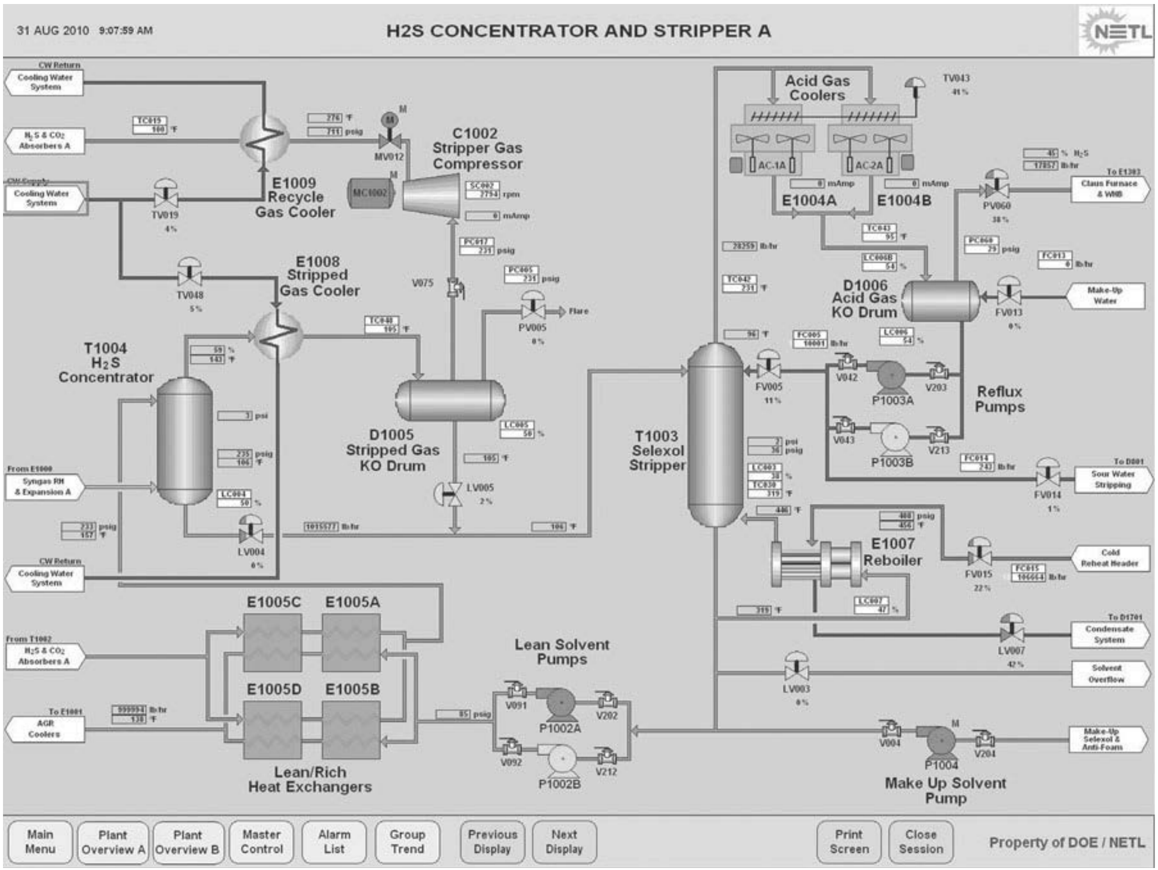

Figure 1.16 Example of an HMI Interface for an OTS (Reproduced by Permission of the DOE's National Energy Technical Laboratory and Invensys Systems Inc., Property and Copyright of Invensys plc, UK)

operator to evaluate the accessibility of critical process components and to obtain a feel for how the plant will look (and operate) when constructed. The engineer may access this information through either a 2-D viewer or a 3-D virtual environment (for example, using 3-D goggles). However, no matter how the information is viewed, the resulting images are essentially static and are generally of low to medium fidelity. Therefore, when viewing a 3-D plant model, it will always be clear to the viewer that it is just a model, and that the representation of the 3-D object is crude.

The visual enhancement of 3-D models using sophisticated imaging software and overlaying photorealistic images on top of a skeleton of the 3-D representation are now not only possible but commonplace for higher-end video games. Computer-generated graphics are now so advanced that, as any movie fan will attest, it is often difficult to determine what is "real" and what is animated. This technology is now being applied to develop 3-D immersive training simulators (ITS) for chemical plants. As can be seen from Figure 1.17, the quality and realism captured by computer-generated graphics are truly amazing. Furthermore, the use of avatars to represent plant operators makes it

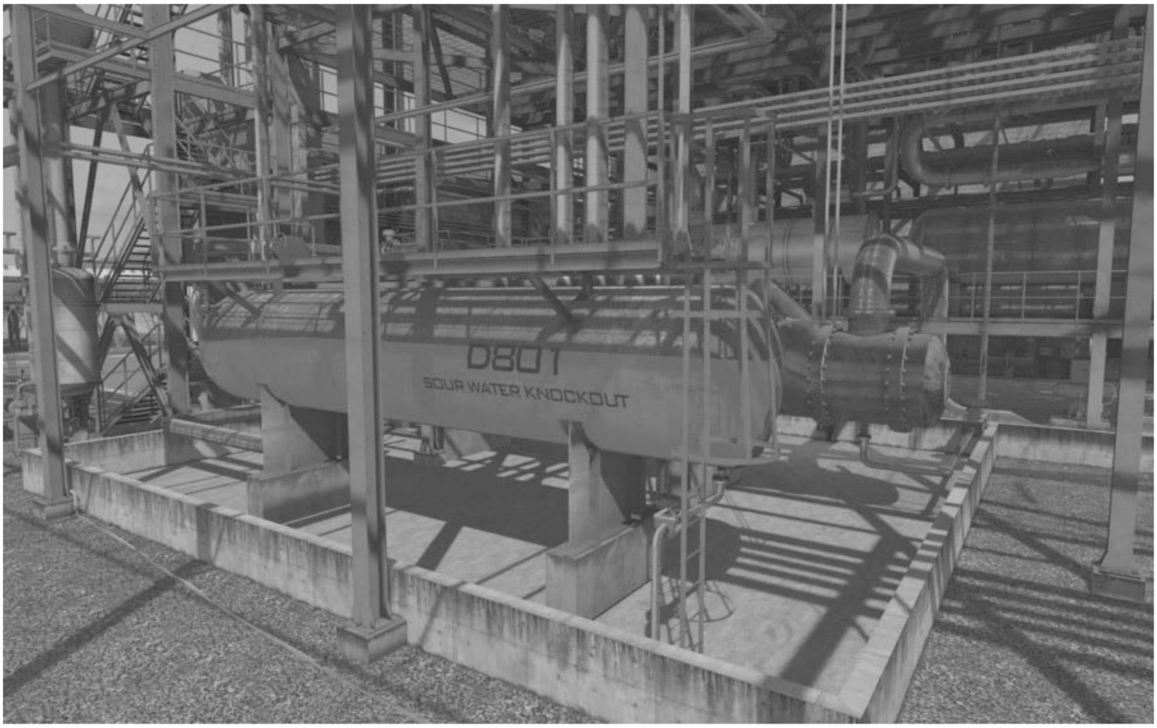

Figure 1.17 An Example of a Computer-Generated Image of a Horizontal Drum (Reproduced by Permission of the DOE's National Energy Technical Laboratory and Invensys Systems Inc., Property and Copyright of Invensys plc, UK)

possible for a user to navigate through, interact with, and be truly immersed in the virtual plant.

1.7.3 Linking the ITS with an OTS

The potential for education and training of engineers, operators, and students using both the OTS and ITS appears to be limitless. Indeed, these two systems can be linked together such that they can communicate, and the real-time operation of the process, both in the control room and outside in the plant, can be simulated in the virtual environment. Consider the following scenario that might occur during the start-up of a chemical process:

Feed to a distillation column from an on-site storage drum has begun. The feed pump has been started and the flow through the pump has been confirmed from the HMI display in the control room. The liquid feed flows into the top of the tower, and the liquid levels on the distillation trays start to increase. The process appears to be working as described in the start-up manual that the operator is following. However, approximately 30 minutes after the start of the feed pumps, a low-level alarm sounds on the on-site storage drum. The operator monitors the level in the drum from the control room and determines that it is continuing to fall and will cause the feed pump to vapor lock (cavitate) if the situation is not remedied. In reviewing the start-up procedure, the operator determines that there is a remote function valve (one that cannot be operated remotely *from the control room) that connects the on-site storage drum to the off-site storage tank, and that this valve may have been closed inadvertently. She then contacts an operator in the field by walkie-talkie and asks him to check the status of the remote function valve. The field operator walks to the storage drum, identifies the tag name on the valve, and confirms that the valve is indeed closed. The control room operator then instructs the field operator to open the valve, which he does. The control room operator then confirms that the level in the drum has started to go back up and thanks the field operator for his help.*

This scenario might well represent an actual incident during a scheduled plant start-up. However, this scenario could just as easily be simulated in the virtual environment. The control room operator would be sitting in front of the HMI screen that is connected to the OTS. A field operator could be sitting in the room next door with a walkie-talkie and wearing 3-D goggles connected to the ITS. The field operator would move his avatar to the location of the on-site storage drum and locate the remote function valve. The field operator using his avatar would then note the setting of the valve and after receiving instructions from the control room operator would open the valve. At this point, the ITS would communicate to the OTS that a valve had been opened, and this would then allow the flow of product to continue to the drum; that is, the dynamic model of the process would respond to the valve being opened and model the flow to the drum. The control room operator, monitoring the HMI, would see the result of the flow of product as an increase in the drum level.

Clearly, any number of scenarios involving control room operators and field operators could be implemented. Moreover, maintenance operations, safety training, and a whole host of other operator functions could be simulated—all in the virtual plant.

Augmented Reality. From the previous example it is clear that any feasible scenario that might occur in the actual plant can be simulated in the virtual environment. However, a series of cases can be simulated that would be almost impossible to simulate in the actual plant but are easily accomplished in virtual reality. For example, it might be helpful to show a young engineer how a particular piece of equipment works by showing him or her the details of the internals of that equipment. In the actual plant, this opportunity might not be available until a scheduled plant shutdown occurs, and that might not happen for one or two years. However, in the virtual environment, the operation of a given piece of equipment can be easily displayed. In fact, the avatar can move into the plant and simply "strip away" the outer wall of a piece of equipment and look inside to see what is happening. This additional feature is sometimes referred to as augmented reality (AR). As an example of AR, the operation of a reboiler and a distillation column is illustrated in Figures 1.18(a) and 1.18(b), respectively.

Another example of AR is the display of process data in the virtual plant. For example, if an operator wanted to check on the trend of a certain process variable, say, the temperature in a reactor, or look at a schematic of a pump, the avatar can simply click on a piece of equipment and display that trend, as shown in Figure 1.19. Clearly, in the virtual environment, there are very few limitations on what information the operator (avatar) can access.

Training for Emergencies, Safety, and Maintenance. The possibilities for training operators and engineers in the virtual plant environment are unlimited. Of particular importance are the areas of safety, emergency response, and routine maintenance. For example, the response of an operator or team of operators to an emergency situation can be

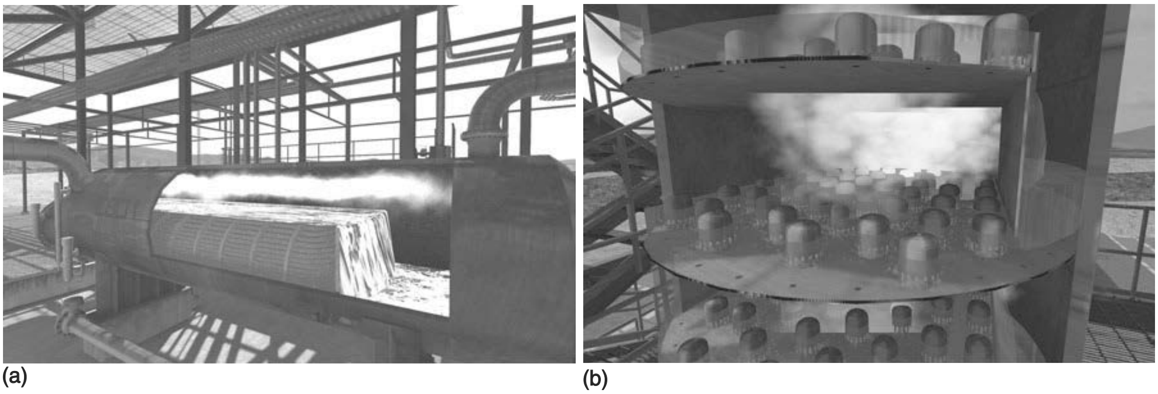

Figure 1.18 Augmented Reality in ITS: (a) Reboiler (b) Bubble-Cap Distillation Column (Reproduced by Permission of the DOE's National Energy Technical Laboratory and Invensys Systems Inc., Property and Copyright of Invensys plc, UK)

monitored, recorded, and played back in the virtual plant. Any mistakes made by the operator(s) can be analyzed, feedback given, and then the exercise can be repeated until the correct response is achieved. Although such training does not absolutely guarantee that when a real emergency arises in the plant the operators will respond correctly, it nevertheless provides crucial emergency training under realistic conditions without the

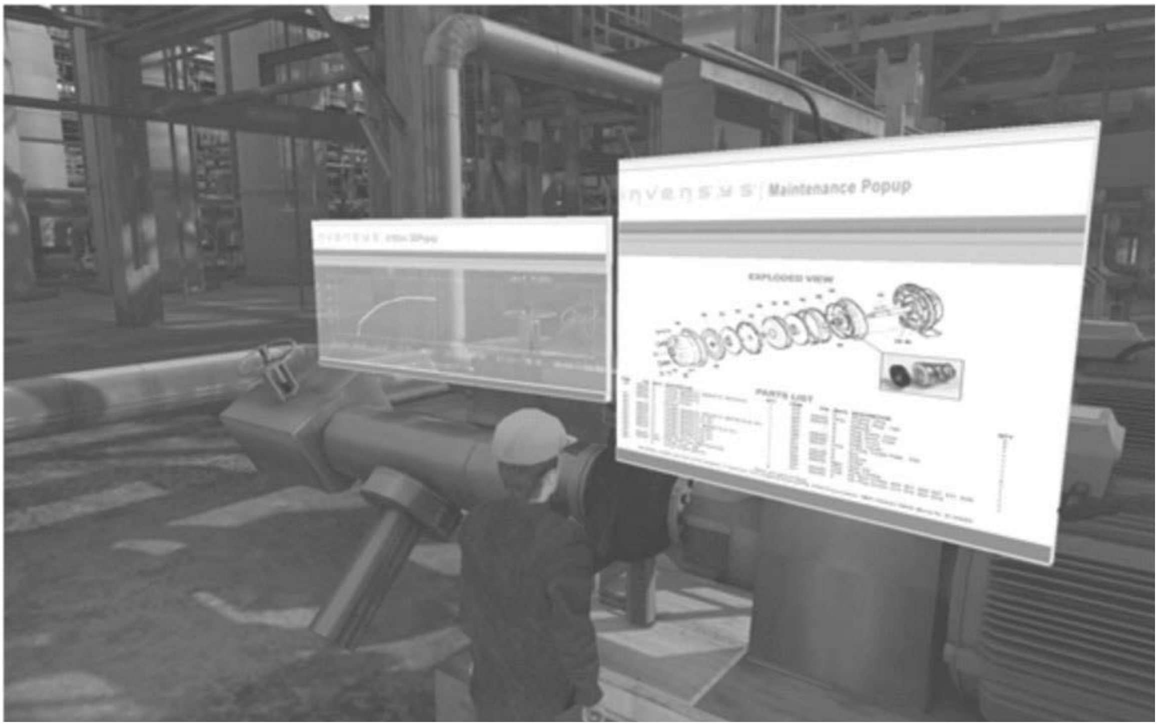

Figure 1.19 An Avatar Can Access Process Trends and Observe Equipment Schematics in AR (Reproduced by Permission of Invensys Systems Inc., Property and Copyright of Invensys plc, UK)

fear of actual harm to personnel and equipment. Furthermore, the more often such scenarios are rehearsed, the more likely are operators to respond correctly when real emergencies occur in the plant.

Corresponding scenarios for safety and maintenance training can also be implemented. Often these activities must follow well-defined procedures, and again, the virtual environment offers a perfect venue to record, analyze, and provide feedback to personnel as they perform these various tasks.

In summary, the use of the virtual plant environment (ITS linked to an OTS) provides unlimited opportunities to a new generation of engineers and operators to learn and to train as process plant personnel and to hone their respective skills in an environment that is both realistic and safe.

1.8 SUMMARY

In this chapter, you have learned that the three principal types of diagrams used to describe the flow of chemical streams through a process are the block flow diagram (BFD), the process flow diagram (PFD), and the piping and instrumentation diagram (P&ID). These diagrams describe a process in increasing detail.

Each diagram serves a different purpose. The block flow diagram is useful in conceptualizing a process or a number of processes in a large complex. Little stream information is given, but a clear overview of the process is presented. The process flow diagram contains all the necessary information to complete material and energy balances on the process. In addition, important information such as stream pressures, equipment sizes, and major control loops is included. Finally, the piping and instrumentation diagram contains all the process information necessary for the construction of the plant. These data include pipe sizes and the location of all instrumentation for both the process and utility streams.

In addition to the three diagrams, there are a number of other diagrams used in the construction and engineering phase of a project. However, these diagrams contain little additional information about the process.

The logic for equipment placement and layout within the process was presented. The reasons for elevating equipment and providing access were discussed, and a 3-D representation of a DME plant was presented. The concept of operator training simulators is presented and the role of 3-D immersive training systems is also introduced.

The PFD is the single most important diagram for the chemical or process engineer and will form the basis of much of the discussion covered in this book.

WHAT YOU SHOULD HAVE LEARNED

- The difference between and uses of the block flow diagram, the process flow diagram, the piping and instrumentation diagram, plot plans, elevation diagrams, and piping isometrics
- A method for drawing consistent process flow diagrams
- How operator training systems and 3-D graphic process representations are used to train operators and engineers

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SHORT ANSWER QUESTIONS

1. What are the three principal types of diagrams used by process engineers to describe the flow of chemicals in a process? On which of these diagrams would you expect to see the following items?
   a. The temperature and pressure of a process stream
   b. An overview of a multiple-unit process
   c. A major control loop
   d. A pressure indicator
   e. A pressure-relief valve
2. A problem has occurred in the measuring element of a level-indicating controller in a batch reactor. To what principal diagram should you refer in order to troubleshoot the problem?
3. Why is it important for a process engineer to be able to review a three-dimensional model (actual or virtual/electronic) of the plant prior to the construction phase of a project?
4. Name five things that would affect the locations of different pieces of equipment when determining the layout of equipment in a process unit.
5. Why are accurate plant models (made of plastic parts) no longer made as part of the design process? What function did these models play and how is this function now achieved?
6. In the context of process modeling tools, what do OTS and ITS stand for?
7. What is augmented reality? Give one example of it.

PROBLEMS

8. There are two common reasons for elevating the bottom of a tower by means of a "skirt." One reason is to provide enough $NPSH_A$ for bottoms product pumps to avoid cavitation. What is the other reason?

9. Which of the principal diagrams should be used to do the following:
   a. Determine the number of trays in a distillation column?
   b. Determine the top and bottom temperatures in a distillation column?
   c. Validate the overall material balance for a process?
   d. Check the instrumentation for a given piece of equipment in a "pre-start-up" review?
   e. Determine the overall material balance for a whole chemical plant?
10. What is the purpose(s) of a pipe rack in a chemical process?
11. When would a structure-mounted vertical plant layout arrangement be preferred over a grade-mounted, horizontal, in-line arrangement?
12. A process that is being considered for construction has been through several technical reviews; block flow, process flow, and piping and instrumentation diagrams are available for the process. Explain the changes that would have to be made to the three principal diagrams if during a final preconstruction review, the following changes were made:
    a. The efficiency of a fired heater had been specified incorrectly as 92% instead of 82%.
    b. A waste process stream flowrate (sent to a sludge pond) was calculated incorrectly and is now 30% greater than before.
    c. It has been decided to add a second (backup) drive for an existing compressor.
    d. The locations of several control valves have changed to allow for better operator access.
13. During a retrofit of an existing process, a vessel used to supply the feed pump to a batch reactor has been replaced because of excessive corrosion. The vessel is essentially identical to the original one, except it is now grounded differently to reduce the corrosion. If the function of the vessel (namely, to supply liquid to a pump) has not changed, answer the following questions:
    a. Should the new vessel have a new equipment number, or should the old vessel number be used again? Explain your answer.
    b. On which diagram or diagrams (BFD, PFD, or P&ID) should the change in the grounding setup be noted?
14. Draw a section of a P&ID diagram for a vessel receiving a process liquid through an insulated 4-in schedule-40 pipe. The purpose of the vessel is to store approximately 5 minutes of liquid volume and to provide "capacity" for a feed pump connected to the bottom of the pump using a 6-in schedule-40 pipe. The diagram should include the following features:
    a. The vessel is numbered V-1402 and the pump(s) are P-1407 A/B.
    b. The discharge side of the pump is made of 4-in schedule-40 carbon steel pipe and all pipe is insulated.
    c. A control valve is located in the discharge line of the pump, and a double block and bleed arrangement is used (see Problem 1.15 for more information).
    d. Both pumps and vessel have isolation (gate) valves.
    e. The pumps should be equipped with drain lines that discharge to a chemical sewer.
    f. The vessel is equipped with local pressure and temperature indicators.
    g. The vessel has a pressure-relief valve set to 50 psig that discharges to a flare system.
    h. The tank has a drain valve and a sampling valve, both of which are connected to the tank through separate 2-in schedule-40 CS lines.

i. The tank level is used to control the flow of liquid out of the tank by adjusting the setting of the control valve on the discharge side of the pump. The instrumentation is similar to that shown for V-104 in Figure 1.7.

15. A standard method for instrumenting a control valve is termed the "double block and bleed," which is illustrated in Figure P1.15.

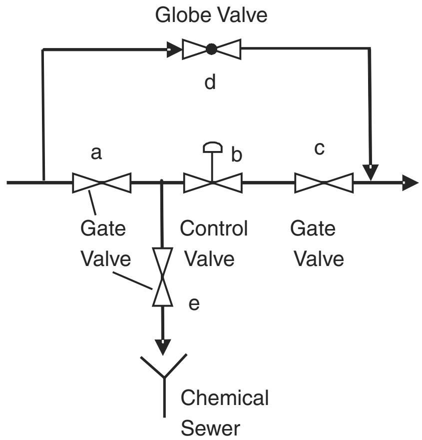


Figure P1.15 Double Block and Bleed Arrangement for Problem 1.15

Under normal conditions, valves a to c are open and valves d and e are closed. Answer the following:

a. Explain, carefully, the sequence of opening and closing valves required in order to change out the valve stem on the control valve (valve b).
b. What changes, if any, would you make to Figure P1.15 if the process stream did not contain a process chemical but contained process water?
c. It has been suggested that the bypass valve (valve d) be replaced with another gate valve to save money. Gate valves are cheap but essentially function as on-off valves. What do you recommend?
d. What would be the consequence of eliminating the bypass valve (valve d)?

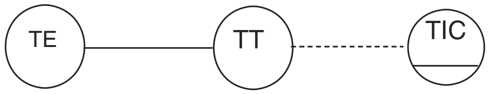
16. Often, during the distillation of liquid mixtures, some noncondensable gases are dissolved in the feed to the tower. These noncondensables come out of solution when heated in the tower and may accumulate in the overhead reflux drum. In order for the column to operate satisfactorily, these vapors must be periodically vented to a flare or stack. One method to achieve this venting process is to implement a control scheme in which a process control valve is placed on the vent line from the reflux drum. A pressure signal from the drum is used to trigger the opening or closing of the vent line valve. Sketch the basic control loop needed for this venting process on a process flow diagram representing the top portion of the tower.

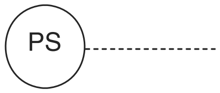
17. Repeat Problem 1.16, but create the sketch as a P&ID to show all the instrumentation needed for this control loop.

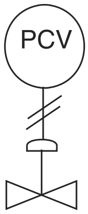
18. Explain how each of the following statements might affect the layout of process equipment:
    a. A specific pump requires a large NPSH.
    b. The flow of liquid from an overhead condenser to the reflux drum is gravity driven.
    c. Pumps and control valves should be located for easy access and maintenance.
    d. Shell-and-tube exchanges may require periodic cleaning and tube bundle replacement.
    e. Pipes located at ground level present a tripping hazard.
    f. The prevailing wind is nearly always from the west.
19. Estimate the footprint for a shell-and-tube heat exchanger from the following design data:
    - Area = 145 m^2
    - Hot side temperatures: in at 300°C, out at 195°C
    - Cold side temperature: bfw at 105°C mps at 184°C
    - Use 12 ft, 1-in OD tubes on a 1 1/4-in square pitch, use a single shell-and-tube pass because of change of phase on shell side
    - Use a vapor space above boiling liquid = 3 times liquid volume
20. Make a sketch of a layout (plot plan only) of a process unit containing the following process equipment:
    - 3 reactors (vertical—diameter 1.3 m each)
    - 2 towers (1.3 and 2.1 m in diameter, respectively)
    - 4 pumps (each mounting pad is 1 m by 1.8 m)
    - 4 exchangers (footprints of 4 m by 1 m, 3.5 m by 1.2 m, 3 m by 0.5 m, and 3.5 m by 1.1 m)

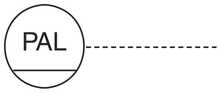
    The two columns and the three reactors should all be aligned with suitable spacing and all the exchangers should have clearance for tube bundle removal.
21. Using the data from Table 1.7, estimate the footprints of all the equipment in the toluene HDA process.
    - For the shell-and-tube exchangers, assume 12 ft, 1.25 in tubes on a 1.5 in square pitch, and assume 2 ft additional length at either end of the exchanger for tube return and feed header.
    - For double pipe exchangers, assume an 8-in schedule-20 OD and a 6-in schedule-40 ID pipe with a length of 12 ft including u-bend.
    - For the footprints of pumps, compressors, and fired heater, assume the following:
        - P-101 use 2 m by 1 m, P-102 use 2 m by 1 m
        - C-101 (+D-101) use 4 m by 2 m
        - H-101 use 5 m by 5 m
22. With the information from Problem 1.21 and the topology given in Figure 1.5, accurately sketch a plant layout (plot plan) of the toluene HDA process using a grade-mounted, horizontal, in-line arrangement similar to the one shown in Figure 1.9. You should assume that the area of land available for this process unit is surrounded on three sides by an access road and that a pipe rack runs along the fourth side. Use the information in Table 1.11 as a guide to placing equipment.

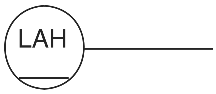
23. What do the following symbols (as seen on a P&ID) indicate?

(a)


(b)


(c)


(d)


(e)


24. Determine all the errors in the section of a P&ID shown in Figure P1.24.

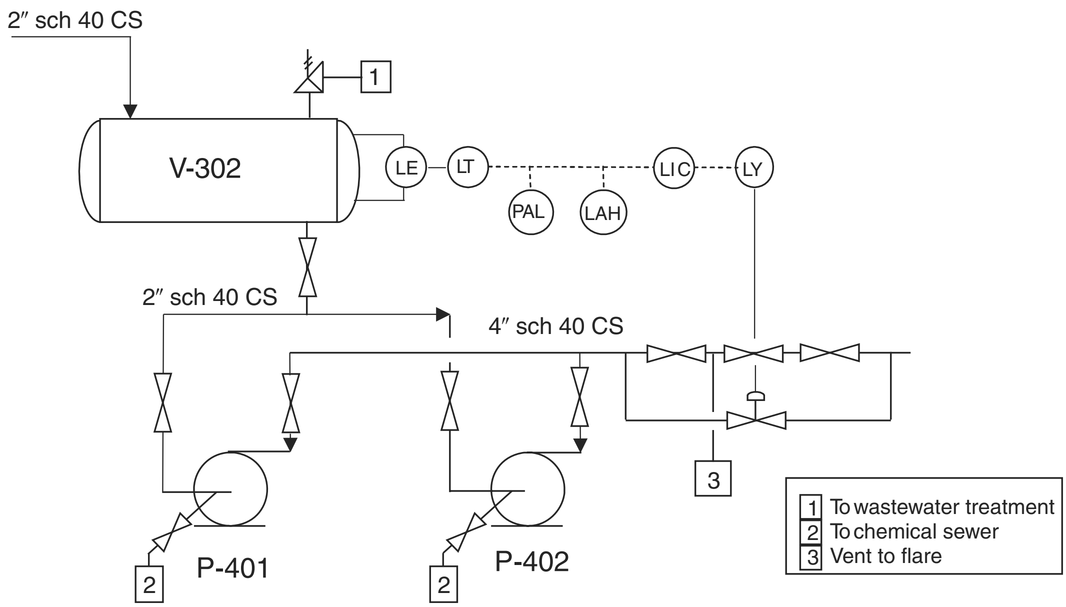


Figure P1.24 A Section of a P&ID to Be Used in Problem 1.24

Index

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F

G

M