In the design and operation of separation processes, there are several factors to be considered that are important regardless of the particular separation methodology. These general processing considerations include contacting modes, effective integration of the separation unit or units into the overall process, development and implementation of a process control strategy, and potential difficulties that arise from particular situations.

The purpose of this chapter is to provide some insight into several areas of importance to the designer or practitioner of separation processes.

4.1 METHODS OF OPERATION

Separation processes are based on the mass transfer of one or more components from one phase to another due to the existence of a driving force arising from differences in chemical potentials. In practice, this requires the intimate contact of the phases for some period of time, during which equilibrium is approached as mass transfer proceeds. A stage is the unit in which the contacting occurs and where the phases are separated physically. A single-stage process is one in which the contacting is done once and, if equilibrium actually is achieved, further classification as an ideal or theoretical stage is appropriate. Because of economic considerations, the contacting time in a particular stage may not be long enough for equilibrium to be reached; the fractional approach to equilibrium is a measure of the mass transfer efficiency of the process.

Consider the following single-stage cocurrent contacting process:

\[
\begin{align*}
y_0, A_0 & \rightarrow \text{Single-stage process} \rightarrow y_1, A_1 \\
x_0, B_0 & \rightarrow \text{process} \rightarrow x_1, B_1
\end{align*}
\]

A steady-state material balance can be used to track the separation taking place in the process. As a simplification, only the transfer of a single component will be considered. Taking into account only the bulk-averaged compositions of the flows into and out of the stage, we can make the following balances:
Total Balance

\[ A_0 + B_0 = A_1 + B_1 \]  
\[(4.1-1)\]

Component Balance

\[ A_0y_0 + B_0x_0 = A_1y_1 + B_1x_1 \]  
\[(4.1-2)\]

where \( A \) and \( B \) refer to the bulk mass or molar flow rates entering and leaving the stage and \( x \) and \( y \) are the mass or mole fractions of the transferring component in \( A \) and \( B \).

The separation taking place in the single-stage process is represented best on an operating diagram which can be drawn from phase equilibrium information available for the system along with the material balance data. In this example, and for any case where the inlet streams to the process are mixed together, the contacting pattern is said to be cocurrent. An operating diagram for the steady-state mass transfer of a single component between two phases is shown in Fig. 4.1-1. This diagram shows the transfer of a component from phase \( A \) to phase \( B \). For transfer in the other direction, the equilibrium line remains the same, but the operating line would be plotted below the equilibrium relationship from the case shown above. As the end of the operating line, representing the exit stream from the process, approaches the equilibrium curve, the single-stage process approaches an ideal or theoretical stage. If the operating line reaches the equilibrium curve, the single-stage device is a theoretical stage.

The shape of the equilibrium curve on the operating diagram arises from the phase equilibria of the system which must reflect changes in temperature, pressure, ionic strength, and so on that occur in the single-stage process. The shape of the operating line reflects changes in the quantity of material in streams \( A \) and \( B \) as mass is transferred from one phase to another. For reasons that will become apparent shortly, it is often desirable, for calculational purposes, to work with linear or nearly linear equilibrium relationships and operating lines.

To reduce the degree of curvature of the operating line, the use of mole or mass ratios often is preferred to mole or mass fractions. This conversion is accomplished by taking the ratio of the number of moles or mass of a transferring species to the number of moles or mass of those components that do not transfer:

\[ \frac{A_s y_0}{1 - y_0} = A_s Y_0 \]  
\[(4.1-3)\]

where \( A_s \) is the mass or molar flow rate of the nontransferring portion of \( A \) and

\[ Y_0 = \frac{\text{moles of transferring component}}{\text{moles of nontransferring component}} \]

A similar expression can be written for stream \( B \). A component balance can be used to derive an operating line expression in terms of mole or mass ratios:

\[ A_s(Y_0 - Y_1) = B_s(X_1 - X_0) \]  
\[(4.1-4)\]

or

\[ -A_s(Y_1 - Y_0) = B_s(X_1 - X_0) \]  
\[(4.1-5)\]

\[ x, \text{ mole or mass fraction} \]

\[ y, \text{ mole or mass fraction} \]

**FIGURE 4.1-1** Operating diagram: single-stage device.
The operating line is therefore a straight line passing through points \((X_0, Y_0)\) and \((X_1, Y_1)\) with a slope of \(-B/A\). All points in the single-stage device must satisfy the material balance and lie on the operating line, although their position on the operating line is a function of the conditions and related phenomena of the separation process of interest.

Because, at best, the exiting streams from a single-stage device will be in equilibrium, it is usually desirable to use multiple stages for a given separation. When multiple stages are used, some thought must be given to the pattern of contacting of the two phases. Cocurrent contacting, where the inlet stream from one phase is mixed with the inlet stream of another phase, can provide, at best, the equivalent of only one theoretical stage no matter how many actual stages are used. Nonetheless, multiple-stage cocurrent contacting is sometimes used to promote better mixing or heat transfer.

To maximize driving forces throughout a particular system, countercurrent contacting is frequently used. In this contacting mode, the inlet stream for one phase is mixed with the outlet stream of the other phase. For the two-stage countercurrent contacting system,

\[
\begin{align*}
Y_0, A_2 \rightarrow & \quad \text{Stage 1} \rightarrow Y_1, A_3 \rightarrow \text{Stage 2} \rightarrow Y_2, A_4 \\
\leftarrow X_1, B_2 \rightarrow & \quad \leftarrow X_2, B_3 \rightarrow \leftarrow X_3, B_4
\end{align*}
\]

the following material balance can be made, using mole or mass ratios:

**Overall Component Balance**

\[
A_1 Y_0 + B_3 X_3 = A_2 Y_2 + B_3 X_3
\]  

(4.1-6)

The operating line for countercurrent contacting is shown in Fig. 4.1-2. Here, the diagram shows the transfer from phase \(A\) to phase \(B\). If transfer were in the opposite direction, the operating line would be located below the equilibrium line. In general, for a given number of stages, countercurrent contacting yields the highest mass transfer efficiency for interphase mass transfer where at least one stream is not a pure component. (This is not to be confused with tray efficiencies which usually represent the fractional approach to equilibrium on a given stage.) The reason for this is that the average mass transfer driving force across the device is greater than would be the case with cocurrent contacting.

Crosscurrent contacting, which is intermediate in mass transfer efficiency to cocurrent and countercurrent contacting, is shown below for a two-stage cascade:

\[
\begin{align*}
Y_0, A_2 \rightarrow & \quad \text{Stage 1} \rightarrow Y_1, A_3 \rightarrow \text{Stage 2} \rightarrow Y_2, A_4 \\
\downarrow & \quad \downarrow & \quad \downarrow & \quad \downarrow \\
X_1, B_2 & \quad X_1, B_3 & \quad X_2, B_3 & \quad X_3, B_4
\end{align*}
\]

Although the phase \(B\) feed to both stages is the same, this need not be the case; the feed rate to each stage can be different as can the composition of that feed stream. To draw the operating diagram, the following balances can be made:

![FIGURE 4.1-2 Operating diagram: countercurrent contacting.](image-url)
As can be seen, the balance for each stage is similar to that for a cocurrent process. However, the stages are coupled. For this case, the operating diagram is presented in Fig. 4.1-3. Crosscurrent contacting is not used as commonly as cocurrent and countercurrent contacting but may be found in extraction, leaching, and drying operations.

**Example 4.1-1 Comparison of Contacting Modes**

To illustrate best the relative efficiencies of the various contacting modes, consider the following example. Suppose we have two discrete stages that can mix and separate phases, and that the stages can be connected cocurrently, crosscurrently, or countercurrently for gas–liquid contacting. Find the contacting pattern that will give the maximum removal of a single transferring component from the gas phase if a fixed amount of solvent is to be used. We have the following data:

- Inlet liquid flow, \( B = 20 \) units/time.
- Inlet liquid composition = 0% transferring component.
- Inlet gas flow, \( A = 20 \) units/time.
- Inlet gas composition = 30 mol % transferring component.
- Only one component transfers between gas and liquid.
- Process is isothermal and isobaric.
- Each stage can be considered to be an ideal stage.
- Equilibrium data in terms of mole ratios: \( Y = 0.408X \), where \( X \) and \( Y \) are the ratios of the transferring component to the nontransferring component.

**Solution.** Consider first a single stage:

\[
A_x(Y_0 - Y_1) = B_x(X_1 - X_0) \tag{4.1-7}
\]

\[
A_x(Y_1 - Y_2) = B_x(X_2 - X_0) \tag{4.1-8}
\]

The inlet gas mole ratio is \( Y_0 = 0.3/(1 - 0.3) = 0.429 \). The inlet liquid mole ratio is \( X_0 = 0.0 \). The ratio of flows of nontransferring components is

\[
\frac{B_x}{A_x} = \frac{20}{20 - 0.3(20)} = \frac{20}{14} = 1.429
\]

**FIGURE 4.1-3** Operating diagram: crosscurrent contacting.
The outlet mole ratios, \( X_x \) and \( Y_x \), can be found through graphical construction on the operating diagram by constructing a line of slope \(-BJ/\mathcal{A}_s\) from \((X_0, Y_0)\) to the equilibrium line since this is a theoretical stage. Since the inlet mole ratio \( X_0 = 0.0 \), an analytical expression can also be developed to find \( X_1 \) and \( Y_1 \).

By material balance,

\[
A_1 Y_0 + B_1 X_0 = A_1 Y_1 + B_1 X_1
\]

But, \( X_1 = Y_1/0.408 \) from the equilibrium relationship. Noting that \( X_0 = 0.0 \) and rearranging, we obtain

\[
Y_1 = \frac{Y_0}{1 + B_1/(0.408 A_1)} = \frac{Y_0}{1 + K}
\]

where \( K \) is the absorption factor, \( K = B_1/\mathcal{A}_s \), and \( m \) is the slope of equilibrium line. By either method,

\[
Y_1 = 0.095 \quad \text{and} \quad X_1 = 0.233
\]

Note that \( K \) is used to represent the absorption factor in this and later examples. However, the symbol for this quantity is often \( \mathcal{A} \).

1. **Cocurrent Contacting.** As stated previously, cocurrent contacting, even for a cascade of stages, yields at best one theoretical stage. This can be demonstrated as follows. Two cocurrent stages in series are shown below:

\[
\begin{align*}
A_1, Y_0 & \rightarrow \text{Stage 1} \rightarrow A_1, Y_1 \rightarrow \text{Stage 2} \rightarrow A_1, Y_2 \\
B_1, X_0 & \rightarrow \text{Stage 1} \rightarrow B_1, X_1 \rightarrow \text{Stage 2} \rightarrow B_1, X_2
\end{align*}
\]

In Fig. 4.1-4a, it is evident that the streams leaving the first stage are in equilibrium. The addition of a second cocurrent stage will not result in any further mass transfer. Using a material balance around stage 2, given the exiting conditions from stage 1, the following analytical expression to determine \( Y_1 \) can be developed:

\[
Y_2 = \frac{Y_1 + (B_1/A_1) X_1}{1 + K}
\]

With \( Y_1 = 0.095 \) and \( X_1 = 0.233 \), the outlet gas composition remains at 0.095. Thus, the addition of another cocurrent stage does nothing to enhance the transfer of solute as will be the case no matter how many stages are added.

2. **Countercurrent Contacting.** The two stages are now arranged countercurrently:

\[
\begin{align*}
Y_0, A_1 & \rightarrow \text{Stage 1} \rightarrow Y_1, A_1 \rightarrow \text{Stage 2} \rightarrow Y_2, A_1 \\
X_0, B_1 & \rightarrow \text{Stage 1} \rightarrow X_1, B_1 \rightarrow \text{Stage 2} \rightarrow X_1, B_1
\end{align*}
\]

A solute balance around stage 1 yields the following result:

\[
Y_1 = \frac{Y_0 + (B_1/A_1) X_2}{1 + K}
\]

A balance around stage 2 gives a similar result:

\[
Y_2 = \frac{Y_1 + (B_1/A_1) X_3}{1 + K}
\]

Recognizing that \( X_3 = 0.0 \) and that \((B_1/A_1)X_2\) is the same as \( K Y_2 \), the following expression can be derived:

\[
Y_2 = \frac{Y_0}{1 + K + K^2}
\]

This means that \( Y_2 = 0.026 \), which is much less than that obtained from the cocurrent case. This result is shown graphically in Fig. 4.1-4b. For the special case in which the inlet liquid contains no transferring
FIGURE 4.1-4 (a) Cocurrent contacting, (b) countercurrent contacting (two stages), and (c) crosscurrent contacting (two stages).

component, the above result can be generalized for any number of stages to

\[ Y_N = \frac{Y_0}{\sum_{n=0}^{N} K^n} \]

which converges to \( Y_N = 0 \) for \( K \geq 1 \) and to \((1 - K)Y_0\) for \( K < 1 \) as \( N \to \infty \).
3. Crosscurrent Contacting. The following arrangement is used for crosscurrent contacting:

Using a material balance around stage 1, with $X_0 = 0.0$, the following expression for $Y_1$ can be developed:

$$Y_1 = \frac{Y_0}{1 + K/2}$$

Similarly, for stage 2, with $X_0 = 0.0$,

$$Y_2 = \frac{Y_1}{1 + K/2}$$

Combining the two expressions, $Y_2$ can be found as a function of $Y_0$:

$$Y_2 = \frac{Y_0}{(1 + K/2)^2}$$

Thus, $Y_2$ thus can be calculated to be 0.057, which is a value intermediate to cocurrent and countercurrent contacting. This result is illustrated in Fig. 4.1-4c. The above result can be generalized for any number of stages:

$$Y_N = \frac{Y_0}{(1 + K/N)^N}$$

which approaches $Y_0/\exp(K)$ as $N \to \infty$. 

![Equilibrium relationship](image)
SUMMARY
In our example, the lowest value of $Y_2$ that can be attained with crosscurrent contacting with the inlet liquid stream split equally among $N$ stages is 0.013. Theoretically, $Y_2$ can be reduced to zero with countercurrent contacting in our example. These results are plotted in Fig. 4.1-5. Thus, this simple example illustrates the relative effectiveness of the three classic contacting modes, which are listed in Table 4.1-1.

4.2 PROCESS SYNTHESIS
After one has obtained the necessary data on physical properties, transport properties, phase equilibria, and reaction kinetics, sorted out the flow of material through the system, and exploited any particular charac-

### TABLE 4.1-1 Comparison of Contacting Modes

Fraction removed for $N$ stages

<table>
<thead>
<tr>
<th>$N$</th>
<th>Cocurrent</th>
<th>Crosscurrent</th>
<th>Countercurrent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.778</td>
<td>0.778</td>
<td>0.778</td>
</tr>
<tr>
<td>2</td>
<td>0.778</td>
<td>0.868</td>
<td>0.940</td>
</tr>
<tr>
<td>3</td>
<td>0.778</td>
<td>0.902</td>
<td>0.983</td>
</tr>
<tr>
<td>4</td>
<td>0.778</td>
<td>0.919</td>
<td>0.995</td>
</tr>
<tr>
<td>5</td>
<td>0.778</td>
<td>0.930</td>
<td>0.999</td>
</tr>
<tr>
<td>$N \to \infty$</td>
<td>0.778</td>
<td>0.970</td>
<td>1.000</td>
</tr>
</tbody>
</table>
teristics for a given separation, perhaps the hardest task remains: For a multicomponent system, how should the choice and sequence of separation tasks be made to maximize efficiency and minimize costs? Process synthesis, despite its critical importance in the design and analysis of separation processes, has only recently emerged as a distinct area of study and research. The pioneering work of Rudd in the late 1960s has led to a high degree of interest in this subject by those involved in plant design and/or the improvement of existing processes. This interest in process synthesis has been fueled by numerous examples of how systematic and informed development of process flowsheets can lead to substantial economic benefits.

Process synthesis represents the inventive aspect of process design. The analytical aspect of design, which is emphasized in undergraduate engineering school curricula, is relatively well established and includes the sizing and specification of the separator and its operating conditions. Sophisticated computer algorithms, which are constantly being improved, can now often be relied on to execute design calculations for individual separators. However, the systematic sequencing of separators (often along with other units such as reactors and heat exchangers) in the best possible arrangement is a complex problem that has not been solved completely except for a few simplified systems.

Process synthesis can be broken down into two broad tasks: (1) selection of the separation technique or techniques to be used for a particular system and (2) the arrangement or sequencing of separators and auxiliary equipment (e.g., heat exchangers) to provide an optimal process from both economic and engineering perspectives. Unfortunately, neither of these objectives can be satisfied independently. For a particular multicomponent separation, there might be several ways in which the products could be recovered; each process to be considered might be composed of a variety of separation techniques arranged in several different configurations. The optimum design must arise from careful consideration of all feasible alternatives, which is usually a complex undertaking.

To illustrate the complexity that must be dealt with in developing an optimal process, Thompson and King made the following calculation. If a process stream containing $N$ components is to be separated into $N$ pure-component products, using $M$ different separation methods, the number of possible sequences $R$ can be determined as follows:

$$R = \frac{[2(N - 1)]!}{N!(N - 1)!} M^{N-1}$$ (4.2-1)

The assumption made in this calculation is that each separator will yield two product streams from one feed stream and each component can exit in only one of these streams. This ignores, for example, distillation columns with sidestream removal. Nonetheless, the combinatorial problem that arises can be monumental for even apparently simple synthesis problems:

<table>
<thead>
<tr>
<th>Components</th>
<th>Separation Methods</th>
<th>Possible Sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>224</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>1,134</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>95,698,746</td>
</tr>
</tbody>
</table>

It should be apparent that as the number of components and possible separation methods increase, the development of an optimal design becomes nearly impossible without some systematic method to discard alternatives that are not feasible.

### 4.2-1 Separation Process Selection

Before one can begin addressing the problem of sequencing separators, the choice of a particular separation method or methods must be made. Of course, decisions are based on both technical and economic merits and it is not uncommon for conflicts to arise. For instance, although the technical feasibility of a given separation method might be attractive, it may not be compatible with the expected product value.

The wide variety of possible choices of separation processes has been catalogued by King. Also, a detailed discussion of procedures for selecting a separation process is provided by Null in Chapter 22. Here, some comments on separation process selection are included to provide some perspective for later discussion.

### Separation Methods

In general, separation methods fall into one of three categories:

- Energy-related separations
Mass-related separations

Transport-related separations

The most common example of the use of an energy-related separating agent is distillation where heat is used to produce two phases of differing composition. In general, the use of an energy-related separating agent also results in a relatively low amount of energy consumption compared to the use of other separating agents. On the other hand, the separation potential (e.g., relative volatilities in distillation) tends to be the smallest for cases in which an energy-related separating agent is used. Crystallization is another example in which an energy-related separation agent is used.

Mass separation agents are employed in processes where an additional phase or phases are added to the system to effect the separation. Extraction and gas absorption are two well-known examples. Because mixing of homogeneous materials is an irreversible process, energy is needed to separate products from the mixture at constant temperature and pressure. This is one reason why mass separating agents usually are associated with lower thermodynamic efficiencies than energy-related separating agents.

Transport-related separations are usually the least energy-efficient but will often produce the highest separation potential. The contacted phases are not allowed to equilibrate and hence a relatively large driving force is maintained across the separator. Advantage is taken of the fact that components will migrate from phase to phase at different rates governed by the relevant transport phenomena. Many diffusional processes fall into this category, including membrane separations.

It should be pointed out that combinations of the above three separation types are frequently found. Extractive and azeotropic distillation, in which a mass separating agent is added to enhance or make feasible a particular separation, are two examples. A recent invention in which distillation and centrifugation are combined to improve the separation potential of ordinary distillation is another example.

STAGING

As was shown in a preceding section, the method of contacting phases can be a crucial consideration in designing an efficient separator. When at least one phase contains more than one component, countercurrent contacting will usually improve the efficiency of the separation. The concept of staging thus becomes an important consideration in choosing a separator. Recall that staging requires the mixing and subsequent separation of phases. (Note that for continuous-contacting devices, such as packed columns, effective staging occurs but not in the discrete manner that is associated with tray columns, for instance. The concept of the height equivalent to a theoretical stage, which is frequently used for systems such as chromatographic separations, is an attempt to make the connection between the efficiencies of the two types of contacting device.) For separation methods such as distillation, where countercurrent and staging can be accomplished within the same vessel, high separation efficiencies can be achieved economically. Membrane processes, however, are often difficult to stage although they generally do have large driving forces for single-stage devices. Therefore, in selecting a separation method, consideration must be given to the ease with which the separator of choice can be used in a multistage configuration.

OTHER CONSIDERATIONS

There are numerous other factors that must be weighed in choosing a separation method. These include the sensitivity of products to operating conditions, the amount of material that must be processed, the value of the product, environmental factors, safety problems, corrosion problems related to materials of construction, and special regulations that may apply (e.g., in the food and drug industries).

Another important but often overlooked consideration is the capability to design accurately and control the separator. It is often the case that the most attractive technical option is the most difficult to design. This is especially true for new technologies but examples can be found of systems that are difficult to design and have been used for 50 years. Precise design usually results in a better functioning process and more attractive economics. Also, where transport-related separations are concerned, overdesign can lead to a failure to accomplish processing objectives. Finally, it is always easier to control a process whose design is well conceived and understood.

Additional discussion of processing considerations will follow later in the chapter.

4.2-2 Sequencing Separation Processes

Once the possible separation methods have been established, it becomes necessary to assemble them into a process flowsheet. Motard and Westerberg cite three problems that arise at this point:

1. How can it be ensured that all alternatives are considered but that infeasible options are ruled out?
2. Can an evaluation process be developed that balances speed and accuracy?
3. In an evolutionary sense, what strategy can be adopted that continually moves toward better alternatives?

Despite a fair amount of effort to find a process synthesis methodology that can handle the above problems,
FIGURE 4.2-1 Separation of feed stream into pure components A, B, and C through (a) ordinary distillation and (b) a more complex arrangement that includes thermal coupling and sidestream feed and removal.

no techniques currently exist that are universally applicable. Most of the work reported in the literature deals with simple (a single feed stream is divided into two product streams) or sharp (each entering component exits in only one product stream) separations. In considering only these types of separations, many economically attractive alternatives are neglected; for instance, multiple feed and removal streams from a distillation column may reduce the number or size of columns needed for a particular separation. Also, effective heat exchange may improve the thermodynamic efficiency of the system. (See Fig. 4.2-1.) Nonetheless, the complexity associated with sequencing simple, sharp separators still represents a considerable challenge as evidenced by the previously cited calculation of Thompson and King.¹

**PROCESS SYNTHESIS METHODOLOGIES**
Although there are numerous approaches to synthesizing an optimal process for a particular separation or separations, they usually can be categorized as heuristic, evolutionary, or algorithmic.

In practice, most methodologies used today are hybrid techniques based on features of at least two of
Heuristic Approaches. To facilitate the development of flowsheets and subsequently improve an existing flowsheet, rules of thumb have been suggested by those experienced with the design and sequencing of separators. These rules of thumb, or heuristics, are somewhat empirical but useful guidelines for choosing and sequencing separations. It must be stressed that the heuristics are not absolutes and must be applied carefully if they are to serve a purpose. Also, the most commonly used heuristics can be contradictory, which can lead to two or more sequences being suggested. Nevertheless, even with the advent of digital computing for computer-aided process synthesis, heuristics almost always are factored into sequencing and selection decisions. This is because their usage reduces an overwhelmingly complex combinatorial problem into a more tractable one.

Process synthesis heuristics fall into several categories. Many of these were proposed originally for multicomponent distillation but have since been applied to other types of separation. Some heuristics have been verified through calculation and experimentation while others are described best as common sense. In any case, they serve as effective guidelines in the selection and sequencing of separation processes.

Presented below is a list of those heuristics most commonly cited in separation process synthesis. This is certainly not a complete list but a compilation of several proposed in the literature. If anything, what is needed is a more detailed list of heuristics that have been tested through calculation and experimentation. As more emphasis is placed on process synthesis as a vital part of process design, a more comprehensive and useful set of heuristics will evolve.

General Heuristics. Below are listed a set of heuristics that generally are applicable to separation process synthesis. A summary of these heuristics appears in Table 4.2-1.

1. Select the Separation Methods First. Rudd et al. point out that for a given process the most difficult task involves separating components from a mixture. In the section on selection of separation techniques, many of the factors that must be taken into account during the separation task selection were pointed out. The most important consideration involves evaluating the basis for separation which requires examining data on physical and chemical properties. Ranked lists are generated that are then used to evaluate possible separation methods. For instance, if components A, B, C, D, and E are to be separated, their relative volatilities and solubilities in a particular solvent may be pertinent. The following ranked lists, in descending order, might result:

<table>
<thead>
<tr>
<th>Normal Boiling Point</th>
<th>Solubility in Solvent</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>B</td>
<td>E</td>
</tr>
<tr>
<td>C</td>
<td>A</td>
</tr>
<tr>
<td>D</td>
<td>B</td>
</tr>
<tr>
<td>E</td>
<td>D</td>
</tr>
</tbody>
</table>

Depending on the objectives of the process, distillation or extraction (or, perhaps, a combination of both) might be used to affect the separation. If component C is the only desired product, an extraction scheme might be preferred while distillation might be used if only A is desired. For multiple products, the separation problem becomes more complex but can be approached by examining the possible splits in the ranked lists.

When using ranked lists as a basis for separation process selection, avoid separation factors close to one and draw on experience to weigh theoretical potential with practical expectations. A more detailed discussion of the selection of a separation process is given in Chapter 22.

TABLE 4.2-1 Summary of General Heuristics

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Select the separation methods first.</td>
</tr>
<tr>
<td>2.</td>
<td>Always attempt to reduce the separation load.</td>
</tr>
<tr>
<td>3.</td>
<td>Remove corrosive and unstable materials early.</td>
</tr>
<tr>
<td>4.</td>
<td>Separate the most plentiful components early.</td>
</tr>
<tr>
<td>5.</td>
<td>Save the most difficult separations for last.</td>
</tr>
<tr>
<td>6.</td>
<td>Separations with high recovery fractions should be done last.</td>
</tr>
<tr>
<td>7.</td>
<td>Move toward sequences with the smallest number of products.</td>
</tr>
<tr>
<td>8.</td>
<td>Avoid adding foreign species to the separation sequence.</td>
</tr>
<tr>
<td>9.</td>
<td>If used, immediately recover a mass separating agent.</td>
</tr>
<tr>
<td>10.</td>
<td>Do not use another mass separating agent to recover the original one.</td>
</tr>
<tr>
<td>11.</td>
<td>Avoid extreme operating conditions.</td>
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2. **Always Attempt to Reduce the Separation Load.** Rudd et al.\(^5\) assume that operations to mix and divide process streams are relatively inexpensive as long as no component separation is required. It is usually better to blend two streams of similar composition and separate the species of interest than to treat each stream independently.

3. **Remove Corrosive and Unstable Materials Early.** The early separation of corrosive and unstable materials is desirable. The early removal of corrosive materials probably will increase the lifetime of downstream processing units or allow them to be constructed of less expensive materials. Unstable species that are sensitive to temperature, shear, and so on should be removed early, as should potentially toxic components. Components that might undergo unfavorable side reactions also should be removed early.

4. **Separate the Most Plentiful Components Early.** Components comprising a large fraction of the feed should be removed first. Clearly, the separation load will depend on the amount of material to be processed. By reducing the amount of this material early in the sequence, processing costs can be cut.

5. **Save the Most Difficult Separations for Last.** When the differences in properties (boiling point, density, etc.) of the components to be separated are not far apart, separation of those components is done best in the absence of other nonkey components. In the case of gas absorption, as the solubility of a particular component in a solvent decreases, the number of trays or height of packing required for the separation increases. Also, as the liquid and gas inventories in the column go up, the diameter of the column goes up. Thus, as the amount of material to be processed is reduced, so too is the cost of the separation. The same argument is equally valid when a particularly difficult separation requires specialized equipment.

6. **Separations with High Recovery Fractions Should Be Done Last.** This heuristic follows 5 and is justified by the same arguments.

7. **Move Toward Sequences with the Smallest Number of Products.** Usually, following this strategy will result in the need for the minimum number of separators.

8. **Avoid Adding Foreign Species to the Separation Sequence.** It is best to avoid adding mass separating agents, such as in azeotropic distillation and leaching, because these agents subsequently must be recovered, often creating a separation problem. This is one reason why energy separating agents often are preferred.

9. **If Used, Immediately Recover a Mass Separating Agent.** The mass-related separating agent should be recovered in a subsequent step so that it does not interfere with downstream processing. This is important because mass separating agents usually are found in large quantities and often are chemically different from the original feed stream. Of course, if the mass separating agent facilitates downstream separations (which is rare), it should be left in the system.

10. **Do Not Use Another Mass Separating Agent to Recover the Original One.** It is obvious that this might complicate the original separation problem and negate any benefit associated with adding a mass separating agent in the first place.

11. **Avoid Extreme Operating Conditions.** This heuristic is aimed primarily at conditions of extreme temperature and pressure. If excursions in temperature or pressure are necessary, it is better to aim high rather than low. For the case of temperature, heating costs are usually significantly lower than refrigeration costs, often by a factor of 5 or more. Also, pressure equipment is easier to build and maintain than vacuum equipment.

**Heuristics for Multicomponent Distillation Sequences.** The origin of many heuristics can be traced to multicomponent distillation problems and, with the possible exception of heat exchange network synthesis, most process synthesis study has been in this area. This is not surprising since distillation is the backbone of the chemical industry. Heuristics for multicomponent distillation are summarized in Table 4.2-2 and discussed below.

1. **Favor Distillation.** Because of the vast experience associated with the design and operation of distillation columns, this separation technique almost always is considered for fluid-fluid separations. Because energy is used as the separating agent, thermodynamic efficiencies can be high and the addition of foreign components to the system is avoided. (Azeotropic and extractive distillation are two notable exceptions.) Also, staging is accomplished easily within the column. Even though energy costs are constantly rising (distillation is said to account for 3% of the energy consumption in the United States), possible alternatives to distillation such as adsorption, chromatography, and membrane processes are technologically

<table>
<thead>
<tr>
<th>TABLE 4.2-2 Summary of Heuristics for Multicomponent Distillation</th>
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<tr>
<td>1. Favor distillation.</td>
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<tr>
<td>2. For distillation, favor sequences that remove components one-by-one as overhead product.</td>
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<tr>
<td>3. As a rule, favor splits that yield equal-sized parts.</td>
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<tr>
<td>4. Favor sequences that recover the most valuable species as a distillate product.</td>
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young and are only beginning to be tried at scales necessary to be competitive. Because of the years of operating experience and the vast amount of study and research put into distillation, it is known to be a reliable and, therefore, desirable separation method.

2. For Distillation, Favor Sequences that Remove Components One-by-One as Overhead Product. This advice is based on the need to condense or remove heat from overhead streams and add heat to bottom streams. Adding non-key components to the overhead stream increases the cooling load on the overhead condenser and the heating load on the reboiler for a simple column. Removing components one-by-one in order of decreasing volatility also minimizes the vapor flow in the column supporting a direct sequence.

For example, if A, B, and C are components to be separated and their boiling points increase as A → B → C, there are two possibilities for sequences for a simple, sharp separation as shown in Fig. 4.2-2. This heuristic favors the direct sequence because it removes the products one-by-one as distillates and therefore minimizes vapor flow in the column. Lockhart points out, however, that the direct sequence is not optimal when the least-volatile component is the primary constituent of the feed stream. In this case, the indirect sequence is preferred.

3. As a Rule, Favor Splits that Yield Equal-Sized Parts. Splitting the feed stream into equal-sized parts leads to a better thermodynamic efficiency in a simple distillation column. This is true because the column traffic in the sections above and below the feed will have better balance.

4. Favor Sequences that Recover the Most Valuable Species as a Distillate Product. By forcing the product away from the bulk stream, higher purities generally will result. Recovery as a distillate product is desirable because it avoids the higher temperatures present in the reboiler which could lead to degradation.

Discussion. The use of heuristics for sequencing multicomponent distillation systems, as well as for separation processes in general, must be used with some discretion on the part of the design engineer. For certain separation problems, some heuristics will be more pertinent than others and for this reason the systematic application of heuristics is difficult. Since heuristics also usually apply to simple, sharp separations, more complex schemes that may be advantageous often are ignored. For example, Petlyuk et al.⁷ and Stupin and Lockhart⁸ showed that more complex separation schemes can be an improvement to the
direct and indirect sequences normally considered. For distillation, they pointed out that the use of intermediate condensers and reboilers can lead to a system that more closely approaches a thermodynamically reversible distillation.

Attempts to apply heuristics systematically to sequencing and selecting separation processes will be discussed in a later section.

**Evolutionary Methods.** The objective of all evolutionary methods for selecting and sequencing separation processes is a systematic approach to an optimal system. These methods all seek to improve the existing flowsheet. Stephanopoulos\(^6\) describes the elements of an evolutionary strategy as follows:

1. Generation of the initial separation sequence.
2. Identification of evolutionary rules.
3. Determination of the evolutionary strategy.

**Generation of the initial separation sequence** is a critical step in finding an optimal process. It is not surprising then that the heuristics discussed in the previous section often are used in the generation of the initial flowsheet. In addition to these heuristics, several workers have suggested additional rules to be followed or have suggested simply a prescribed order in which existing heuristics be applied (Seader and Westerberg,\(^{10}\) Nath and Motard,\(^{11}\) Westerberg,\(^{12}\) Nadgir and Liu\(^{13}\)). Often, the best way to generate an initial flowsheet is to examine similar processes (found in practice or in the literature) that will lead to a feasible initial sequence. Carefully selected initial sequences will be those that are closest to the optimum, and, conversely, poor initial choices may lead to failure in finding the optimal or nearly optimal sequence.

**Identification of evolutionary rules** establishes criteria to evaluate possible changes in the initial sequence. The best set of rules will not only help to identify feasible alternatives but also ensure consideration of all promising sequences. Major changes at each iteration should be avoided so that alternatives worth consideration are not passed over. Examples of rules developed for evolutionary methods can be found in the literature (Stephanopoulos and Westerberg\(^{14}\)). Often the rules involve picking the separation method, characterizing its effect on the sequence, moving the separator earlier in the process, and finally evaluating alternative separation methods at that point in the sequence. As changes are made, downstream product distributions will vary and existing separators in the flowsheet must be altered to achieve the desired product distribution.

The most important step in evolutionary methods is the **determination of the evolutionary strategy.** Perhaps the most difficult part of any design process is developing a strategy that directly leads to improvements in existing flowsheets. Many strategies can be characterized as either *depth-first* or *breadth-first,* both of which are tree-search or network methods. *Depth-first* strategies are aimed at generating a sequence that appears to be an optimum through the repeated application of one or more evolutionary rules. Additional criteria are applied to determine if an optimum in fact has been reached and, if necessary, to suggest an improvement. In this strategy, the optimum will arise through repeated modification of an existing detailed flowsheet.

*Breadth-first* strategies involve the generation of a number of possible sequences that may arise from a single change in an existing flowsheet. All are evaluated and the most promising is selected as a basis for generating another set of flowsheets. Heuristics may be applied through a prescribed weighting procedure to help identify the best choices. The optimum is near when the next generation of flowsheets offer little, if any, improvement over the one from which they were created.

Effective evolutionary methods are important for systematic process synthesis. They usually contain either heuristic or algorithmic elements and can be used effectively with computer-aided design packages.

**Algorithmic Methods.** The use of algorithmic approaches to process synthesis is, in theory, the only certain way to develop an optimal process. This is true because every possible process sequence can be considered rigorously. Unfortunately, because of the nature of the combinatorial problem that arises, even for relatively simple situations, the use of strictly algorithmic approaches is often unrealistic. However, when they are used in conjunction with heuristic and evolutionary strategies, they represent the best hope for rational process synthesis.

As the space of feasible alternatives is increased, the difficulty in finding an optimum process sequence also increases. Factored into most algorithmic approaches is some method to reduce the space of alternatives. In this case, heuristics often are employed in some systematic fashion to rule out options. *Decomposition methods* also are used to attempt to break the problem down into subproblems that can be handled by existing technology. *Bounding methods,* which often are programmed on a computer, can be used to provide some structure to the problem and to reduce the set of alternatives. The idea here is to set some criteria with which to evaluate options at each level of the problem so that only the better alternatives are explored. While bounding methods can be used to find directions to take on each level of the sequence, there is always the chance that the optimum may not be found; setting the bounds in itself can be a critical step.

Decomposition and bounding methods are ways to reduce the problem of balancing speed and accuracy
which often plagues strictly algorithmic approaches to process synthesis. It should be noted that some or all of the above approaches can be combined to reduce the space of alternatives that must be considered by any algorithmic method.

4.2.3 Energy Integration in Process Synthesis

The motivation behind many efforts to sequence separation processes optimally is to reduce energy consumption. Examination of the lists of process heuristics points out this orientation. Unfortunately, addition of energy integration considerations to the often overwhelmingly complex sequencing problem creates an even more difficult situation. This is mainly the result of the fact that the sequencing and energy integration tasks cannot be handled separately. For example, the balance between reflux ratio and the number of stages for columns in a distillation sequence must take into account energy costs. These energy costs are influenced by the degree of heat integration that might be achieved with other parts of the process. Despite the complexity of the problem, effective energy integration for multicomponent separations can produce significant cost reductions and always must be considered if an optimal process is to be developed.

**Minimum Work**

The concepts of *minimum work* and *reversibility* often are applied in the energy analysis of single-stage or multistage separations. From a thermodynamic standpoint, energy efficiency will be best for those processes that approach *reversibility* or minimize the generation of entropy. In a conceptual framework, a process that is thermodynamically reversible can be used as a standard of comparison for evaluating the energy efficiency of a real process. When energy separating agents are used, such as for simple distillation and crystallization, the process is potentially reversible because energy is added as heat. When mass separating agents are used, such as in absorption and extraction, the resulting process is partially reversible because of the inherent irreversibility of homogeneous mixing operations. Separations based on transport phenomena are rate governed and generally irreversible, as would be the case for membrane separations.

To a large extent, *minimum work* for a single separation unit is a function of the separation method used and arises from the degree of irreversibility associated with a given technique. In a sense, *minimum work* can be viewed as a measure of the difficulty of a particular separation. Thus, the actual work for the separation can be compared to the minimum work to provide a measure of energy efficiency. The use of this analysis for separations in which an energy separating agent is involved requires some mechanism for converting heat into work (net work consumption). One possibility for this conversion is through a reversible heat engine. The result of a calculation of this sort is to determine the efficiency of the process; efficiencies of less than 100% are the result of irreversibilities or lost work.

In a practical sense, this type of analysis can be put to use in energy integration schemes. For example, when heat is to be exchanged, it should be done in as thermodynamically reversible a way as possible; that is, exchange heat between streams that are close in temperature. When sequences of separators are considered, the energy analysis can no longer be applied only to single separators. The potential for heat exchange will have a bearing on the sequencing as well as on the selection of separation tasks. Thus, the minimum work for the separation sequence should be considered when a search for an optimum is done.

For more information, the reader is referred to the works of Linnhoff, De Nevers, Sussman, and De Nevers and Seader. Also, the texts of King and Henley and Seader contain some discussion of thermodynamic analysis based on minimum work of separation and net work consumption.

**Heuristics for Reduced Energy Consumption in Separations**

King presents a list of heuristics to be considered in designing an energy-efficient process. Several of these heuristics remind the designer to select options that reduce the degree of irreversibility of the process and are related to those heuristics cited previously. For instance, he advises designers "to avoid the mixing of streams of dissimilar composition and/or temperature," and "to endeavor to use the full temperature differences between heat sources and sinks efficiently." He also suggests that the most-reversible separation method be used; energy separating agents are preferred over mass separating agents, and equilibration processes are preferred over rate-governed processes. King demonstrates the application of these heuristics with two examples.

**Systematic Approaches to Energy Integration**

As might be expected, several workers have attempted to include energy integration considerations in their approaches for optimal process synthesis. Most, if not all, of their efforts involve heat integration for multicomponent distillation sequencing. In this case, overhead vapor streams and bottom products can serve as heat sources while feed and vapor recycle streams from the reboiler serve as heat sinks. The problem here is to find a suitable matching of hot and cold streams to minimize energy consumption within with the usual constraints inherent in finding an optimal sequence. As can be imagined, the considerable amount of work that has gone into optimization of heat exchanger networks is useful in addressing this problem.

Rathore et al. suggested a technique using the list processing approach of Hendry and Hughes along
with an energy match matrix that specified all feasible energy exchanges between hot and cold streams. The energy matrix approach followed the branch and bound heat integration technique of Lee et al.\textsuperscript{22} Heuristics were applied to rule out unlikely sequences and then the proper sequence was developed using dynamic programming methods. Although they did not consider vapor recompression, they did find that heat integration opportunities were best when columns in a distillation train were operated at different pressures. Their approach, however, proved to be too cumbersome for general usage.

Freshwater and Zigou\textsuperscript{23} examined several four- and five-component systems with and without heat integration. They noted that without heat integration a direct sequence was usually best. However, if heat integration were considered, the optimal sequence was often distinctly different. Their work suggests the importance of heat integration in distillation column sequencing.

Siirola\textsuperscript{24} more recently discussed an energy integration scheme, based on the use of heuristics, that makes feasible the simultaneous consideration of sequencing and heat integration. A bounding strategy is used to rule out unattractive options to eliminate the need for complete optimization. Using as an example a four-component separation into pure products by distillation, he compared heat integration schemes to the simple, direct sequence without heat integration or pressure optimization. The results of his study show that if sequencing and heat integration are considered simultaneously, a significant improvement can be achieved over the cases where they are considered separately. Unfortunately, although this method required only limited computer time, it still required the generation of all possible schemes of all design variables before an optimum was apparent. This becomes less feasible as the number of components and potential separation methods is increased. Although it was not useful in his example, Siirola\textsuperscript{24} suggests using conventional process synthesis strategies of decomposition and bounding whenever possible. He also illustrates the potential value of thermodynamic availability analysis in setting a lower bound on the cost of the separation sequence. If a lower thermodynamic bound differs appreciably from the apparent optimum, this may indicate that additional heat integration is desirable through use of additional levels of utilities and heat pumping.

Sophos et al.\textsuperscript{25} employed an optimal, heat-integrated distillation sequence. By first identifying favorable unintegrated sequences, they are able to limit the problem. They assume that the integrated optimum is a member of the set developed in the first screening. These sequences are then looked at for heat integration opportunities given whatever constraints are appropriate.

Thermodynamic analysis is the basis of the efforts by Umeda et al.\textsuperscript{26} and Naka et al.\textsuperscript{27} The former work applies the use of a heat availability diagram to the unintegrated schemes to help to identify optimal heat-integrated approaches and follows techniques used for heat exchanger network synthesis. The latter effort attempts to expand on the work of Umeda et al.\textsuperscript{26} to include heat sources and sinks from other processes and uses in developing an optimal arrangement.

There are many efforts now underway to develop procedures for incorporating heat integration into process synthesis methodology; several of the references for this section should be examined for more information.

It should be apparent that the degree of sophistication for heat integration in separation sequences is not very high. This is not surprising given the nature of the problem. Advances should come as process synthesis methods in general are improved and as applications from the relatively well-developed heat exchange network design are implemented.

**4.2-4 Examples of Process Synthesis**

Many examples of methods to develop optimum process arrangements can be found in the literature. More recently, with the increased usage of digital computers to evaluate sophisticated algorithms, more complex sequencing problems are being addressed. Nevertheless, one must be somewhat familiar with the concepts applied earlier in process synthesis to understand and use the newer methodologies. These concepts are illustrated best by examining several proposed synthesis strategies; these will provide some insight into the types of problem that one encounters in process synthesis. Several will be presented here for illustrative purposes.

**METHOD OF HENDRY AND HUGHES**

The approach used here is to treat separators as list-processing operations using dynamic programming and ranked lists to develop the optimum sequence. The procedure, as originally described by Hendry and Hughes\textsuperscript{21} and later summarized by Hendry et al.,\textsuperscript{28} can be described as follows:

1. Given an initial mixture of A, B, C, and D that must be separated into individual products, the components are ordered into ranked lists based on one or more physical and/or chemical properties. Following Hendry et al.,\textsuperscript{28} consider two properties that result in the following ordering:

   Property 1: A B C D
   Property 2: B A C D
2. Based on these ranked lists, generate all possible subgroups. Each component must appear in at least one list. Since only simple, sharp separations are considered, splits must be between adjacent components in the ranked lists. The optimum process must be composed from these subgroups:

- **Binaries**: A,B C,D A,C
- **Ternaries**: A,B,C B,C,D A,C,D

3. Working backward through the network, determine the least expensive way of separating each binary. This may be done for a variety of feed conditions.

4. Once this is done, evaluate the cost of each three-component separation from the original mixture, which may involve considering several feed conditions. Add this cost to the previously determined binary separation cost and select the sequence with the lowest combined cost for the separation.

Figure 4.2-3 shows all five possible sequences for the separation of the four components into pure products. Each sequence involves the use of three separators. If only one separation method were used and only simple, sharp separations were considered, these five sequences would represent all possibilities. However, with two separation methods, using the formula [Eq. (4.2-1)] of Thompson and King, one finds that there are 40 possible sequences. The combination of list processing and dynamic programming used by Hendry and Hughes can reduce this combinatorial problem into a manageable one. Shown below is one of the possible sequences which is arrived at through the use of two separation methods:
Hendry and Hughes applied this approach in detail to an \( n \)-butylene purification system involving six components and two separation techniques (distillation and extractive distillation). Unfortunately, because all unique subgroups must be evaluated, computational requirements become excessive for large problems. Nevertheless, their work represents a relatively simple but powerful algorithmic method for addressing the combinatorial problem encountered in process synthesis and helps to initiate the development of other process synthesis techniques.

**METHOD OF THOMPSON AND KING**

An approach combining heuristic and evolutionary elements, this method of process synthesis attempts to minimize the formation of extra products while also considering separator costs as flowsheets are generated. Process flowsheets are developed and optimized as follows:

1. Select a feasible product set for the process with the aim of minimizing the generation of extra products that would have to be mixed downstream to form the required products.

2. Combining heuristics with cost information, flowsheets that will produce the set of products chosen in step 1 are generated. A cost factor that incorporates the number of stages and the type of separator is applied; in the first iteration, no weighting is given to the type of separator so that a wide range of options might be considered. Beginning with the feed stream, the first separation technique is chosen to be consistent with the desired product set and based on the heuristic that the cheapest option is to be used.

3. The effluent streams from the first separator are examined and, if necessary, subjected to further separation. The sequence is developed, guided by the cost factor and the heuristic to choose the cheapest of all candidate separations next. The flowsheet is complete when all final effluent streams contain only one of the products of the predetermined set.

4. With the completed flowsheet, a detailed design and cost estimate of the units of the sequence are determined and the weighting factors for particular separators are then redefined.

5. The sequencing process is then repeated with the more accurate cost information until no further improvements are possible. If the apparent optimal sequence contains mass separating agent processes, the initial requirement of a minimum number of products is relaxed and the procedure is repeated using energy separating agents instead.

Thompson and King point out that their method serves as a general strategy for process synthesis and more specific rules should be incorporated for a particular situation. It can be used to reduce the need for large amounts of computer time and will generally produce a set of near-optimal solutions perhaps containing the optimum. It may not be appropriate for highly complex and unusual separations problems, which is true of all existing systematic sequencing procedures.

**METHODS BASED ON THE ORDERING OF HEURISTICS**

Intuitively, one might imagine that the heuristics presented earlier are not of equal merit for all situations. Indeed, many of the process synthesis methods used today rely on the ordering of these heuristics either to generate an initial sequence that can be improved through an evolutionary strategy or to arrive at a final optimal sequence.

Seader and Westerberg used a set of six heuristics along with several evolutionary rules to construct an optimal sequence for the separation problems presented by Hendry and Hughes and Thompson and King. They noted that their technique resulted in a much more rapid and concise treatment of the problem than earlier methods.

Nath and Motard presented a method that extends the techniques used by Seader and Westerberg. They used eight heuristics along with five evolutionary rules to develop the best sequence. Also included is a strategy to refine the best flowsheets. Like Seader and Westerberg, they use heuristics to generate an initial feasible sequence and evolutionary rules to improve on the initial configuration. They emphasize the
importance of a good initial sequence since this will speed up the solution of the problem and favor global over local optima. Their method is shown to work for several previously presented sequencing problems.

More recently, Nadgir and Liu\textsuperscript{13} suggest that an ordered heuristic approach to sequencing based on seven previously described heuristics will produce initial sequences that are very close to the final optimal sequences of Seader and Westerberg\textsuperscript{10} and Nath and Motard.\textsuperscript{39} They also make use of an auxiliary sequencing parameter called the coefficient of ease of separation (CES). They categorize heuristics in the following way: method heuristics; design heuristics; species heuristics; and composition heuristics following the procedure suggested by Tedder.\textsuperscript{30} These are applied along with the CES parameter to generate initial sequences for previously presented problems that are close to the final sequences arrived at by the above heuristic-evolutionary approaches. Nadgir and Liu\textsuperscript{13} also claim to have avoided the complicated mathematics that are associated with more sophisticated optimization methods.

Apparently the above methods are all successful in providing an optimal or near-optimal sequence for a well-defined separations problem. The utility of these approaches to problems that include separations beyond ordinary and extractive distillation is unclear.

**METHOD OF TEDDER AND R U D D**

Most of the work in developing process synthesis methodology centers on the use of simple, sharp separators and ignores the use of more complex separator arrangements. In distillation, where most of the process synthesis efforts have been focused, thermal coupling and sidestream removal are largely ignored despite the advantages this represents in many situations. Given current computational limitations, the only way that more complex configurations can be examined is by defining a relatively limited space of alternatives and by examining the options carefully. This was the approach used by Tedder and Rudd\textsuperscript{31-33}.

In a comprehensive study of the distillation of ternary feeds of light hydrocarbons, Tedder and Rudd\textsuperscript{31-33} considered eight distillation systems including complex arrangements with recycle streams and sidestream removal. Using a parametric approach, they were able to evaluate the eight designs and draw conclusions about the relative merits of each design. The basis used for comparison was the feed composition and a rating system they called the ease of separation index (ESI). They then analyzed their data using an equilateral triangle diagram showing the range of optimality for each of the eight configurations studied. For a given ESI, the spaces for which each design is optimal can be determined once the feed composition is known. In the diagram, each component is represented as one of the vertices of the equilateral triangle. While this limits the technique to ternary systems, the authors suggested that this approach can be extended to larger systems through the generation of pseudoternaries with the most difficult ternary separation taken last. While their technique does not account for complexities that factor into the final cost estimates for these systems, Tedder and Rudd\textsuperscript{31-33} present a useful technique for reducing the set of alternatives for these complex systems. This type of approach, although not algorithmic in the strictest sense, nonetheless provides a mechanism for quantitative evaluation of a restricted set of process options.

**COMPUTER-AIDED PROCESS SYNTHESIS METHODOLOGIES**

Often the overall objective in process synthesis is to arrive at an optimal design for a complete chemical plant. This includes consideration of chemical synthesis, process control, energy efficiency, as well as separation process sequencing. Ultimately, a systematic methodology requiring only the definition of process objectives is desirable. While the use of artificial intelligence or knowledge engineering might someday make this notion a reality, this will not be the case in the near future. The work that has been done in this area takes one of two approaches: (1) no initial process structure is assumed or (2) the process is developed by considering all possible alternatives (integrated or structural parameter approach).

Several procedures have been suggested for systematic process synthesis in which no initial process structure is present. Most of these are heuristic-evolutionary methods but they often contain algorithmic elements as well. Sirola and Rudd\textsuperscript{34} and Powers\textsuperscript{35} developed a heuristics-based method for the computer-aided synthesis of process designs. The program, called AIDES (Adaptive Initial Design Synthesizer), used the repeated application of specific design heuristics to the original feed stream and its subunits until the final product set was achieved. Certain heuristics were applied to select the appropriate separation methods first and then others were used to determine the sequencing. The concept of ranked lists was used along with a weighting procedure based on heuristics for each split from each ranked list. The best process is the one with the most favorable score that is both chemically and physically realistic. AIDES is an attempt to apply design heuristics systematically for process synthesis but relies heavily on the heuristics employed and their relative weighting in the sequencing and selection process. It has been tested on several processes and has been successful in generating alternate flowsheets; the optimum, however, may not be within the set of alternatives. Nonetheless, it was one of the first reasonable attempts to develop a systematic process synthesis methodology and provided the basis on which more sophisticated methods could be developed.

There have been several other proposed procedures for systematic generation of optimal process flowsheets without an initial process structure. Of note is one developed by Mahalec and Motard\textsuperscript{36} and incorporated into a computer program they called BALTAZAR. Like AIDES, it can be used for the synthesis of an entire chemical plant but takes a more sophisticated approach to processing objectives and constraints. It is based on a systematic resolution of conflicts between a set of processing rules and the processing objectives. The procedure is based on a sequential depth-first approach which employs several structural
rules that help to produce feasible flowsheets. An objective function that incorporates heuristic arguments into the flowsheet evaluation process helps to identify promising options. Evolutionary rules also are used to improve the process structure. BALTAZAR has been used to generate alternate flowsheets for several industrial processes including one previously analyzed by AIDES.

Nishida et al. provide an excellent comparison of AIDES and BALTAZAR.

More recent efforts to develop computer-aided process synthesis methodologies can be characterized as either sequential modular, simultaneous modular, or equation oriented. Sequential-modular approaches are best for steady-state simulation where process inputs are defined and process parameters are available. The best feature of sequential-modular approaches is that they are flowsheet oriented, but they are not as flexible as the other methodologies in performing design and optimization tasks.

Equation-oriented approaches are based on sets of equations that are written for the units in a particular flowsheet. Unlike the sequential-modular systems, which often contain the necessary information for a variety of process units, equation-oriented synthesizers require the practitioner to develop the model equations. These are solved through iterative techniques with standard numerical methods.

Simultaneous-modular methods attempt to combine the features of the sequential-modular and equation-oriented approaches to make use of models developed for the former and to include the flexibility of the latter. For more information, the reader is referred to the recent review by Biegler.

There are several reviews that provide additional information about computer-aided process synthesis. A brief discussion of one particular methodology is presented here.

Westerberg and coworkers have described an equation-oriented process synthesis methodology that is being developed at Carnegie-Mellon University called ASCEND-II. It is capable of performing both simulation and optimization calculations. Westerberg describes the following guidelines, characteristic of an evolutionary approach, that were inherent in the development of ASCEND-II and should be considered in its use:

1. **Evolve from Simple to Complex.** It is more important at the outset of a design not to lose perspective by attempting to be overly quantitative. The purpose of initial calculations is to provide some qualitative understanding of the problem.

2. **Use a Depth-First Approach.** The point here is to generate an initial flowsheet that later can be optimized and to avoid backtracking. A great deal is learned on completing an initial feasible design even if it is far from optimal.

3. **Develop Approximate Criteria.** Final design criteria cannot be applied without an initial design in hand. Therefore, use approximate criteria, such as heuristics, to generate alternate flowsheets that can be subjected to more stringent standards.

4. **Use Top-Down/Bottom-Up Design Strategies Alternately.** Approaches that scope out options in light of overall process design objectives should be used alternately with approaches that evaluate these objectives at the local level for feasibility.

5. **Be Optimistic in Generating Design Alternatives.** Most initial design concepts will not work. It therefore pays to be creative in the initial phases of design. It is unlikely that the optimum sequence will be generated immediately. Creativity, on the other hand, may produce an unexpectedly effective design.

Westerberg comments that ASCEND-II offers the following elements to the design engineer: simulation, design, dynamics, and optimization. It is a tool for developing interactive computer models of varying complexities for the process under development; these can be used to improve the design. Westerberg notes that the flexibility of ASCEND-II in helping the design engineer to evaluate options interactively is an advantage of this system over traditional flowsheeting systems.

Others have reported computer-aided process synthesis methodologies that are algorithmic approaches. The so-called integrated or systems approaches to process synthesis depend heavily on optimization theory and linear and nonlinear programming techniques in finding an optimal processing arrangement. The determination of the best processing sequence is performed as a multiobjective optimization problem with consideration given to the entire space of possible alternatives. In practice, this can be done by combining all possible flowsheets into one flowsheet and creating some mechanism for dealing with interconnections between the elements of the process. While the systems or structural parameter approach theoretically will yield the optimum, the solutions to the resulting large-scale nonlinear programming problems are often not available. Also, because many direct optimization approaches are based on the representation of discrete variables by continuous variables, the apparent solution may turn out to be nonoptimal due to numerical difficulties. Nevertheless, as computer-aided process synthesis develops and becomes more useful for design, the systems approach necessarily will become more widely employed as a framework with which to attack the problem. For more information on integrated approaches to overall process synthesis, the excellent reviews of this subject by Umeda and Takama et al. should be examined.

### 4.2-5 Future of Process Synthesis

Several of the review papers referenced at the end of this chapter point out the future needs and directions of research in process synthesis. Some of the recommendations for areas for further work in separation processes are summarized below:
1. Synthesis of separation schemes for processes other than distillation.
2. Heat integration, multiple feed and withdrawal, partial splits, and medium recovery fractions in distillation column sequencing.
3. Use of second law analysis in considering the thermodynamic efficiency of separation schemes.
4. Consideration of nonideal systems and the effect of short-cut or approximate design methods on process synthesis approaches.
5. Integration of process control strategies into the sequencing problem including the consideration of the dynamic behavior of the system.
6. Improvements in methods for developing optimal flowsheets for the overall process, including a more sophisticated approach to incorporating separations into the flowsheet.

Without a doubt, the continued development of process synthesis methodologies has had and will have a significant impact on the design of chemical processes. There is little chance, however, that any systematic procedure or computer-based technique will supplant the need for experienced design engineers in the near future. The most promising developments will involve interactive computer programs that can make the best use of the power of the computer and the experience of the design engineer for both flowsheet simulation (steady-state and dynamic cases) and optimization.

4.3 CONTROL OF SEPARATION PROCESSES

A detailed look at the use of control in separation processes requires a much more comprehensive treatment than is possible here. The literature contains many well-written books and articles dealing with control in general and distillation column control in particular. Several references in each case are included at the end of this chapter.1-9

It would be useful perhaps to provide some perspective as to how the nature of process control is evolving, particularly in the context of design and synthesis of separation processes.

In a classic sense, process control usually implies a single-input-single-output relationship that can be monitored and regulated to ensure that a given system will operate as designed. For a given unit operation or separation, control objectives are specified, following which controlled, manipulated, and measured variables are selected. These are synthesized into a control loop. While this methodology is still a functional one in the chemical industry, it nonetheless is changing rapidly. The proliferation of digital computers and the incentive to design and operate processes and entire chemical plants optimally have led to an expansion of the role that process control plays in the chemical industry.

In most instances, the standard PID (proportional-integral-derivative) controller still is used for the control of single-input-single-output systems. However, individual control loops may be placed in the hierarchy of a distributed control system. By doing so, the control of many single-input-single-output systems can be orchestrated better, and several more sophisticated control methodologies can be considered including cascade control and split-range control. Distributed control also provides a framework for considering multiple-input-multiple-output systems and the interactions that may be inherent in these situations.

Most of the more recent developments in control are linked to improvements in computing at all levels. Digital computers have been developed to the point where the elements of a chemical process can be treated more realistically as the complex, highly nonlinear, and multi-interactive systems that they are. This has led to a more sophisticated use of dynamic modeling and simulation in process control. As computing costs have come down and computing capabilities have expanded, control strategy is being developed in a more global sense using simulation to consider the interaction of process elements and sometimes different processes. As a result, the focus in process control has expanded from the tuning and performance of individual separators is still important but, with the use of distributed control, reliability is maintained (microcomputers are dedicated to particular process units) while overall technical and economic objectives are pursued (mainframe computers can perform complex on-line/off-line optimization). The advantage to distributed control is that it makes effective use of current technology and provides a framework within which control and optimization developments can be implemented. These developments probably will include better simulation and optimization routines that will help to assess the current state of the process plant and to suggest improvements.

There is no doubt that, in many instances, relatively simple approaches are still sufficient to accomplish particular control objectives. However, for example, in the case of separation sequences that involve complex flow arrangements and thermal coupling, more advanced process control strategies will be necessary. As process synthesis methodologies improve, control strategy evaluation and process design and
4.3-1 Process Modeling and Simulation

In the perspective of process synthesis, process control should be viewed not as a separate element in process design and optimization but rather as a component of a coordinated approach. Therefore, the design and sequencing of separation processes must consider the relationship that process control will have to the final process structure. This can be done only through process modeling and simulation.

The most important aspect in the control of separation processes or, for that matter, any chemical process is understanding the process itself. Previously, without the availability of digital computers, overdesign and the neglect of process dynamics were practical necessities. Today, however, through process modeling and simulation with digital computers, a better understanding of the process is possible before any hardware is fabricated. From a control standpoint, this enables the process engineer to investigate the characteristics of the system over a wide range of operating conditions and to obtain a better parametric understanding of the process. This, of course, provides a better basis for selecting appropriate control strategies.

With the continued increase in sophistication of process modeling and simulation, it is becoming apparent that control of chemical processes often requires a unique application of the foundations of control theory. Early work in chemical process control borrowed heavily from other disciplines and practice severely lagged behind theory. Chemical engineers often looked deeper and deeper into sophisticated control theory for answers to problems that arose in process control. It now seems, after useful experience with process modeling and simulation, that less-sophisticated applications of control theory often are adequate for even complex problems. The key to successful process control has been found in an increased understanding of the process rather than sophisticated applications of control theory.

Thus, process modeling and simulation has become a key element in process control. Complex computer programs for these purposes have evolved and become well-accepted tools for chemical engineers. These simulation packages can be used to design new processes as well as to modify and optimize existing ones. Usually, they are comprised of sophisticated physicochemical estimation routines along with process models for a variety of unit operations, reactors, and auxiliary equipment. Typical simulators might include over 1000 subroutines totaling 150,000 lines of FORTRAN computer code. Their overall function is to coordinate material and energy balance information for a variety of processing arrangements and conditions. The utility and accuracy of these simulation programs are a function of how well conceived the models of the components of the process are as well as how effective the necessary convergence techniques are implemented.

The first process simulators developed for general use were for steady-state operation. Process dynamics usually were ignored to avoid excessive computation times and computational difficulties. While steady-state information is useful for control strategy evaluation, process control systems are designed best with some knowledge of process dynamics. As nonlinearities and interactions become more pronounced, information from the time-dependent behavior of a process or processes becomes crucial. There is currently a great deal of effort focused on upgrading process simulators so that they can handle unsteady-state operation. Several of these programs are able to model process dynamics for specific situations.

Because of the computational complexities associated with dynamic process simulation for multunit processes, there is still much to be done before simulators of this type become available for general application. Another problem complicating their development is that process models for even individual separation units are usually for steady-state cases; this is the result of both incomplete understanding of the chemical and physical principles involved and computational difficulties. This is one of the main reasons why process control considerations are difficult to incorporate into chemical process simulation and synthesis and why on-line plant optimization is still far away in most instances.

Process modeling and simulation are nevertheless extremely important tools in the design and evaluation of process control strategies for separation processes. There is a strong need, however, for better process models for a variety of separations as well as process data with which to confirm these models. Confidence in complex process models, especially those that can be used to study process dynamics, can come only from experimental verification of these models. This will require more sophisticated process sensors than those commonly available for temperature, pressure, pH, and differential pressure. Direct, reliable measurement of stream composition, viscosity, turbidity, conductivity, and so on is important not only for process model verification but also for actual process control applications. Other probes, which could be used to provide a better estimate of the state of the system, are needed to contribute to the understanding of the process in the same time frame as that of changes occurring in the process.

There are still many obstacles to overcome before the use of process modeling, simulation, and control reaches the potential that many think it holds. One of the most interesting possibilities is the development of systems capable of performing on-line optimization functions. Although on-line plant optimization is still in the future, optimization of subprocesses is already a possibility. This is true for both continuous and batch processes, and there are now many examples of how process modeling and simulation have enabled process control strategy and design to move beyond strictly performance considerations.
4.3-2 Process Synthesis of Control Structures

The objective in the control of separation processes has evolved from the control of the components of a process that already has been designed and often constructed to an integrated plan involving simulation, design, and control. Chemical process synthesis approaches that include control structures have been suggested only recently and are not well developed.

There have been several attempts at control structure development within process synthesis methodology. Govind and Powers\textsuperscript{24-26} started with steady-state flowsheets and used cause-and-effect diagrams to represent control logic for a particular process. Dynamics were modeled by a first-order lag and deadtime in series. A set of heuristics were used to rule out unfavorable alternatives before any detailed simulation was carried out to determine the best options. Govind and Powers, noting that their work was the first attempt to use non-numerical problem-solving techniques for control structure synthesis, discussed the manner in which their approach could be used to translate steady-state process flowsheets into piping and instrumentation diagrams.

Morari and coworkers\textsuperscript{27-29} describe a procedure for control structure development based on the multilayer-multiechelon approach of hierarchical control theory, which is free of heuristics. The key to the procedure is the effective application of decomposition to produce manageable subsystems of the problem. Examples are provided to show how structural controllability and observability can lead to a control system that is consistent with processing objectives.

Umeda\textsuperscript{30} reviews some of his own work, as well as that of his colleagues, which relates to control system synthesis, instrumentation, and alarm system design. To handle simpler systems, he notes that the development of control heuristics to rule out unfavorable pairings of controlled and manipulated variables might be beneficial. However, even for highly interactive systems with complex control objectives, reasonably simple procedures that can be used by process engineers are desirable even if they are useful only as design tools. Umeda also points out that one should not rule out the rearrangement of process structures to suit control structure synthesis, if necessary.

For additional information on the synthesis of process control structures, the reader is referred to the reviews of Umeda,\textsuperscript{30} Nishida et al.,\textsuperscript{31} Morari,\textsuperscript{32} and Stephanopoulos\textsuperscript{33} and the ongoing work of Fisher et al.\textsuperscript{34}

4.4 SPECIAL PROBLS

Many situations exist in which conventional approaches to design and operation of separation processes must be modified or changed altogether to meet processing objectives. Usually, these cases involve systems that are characterized by certain constraints that limit the potential range of operating conditions or scope of separation alternatives. Sometimes, even completely new separation methods must be developed.

Some examples of situations that require special processing consideration are discussed below.

4.4-1 Biological Separations

To be able to bring the advances in biotechnology to the marketplace, the products of many biotransformations somehow must be recovered from the complex reaction media in which they are formed. Because of the nature of biological products, conventional separation methods (e.g., distillation) often are not appropriate, and completely new approaches often have been developed.\textsuperscript{1-7}

The recovery of most biological products begins with the isolation of cells or proteins from fermentation broths. These broths can be viscous solutions which must be treated carefully because of the damaging effects of heat and mechanical stresses on their contents. If the desired product is extracellular, it must be removed from a complex mixture of similar chemicals which often contains significant amounts of biomass. Another important consideration is that the concentration of the product in the mixture may be less than a fraction of a gram per liter. If the product is intracellular, it must first be released from the cell, which may involve harvesting and disrupting the cells, and then recovered from the resulting debris.

The approach taken to recover biological products depends on the nature of the product. Biological products can be classified as either high-value-low-volume or low-value-high-volume. In the case of the former, many of the techniques used in analytical applications have been adapted to larger scale to handle product purification. For low-value-high-volume products, such as ethanol, more conventional procedures can be used, but these often require some modification.

For any intracellular product, the cells first must be harvested from the fermentation broth and lysed, or broken open, to release their contents. The liquid fraction, which contains the product, must then be separated from the cells. Cellular debris can be removed by either filtration or centrifugation, or a combination of both. Crossflow filtration, using microporous media or ultrafiltration membranes, has been shown to be extremely effective for this step, but problems with membrane blockage have been reported.

For extracellular products, one is faced with the problem of removing the liquid phase, which contains the product, from the biomass. This can be accomplished using techniques similar to those used for
removing cellular debris. It should be noted that there are emerging genetic engineering techniques that induce microorganisms to secrete normally intracellular products into the fermentation broth to facilitate recovery. Also, for biotransformations that do not involve microbial growth, immobilization techniques can be implemented which allow the use of a biocatalyst in much the same way that conventional heterogeneous catalysts are used. Cells or enzymes are attached or entrapped in a solid support and are contacted with a solution containing the reactants. This mode of processing greatly simplifies the downstream processing steps.

After harvesting and, if necessary, cell lysis, one is still left with a very dilute mixture of proteins or other biological compounds which is subjected usually to some form of chromatography. High performance liquid chromatography (HPLC), which may include normal-phase, reverse-phase, ion-exchange, and gel-permeation columns, has been the focus of many efforts to scale analytical procedures to commercial applications. Packing stability and liquid distribution and collection often present scale-up problems. Solutions to these problems as well as better approaches to packing selectivity probably will come in the not too distant future. Affinity chromatography, based on the unique attraction of one molecule for another (i.e., antigen-antibody interaction), represents a potential solution to the problem of recovering trace amounts of a high-value product from dilute liquid solutions. The compound of interest is removed from solution by complexing or reacting with another compound immobilized on the column packing. Of course, each application of this technique requires the development of the particular chemistry.

Continuous electrophoretic separations also have been proposed for the recovery of biological material from dilute solution. Under an electric field, and often in a pH gradient as well, proteins will migrate to their isoelectric point or point of zero net charge. As a laboratory technique, electrophoresis has long been a valuable tool. Commercial scale applications, which have been limited because of problems with remixing of the separated fractions, are seen to be possible with the development of a new system by Harwell for the United Kingdom's Atomic Energy Authority. This system avoids remixing by processing under laminar flow using a rotating outer electrode.

While it is often economically justifiable to implement sophisticated separation schemes for high-value-low-volume biological products, this is not the case for commodity chemicals, such as solvents and organic acids. Distillation still is used to recover ethanol from fermentation broths or from the product stream of an immobilized cell reactor. This represents a fairly energy-intensive undertaking since the distilled solution is usually 90% (weight) water. Molecular sieves, which avoid the water-ethanol azeotrope, and supercritical extraction with carbon dioxide have been used in an attempt to improve both energy and recovery efficiencies. The recovery of organic acids through the use of membrane technology, including electrodialysis, also has been tried to avoid distillation.

Indeed, biological separations present some unique problems for separations engineers. It is likely that this will lead to concentrated efforts to develop new techniques that may be used in place of or along with more conventional separation processes.

4.4-2 Thermally Sensitive Materials

In addition to biological products, there are many chemical compounds that will degrade or change if, during recovery or concentration from solution, processing temperatures are increased to any great extent. This is particularly true in the foods industry and in polymer processing. Fruit juices, sugars, and gelatins in addition to many plastics and resins are good examples of materials that are sensitive to thermal processing. They present particularly difficult separations problems because, in addition to their thermal sensitivity, they often are present in highly viscous solutions which makes large amounts of heat transfer in short residence times particularly difficult.

In the concentration of fruit juices, it is important to keep temperatures low and processing times as short as possible. Operation under vacuum is common. Because the concentrate contains solid particulates, the slurry must be moved quickly across any heat transfer surface to avoid the loss of solids due to surface adhesion. Also, because many vitamins are affected adversely by thermal processing, short residence times at elevated temperatures are crucial.

Most polymers are dissolved in either aqueous or organic solvent at some point in their processing. The concentration of rubber latex from emulsion polymerization solutions and the recovery of plastics and resins from batch polymerization reactors are two examples. In addition to problems of polymer degradation due to exposure to high temperatures for any significant period of time, there exists the additional problem of molecular weight distributions. In many cases, holding polymer solutions at elevated temperatures will lead to additional polymerization of any residual monomer and hence to a product that might not meet specifications. Many polymer recovery processes must be operated carefully to avoid degradation as well as to eliminate product variability arising from any temperature excursions.

For the concentration of viscous, heat-sensitive materials, thin-, agitated- or wiped-film evaporators can be used. Among the materials that have been processed through these systems are foods, fruit juices, plastics and resins, pharmaceuticals, vitamins, and radioactive wastes. The heat transfer surfaces in these evaporators are either wiped by a rotating blade or held at a small, fixed distance from the rotating blade to reduce surface fouling and to promote high heat transfer rates. The vapors leaving the heat transfer
surface can be recovered by internal or external condensers. These evaporators, which often are operated under vacuum, are designed to promote short residence times to reduce the adverse effects of thermal processing as well as to facilitate the treatment of viscous materials. By adjusting the heat transfer surface temperature, the feed rate, and the vacuum level, processing conditions can be adapted for a wide variety of applications. Another advantage of these types of evaporator is that they can be operated continuously and are scaled and instrumented easily.

4.4-3 High-Purity Materials

There are many instances in which the objective of a separation process is to recover a given compound at a very high level of purity. When this is the case, it is sometimes necessary to take a different approach to the particular separation. For example, the ethanol-water azeotrope precludes the recovery of pure ethanol using ordinary distillation. For higher purities, azeotropic distillation, solvent extraction, or the use of molecular sieves can be used. Clearly, the necessity to recover ethanol in concentrations above the azeotrope requires an alternative separations strategy.

The need for high purity in a separations process is common in many industries: semiconductor manufacture, pharmaceuticals processing, and the foods industry, as well as in many cases of more-conventional chemical processing. It is also very important in separation processes that are oriented to cleaning gas, liquid, and solid streams for environmental purposes. The low concentrations required of many environmentally significant compounds prior to discharge from a chemical plant have created a need for a new class of separation methods and have focused attention on many techniques that often have been ignored. Adsorption, ultrafiltration, electrostatic precipitation, reverse osmosis, and electrodialysis are just a few examples of separation processes in which there has been an increased level of interest partly because of their potential in environmental applications.

4.4-4 Summary

It is important in the design of a separation process to be cognizant of the limitations presented by the available alternatives. As the required level of purification increases, the technical and economic feasibilities of a given separation method may be reduced to the point at which some alternative must be identified. Failure to recognize this in the design stages will lead to unsatisfactory processing results.

REFERENCES

Section 4.1


Section 4.2


Section 4.3


Section 4.4


