READING QUESTIONS

1. In the definition of a chemical process, what is the purpose of the equipment and conditions used in the process?

2. How does a continuous process differ from a batch process?

3. What distinguishes a process as being steady-state?

4. How does a PFD differ from a block diagram?

5. In our example of making chemical C from A and B, we formulated an automated process (Fig. 2.2) to replace a laboratory scheme (Fig. 2.1). What equipment in the automated process replaced each of the following laboratory equipment items?

test tubes
laboratory burner
reaction vessel
distillation apparatus

HOMEWORK PROBLEMS

1. Classify the following as either *batch* or *continuous* processes, and indicate whether each is a *steady-state* or an *unsteady-state* process:

- **a.** A "surge tank" is used when a liquid is coming from one part of a process at a variable rate and we want to provide a reservoir of that liquid to feed another part of the process. Thus, a surge tank continuously (but at varying flow rates) receives liquid from an incoming stream and also loses that same liquid continuously (also possibly at changing flow rates) in an outgoing stream. The volume in the tank also changes with time.
- **b.** We bake a cake by mixing together the ingredients in a cake pan, placing the pan and mixture in an oven for a prescribed amount of time, and then removing the cake to cool down.
- **c.** A company produces latex paint base by mixing together the ingredients for the paint. All flow rates are held constant to maintain the proper ratio of ingredients. Working around the clock, the company makes approximately 800 *gallons* of paint every 24 *hours*.

2. The procedure for treating patients with insufficient kidney function is called "hemodialysis." This procedure typically takes place for approximately 4 hours, three times per week. The following configuration is representative:

- **A.** The "impure" blood (containing waste products that need to be removed) is caused to leave the body from a blood vessel through plastic tubing.
- **B.** An anticoagulant called "heparin" is added continuously to the tubing carrying the "impure" blood to prevent clotting in the hemodialysis system.
- **C.** The blood passes through a centrifugal pump, which provides the flow of the blood through the system.
- **D.** The blood passes through the "tube" side of a shell-and-tube "mass exchanger' (which is called a "hemodialyzer" and is very similar to a shell-and-tube heat exchanger). A liquid stream of "warm dialysate" passes through the "shell" side of the hemodialyzer. In the hemodialyzer, the waste products in the blood pass through the walls of the tubes and enter the dialysate.
- **E.** The blood leaving the hemodialyzer passes through a filter, which traps particulates (typically, clusters of cells) and removes them from the blood.
- **F.** The "cleansed" blood returns to the patient.
- **G.** The dialysate is prepared from a dialysate concentrate, which is purchased and diluted during the procedure to the desired concentration. To accomplish this dilution, the concentrate is pumped through tubing to a junction in the tubing where it joins another tubing stream carrying ultrapure water. The ultrapure water is prepared by pumping it from a distilled water source through tubing and through an ultrapure filter before joining the dialysate concentrate. After the dialysate concentrate and ultrapure water streams join, the dialysate is at its proper diluted concentration, as determined by the relative pumping flow rates of the water and concentrate pumps.
- **H.** The diluted dialysate flows through a heater (coil-in-tank type, with a stream of hot water flowing through the heater to provide the heat) to produce "warm dialysate."
- **I.** The "warm dialysate" stream passes through the hemodialyzer as described in part D and then flows to the drain.

Construct a pictorial Process Flow Diagram (without the stream table) using the symbols given in Figure 2.5.

Chapter 2

The Role of Chemical Processing

The terms "chemical process" and "chemical processing" are very common in chemical engineering and, in fact, are at the heart of most of what chemical engineers do. Therefore, this chapter addresses the following question:

2.1 WHAT IS A CHEMICAL PROCESS?

Definition of a Chemical Process

> A chemical process is a combination of steps in which starting materials are converted into desired products using equipment and conditions that facilitate that conversion.

To explain this answer, let's go back to your experience with chemistry. You will remember that chemistry involves the use of chemical reactions to make a desired product. For example, we may be interested in making product "C" from chemicals "A" and "B" via the reaction

$$A + B \rightarrow C \tag{2.1}$$

In a laboratory, you may have produced this reaction by pouring chemical A into a test tube and chemical B into another test tube (Figure 2.1). You may have then heated each test tube over a laboratory burner or heater to increase the temperatures of those two materials. The next step might have been to mix the two chemicals together so that they would react to form chemical C. Finally, because other chemicals were present along with the C in the product mixture, you probably needed to separate C from the mixture by boiling it off from the mixture, by allowing it to settle to the bottom of a flask, or by some other means. These manual steps are illustrated in Figure 2.1.

One of the things that chemical engineers do is to build upon laboratory-type manual processes to create useful automated processes. They may create new processes to make new products or to utilize better strategies for making existing products through increased efficiency and the use of environmentally friendly methods. Or they may improve existing chemical processes in order to increase production rate and product quality. In some cases, this means scaling up an existing process to produce larger quantities of a product for the marketplace.

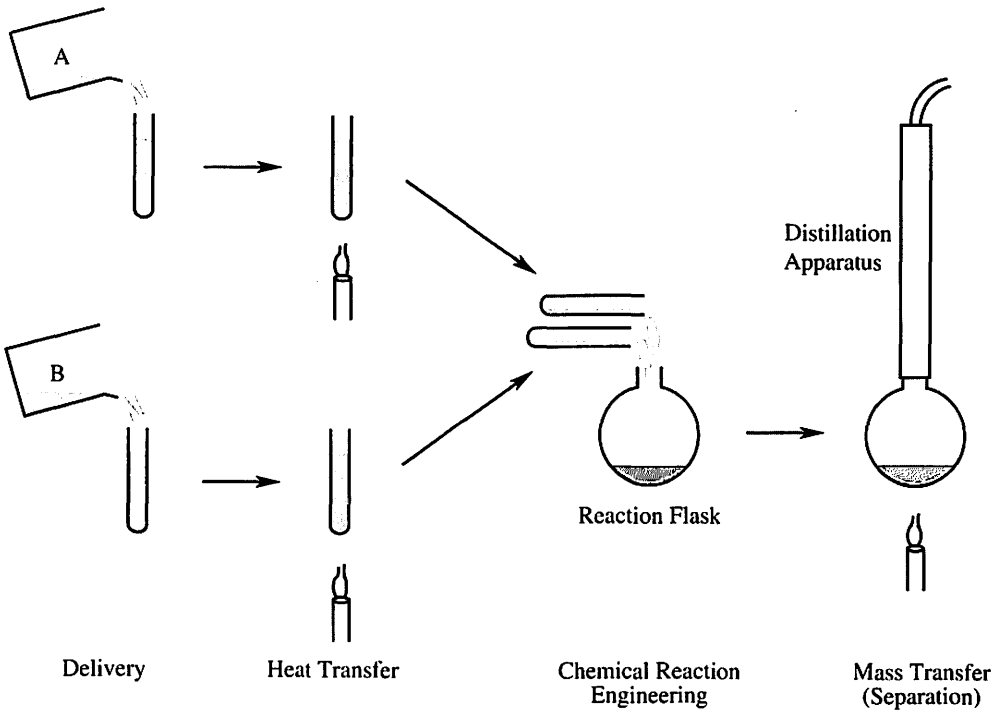


Figure 2.1 Diagram of a manual laboratory scheme for producing C from A and B

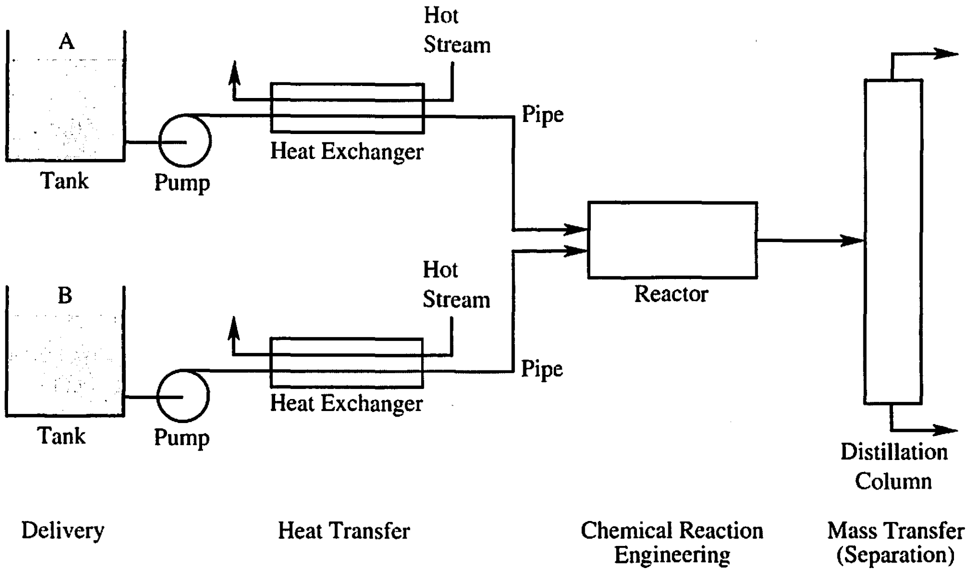


Figure 2.2 Diagram of an automated industrial process for producing C from A and B (based upon the laboratory scheme represented in Figure 2.1 but automated using chemical engineering principles)

Figure 2.2 shows an automated implementation of the laboratory process from Figure 2.1 as a possible industrial process. In this case, the analog of the laboratory procedure might be to pump chemical A from a tank through a pipeline containing a *heat exchanger* (which transfers heat from a warmer stream to our colder stream of A). Similarly, we would probably pump B from another tank and through another heat exchanger. These *reactant* streams might then be brought together in a reactor with the needed temperature, pressure, and catalysts. It would be important that the reactor be designed so that the chemicals spend the needed amount of time inside the reactor before leaving, thus allowing the reaction to proceed far enough (i.e., so that enough A and B would be converted to C). A final step might be to send the *product* stream to a continuous distillation (boiling) unit or to a settling tank or to another type of device that would separate C away from the other chemicals in the stream. In practice, leftover A or B would likely be recycled in order to reduce waste and improve efficiency. Automated controllers would be used to monitor important parameters (e.g., temperature and concentration) and to continuously adjust process variables in order to operate the entire chemical process efficiently, effectively, safely, and in an environmentally friendly way.

A chemical process can be operated either as a *batch* process or a *continuous* process. Furthermore, a continuous process can be *steady-state* or not. These are defined as follows:

Definitions of Process Categories

In a **batch process**, an allotment of starting material is introduced into the process, and a sequence of steps to treat that material is started and finished within a certain period of time, often within the same piece of equipment. The process is then interrupted, the processed material is removed, another allotment of the starting material is introduced, and the sequence of steps is repeated. Example: materials are loaded into a reactor, a reaction is carried out in the reactor, and then the final materials are removed.

A **continuous process** operates without interruption in the flows and reactions of the process. The starting material enters continuously, is usually subjected to various steps by moving from one piece of equipment to another, and exits the process continuously. Example: materials continually flow into and out of a reactor, while the reaction proceeds as the material moves through the reactor.

A **steady-state process** is one in which none of the process characteristics (temperatures, flow rates, pressures, and so forth) change with time. A process that is not steady-state is termed *unsteady-state* or *transient*.

You will recognize that a batch process is clearly not a steady-state process. A continuous process may or may not be steady-state, again depending upon whether any of the process characteristics vary with *time*. This should not be confused with the fact that the process variables may vary between different *locations* in the process. To clarify, when a steady-state process is observed at a certain point in time and then observed again a few minutes later, no change is seen. For example, in the process illustrated in Figure 2.2, as described previously, the streams coming from both of the tanks pass through heat exchangers, which heat those streams so that the outlet stream temperatures are different from those of the inlet streams. If the process is steady-state, the inlet and outlet temperatures (and all other temperatures in the process) remain constant with time, in spite of the fact that those temperatures are not the same in the various locations. The same would be true of the pressures, chemical compositions, and other characteristics of the inlet and outlet (and other) streams in the process.

EXAMPLE 2.1 A plant containing a reactor is being started up (being put into operation). In the *startup phase*, with fluid flowing in all of the streams, the temperatures of the reactor and some of the streams are seen to be changing with time as they move toward the values at which they will eventually be held. The chemical composition of the material coming from the reactor is also changing with time in response to the changing reactor conditions. The startup phase is over when the temperatures and compositions reach their desired values and no longer change with time. Classify the startup phase and the period after the startup phase in terms of being *batch* or *continuous* and *steady-state* or *unsteady-state*.

SOLUTION During both phases, the process is *continuous*, because the flows and operation continue without interruption or "starting over." During the startup phase, the process is at *unsteady-state*, because some of the process parameters are changing with time. After the startup phase, the process is at *steady state*, because there are no changes with time.

2.2 REPRESENTING CHEMICAL PROCESSES USING PROCESS DIAGRAMS

Processes are often represented by simplified process diagrams such as that illustrated by Figure 2.2. Such diagrams obviously leave out a great deal of detail, but they are useful because they show important sequences and relationships of steps in a chemical process and allow the engineer to easily visualize the process. They also provide important information about the process, such as the compositions, temperatures, and flow rates of process streams. Process diagrams are used by engineers and others involved in construction and maintenance (working on such things as piping, instrumentation, equipment design and plant layout), for the training of operating personnel, and for the preparation of operating manuals. The process diagram represents the key documentation of the design and is the basis for comparison of actual operating performance with design specifications. Let's talk about three types of diagrams: (1) Block Diagrams, (2) Process Flow Diagrams, and (3) Piping and Instrumentation Diagrams.

2.2.1 Block Diagrams

A *block diagram* provides a simple representation of a chemical process in which a box or block is used to represent either a single equipment item or a combination of equipment items that collectively accomplish one of the principal steps in the process. Such diagrams are especially useful at the early stages of process design before details have been determined. They can also be used to provide a simplified overview of the principal stages of a complex process. An example of a block diagram is shown in Figure 2.3, which represents a chemical plant for making nitric acid. Additional information such as stream flow rates and compositions may be shown on the diagram itself, or in a separate table.

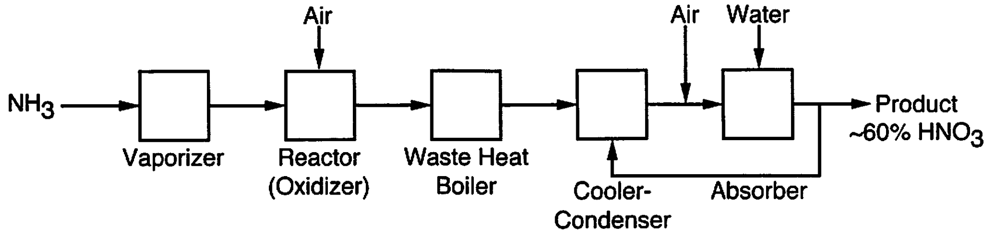


Figure 2.3 Block diagram for a low-pressure process to produce nitric acid[1]

Block diagrams apply to chemical processes of all shapes and sizes. For example, Figure 2.4 is a block diagram showing in a simplified way the process by which digestion takes place in your body.

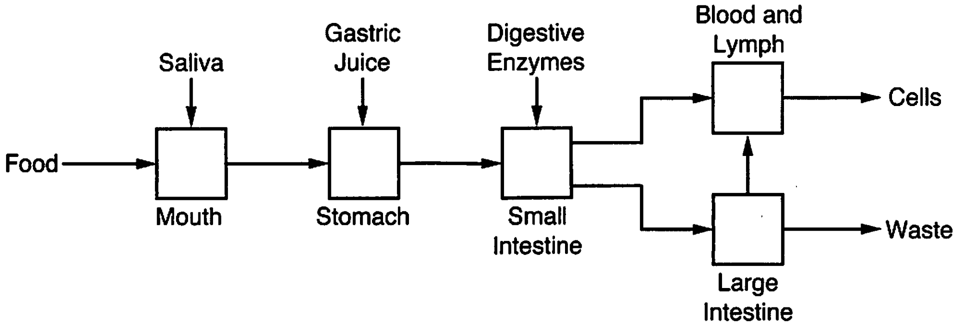


Figure 2.4 Block diagram as a simple representation of the human digestion process

2.2.2 Process Flow Diagrams (PFD)

A *process flow diagram* (PFD) provides more detail than a block diagram and is a standard method for documenting engineering designs. This type of diagram shows the arrangement and interconnection of all the major pieces of equipment and all flow streams, and the equipment is represented by symbols or icons that "look like" the actual equipment. Standard symbols for various equipment items can be found in the American National Standards Institute (ANSI) publication on flowsheet design, but many companies have adopted their own symbols. Figure 2.5 shows some typical process equipment symbols, but minor equipment, such as pumps and valves, may or may not be included in the PFD.

Examples of some simple PFDs are shown in Figure 2.6, which also illustrates the wide variety of chemical processes that are encompassed by the versatile and broad field of chemical engineering. Also see Figure 2.7 for photos of chemical engineering applications of the same scales as represented by the flow diagrams in Figure 2.6.

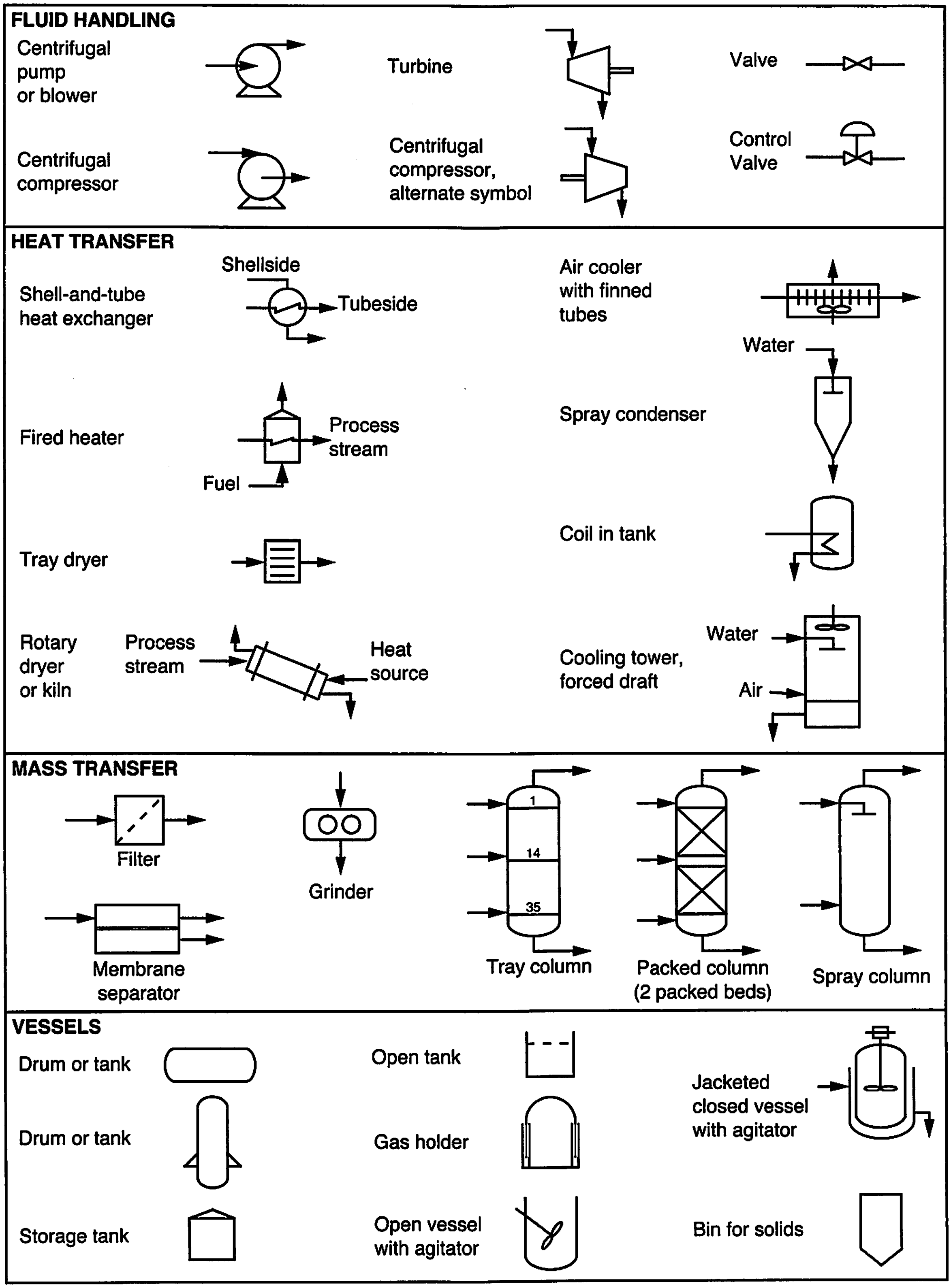


Figure 2.5 Typical symbols used in process flow diagrams and piping and instrumentation diagrams

Since a few homework problems in this book include the construction of some simple process flow diagrams, the following procedure is suggested for that construction:

IMPORTANT SUMMARY!

Steps for Constructing a Process Flow Diagram

1. **Identify streams** entering the process ("feed streams") and exiting the process ("product streams").
2. **Identify key process steps and major equipment items** needed for the process.
3. **Determine the symbol** to be used for each major piece of equipment.
4. **Draw the symbols on the flow diagram** and connect them with appropriate stream lines. The general flow of the diagram should be from left to right.
5. **Label major pieces of equipment,** usually using abbreviations of a few letters and numbers (e.g., P-2 for pump #2 and HX-15 for heat exchanger #15). For this introductory course, full names can also be used (as in Figure 2.6).
6. **Label streams** with a number and/or letter (e.g., 10, A, or 10A).
7. **Include a stream table,** if desired, that contains information about each stream (described below).

EXAMPLE 2.2

A common practice when performing open-heart surgery is to divert the patient's blood through a "cardiopulmonary bypass" system or "heart-lung machine." The following configuration is an example:

A. The blood from the main veins (called "venous blood") is caused to leave the body through plastic tubing.

B. An intravenous (IV) line adds anticoagulant drugs to the tubing.

C. The blood passes through a centrifugal pump, which provides the flow of the blood through the system.

D. The blood passes through the coil side of a coil-in-tank-type cooler to cool the patient's blood (to reduce oxygen requirements). Ice water enters and leaves the tank to supply the cooling.

E. The cooled blood passes through a membrane separator (called an oxygenator) where it flows along one side of the membrane. An oxygen-rich gas stream also passes through the oxygenator, where it passes along the other side of the membrane. Thus, in the oxygenator, oxygen passes through the membrane and enters the blood, where the following reactions occur:

$$\mathrm{Hb} + 4\mathrm{O}_2 \rightarrow \mathrm{Hb}(\mathrm{O}_2)_4$$

$$\mathrm{H}_2\mathrm{CO}_3 \rightarrow \mathrm{H}_2\mathrm{O} + \mathrm{CO}_2$$

Hb represents "hemoglobin," the protein inside red blood cells that carries the oxygen. The carbon dioxide passes from the blood through the walls of the tubes and into the gas stream. Thus, when the gas stream enters the oxygenator, it consists mainly of oxygen, and when it leaves, it contains much more carbon dioxide than when it entered.

F. The blood leaving the oxygenator passes through a filter, which traps air bubbles and removes them from the blood to form an air stream output from the filter.

G. The blood (now called "arterial blood") returns to the patient and enters the main artery.

Construct a pictorial process flow diagram using the symbols in Figure 2.5 (without a stream table).

SOLUTION

The solution is shown as an example of biomedical engineering in Figure 2.6c (also see Figure 2.7c).

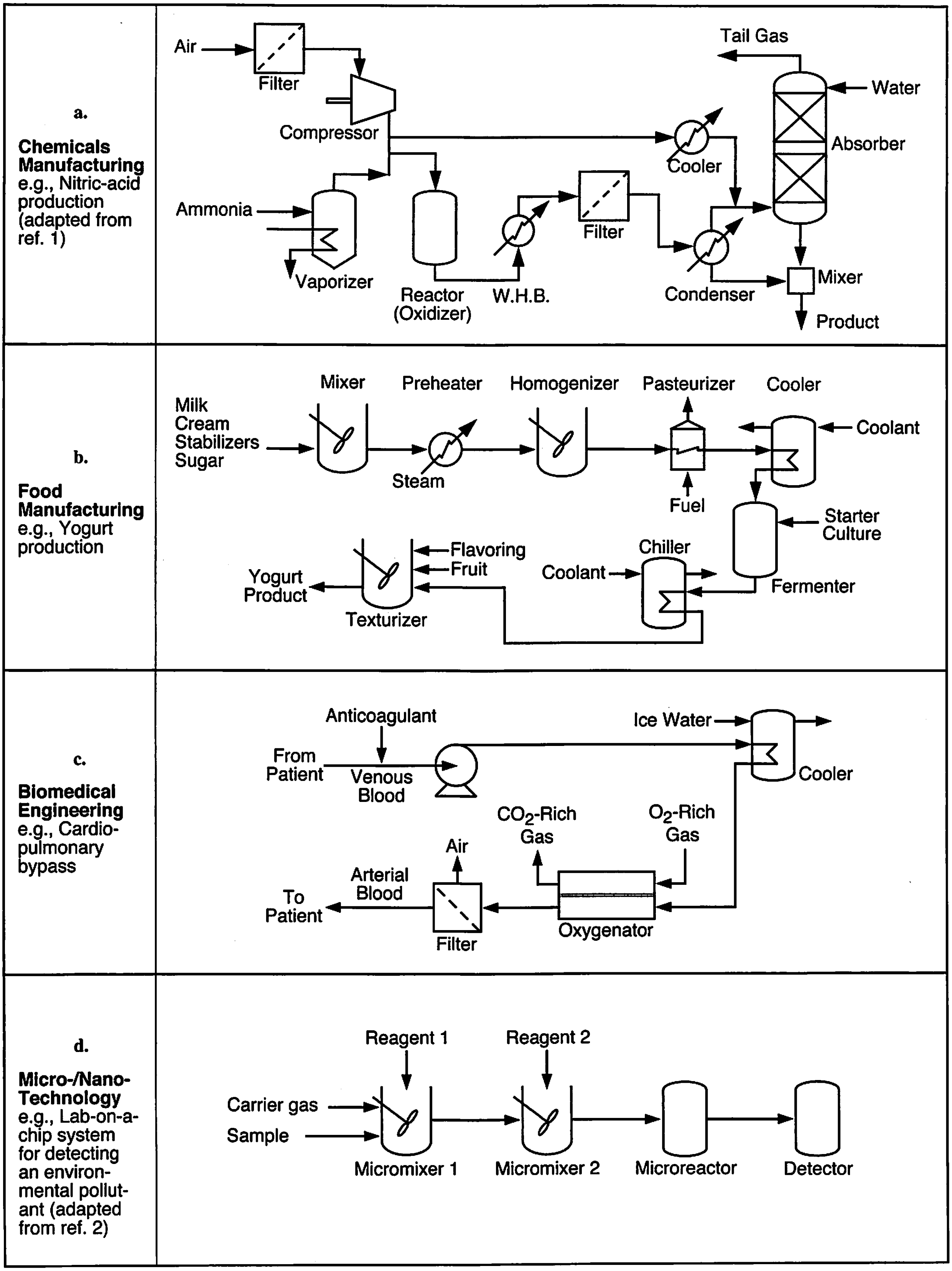


Figure 2.6 Sample process flow diagrams from a variety of chemical processes

Often, the pictorial representation of a PFD is accompanied by a *stream table,* which provides quantitative information about each stream in the diagram. Figure 2.8 shows the PFD for the same nitric acid plant represented in the block diagram in Figure 2.3 and the Chemicals Manufacturing in Figure 2.6a, but now accompanied by a stream table. Each stream is identified with a number or letter, and the data for the streams are usually compiled in a stream table at the bottom of the flowsheet. The amount of information given in the stream table will vary but usually includes:[1]

1. Stream composition. Most commonly, this is given as either of
   - **a.** the flow rate of each individual chemical species
   - **b.** the percentage or fraction of each species in the stream
2. Total stream flow
3. Stream temperature
4. Normal operating pressure of the stream
5. The basis for the information in the table (e.g., in Figure 2.8, the indication in the top left corner of the table that the flow rates are in units of kg/hr)

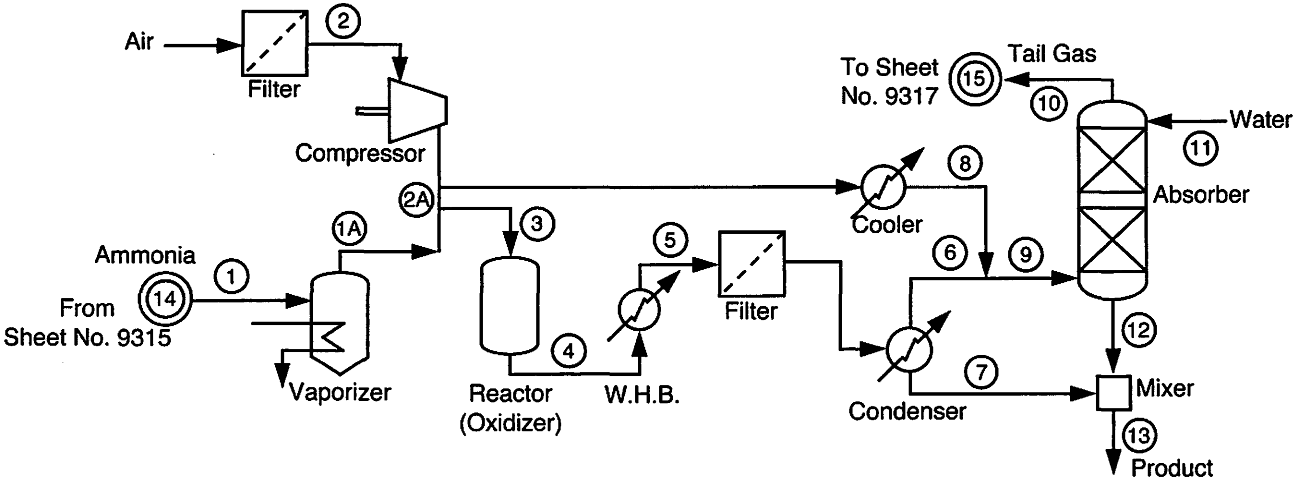
Other information, such as physical property data, composition, and so forth, may also be added.

2.2.1 Piping and Instrumentation Diagrams (P&ID)

A *piping and instrumentation diagram* (P&ID) provides even greater detail for a process than do PFDs. Further, P&IDs are prepared to be consistent with PFDs, usually using the same numbers or letters as in the PFD to represent streams and equipment. However, P&IDs also include the engineering details of equipment, instrumentation, piping, valves and fittings. Piping size, material specification, process instrumentation, and control lines are all shown on P&IDs. Utility (steam and high-pressure air) lines are also included on the diagram. All streams and utility lines entering and leaving the diagram are identified by source or destination. Figure 2.9 is an example of a small portion of such a diagram.

CONCLUDING COMMENTS

This chapter has provided a brief introduction to chemical processes. Such processes are used to make the many intermediate and final products described in Chapter 1. Throughout the remainder of this textbook, the basic phenomena in chemical processes will be introduced, along with fundamental principles that govern those phenomena. Simplified design of processes will be demonstrated, and opportunities will be presented to practice those design exercises. Meanwhile, an entire process will be developed to address the original "assignment" presented in Chapter 1.



Flows kg/h Pressures nominal

Line no. Stream Component	1 Ammonia feed	1A Ammonia vapour	2 Filtered air	2A Oxidizer air	3 Oxidizer feed	4 Oxidizer outlet	5 W.H.B. outlet	6 Condenser gas	7 Condenser acid	8 Secondary air	9 Absorber feed	10 Tail (2) gas	11 Water feed	12 Absorber acid	13 Product acid	C & R Construction Inc.
NH_3	731.0	731.0	—	—	731.0	Nil	—	—	—	—	—	—	—	—	—	Nitric acid 60 percent
O_2	—	—	3036.9	2628.2	2628.2	935.7	(935.7)(1)	275.2	Trace	408.7	683.9	371.5	—	Trace	Trace	100,000 t/y
N_2	—	—	9990.8	8644.7	8644.7	8668.8	8668.8	8668.8	Trace	1346.1	10,014.7	10,014.7	—	Trace	Trace	Client BOP Chemicals
NO	—	—	—	—	—	1238.4	(1238.4)(1)	202.5	—	—	202.5	21.9	—	Trace	Trace	SLIGO
NO_2	—	—	—	—	—	Trace	(?)(1)	967.2	—	—	967.2	(Trace)(1)	—	Trace	Trace	Sheet no. 9316
HNO_3	—	—	—	—	—	Nil	Nil	—	850.6	—	—	—	—	1704.0	2544.6	
H_2O	—	—	Trace	—	—	1161.0	1161.0	29.4	1010.1	—	29.4	26.3	1376.9	1136.0	2146.0	
Total	731.0	731.0	13,027.7	11,272.9	12,003.9	12,003.9	12,003.9	10,143.1	1860.7	1754.8	11,897.7	10,434.4	1376.9	2840.0	4700.6	
Press bar	8	8	1	8	8	8	8	8	1	8	8	1	8	1	1	Dwg by Checked
Temp. °C	15	20	15	230	217	907	234	40	40	40	40	25	25	40	43	Date 25/7/1980

Figure 2.8 Process flow diagram (PFD) with stream table for a low-pressure nitric-acid process (adapted from ref. 1)

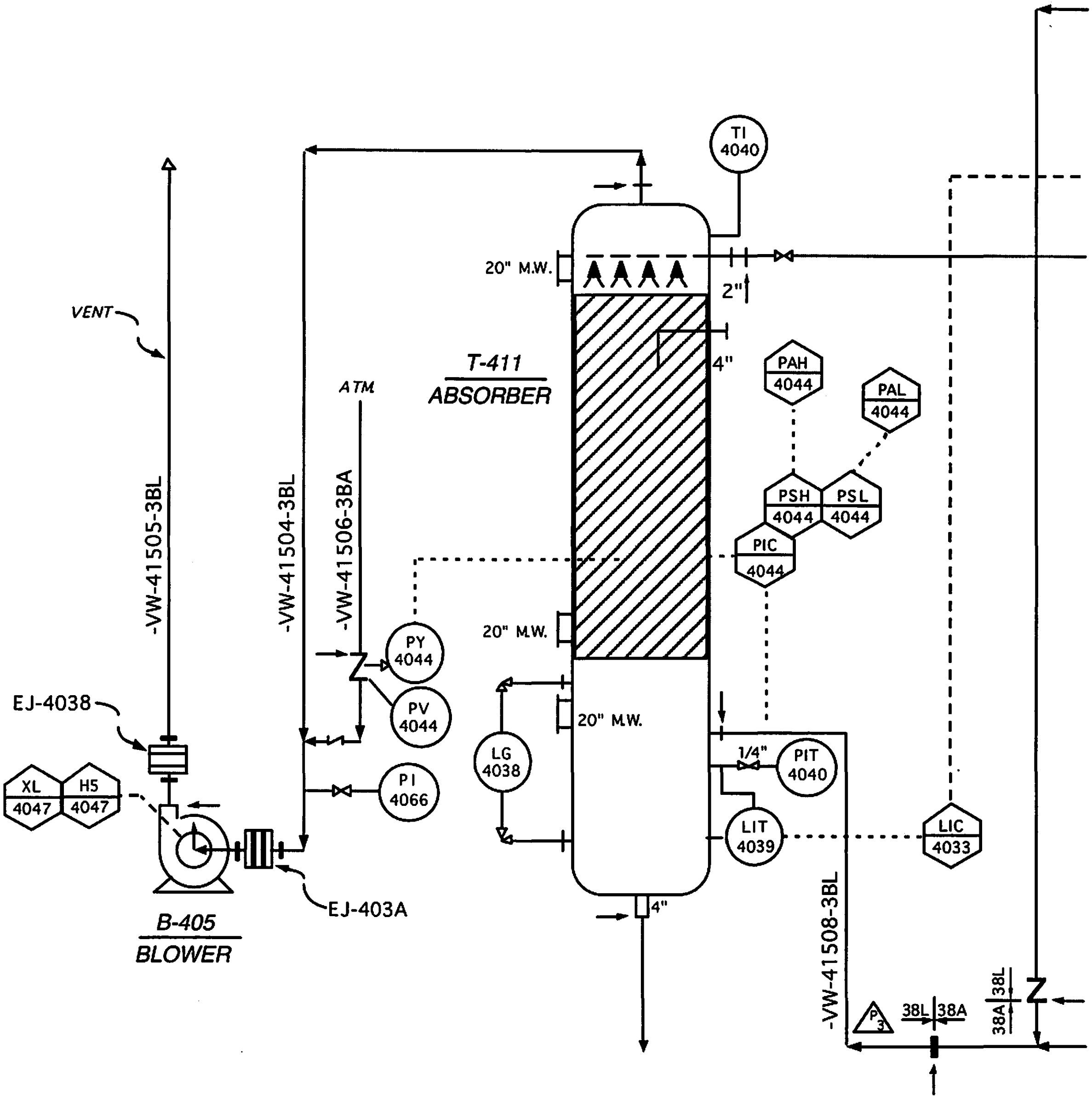


Figure 2.9 Example showing a portion of a piping and instrumentation diagram (adapted from ref. 3)

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14.3 CASE STUDY 2: MANUFACTURE OF XYLENES

Project Description

Xylenes are used as raw materials for the manufacture of polyesters, which are used for textile fibers, photographic film, and soft-drink bottles. The process to be added to an existing facility involves an isomerization reactor wherein meta-xylene (m-x) is converted to ortho-xylene (o-x) and para-xylene (p-x). Note that all three of these compounds are isomers (same elemental composition with different chemical structure). Therefore, they have the same molecular weight ($MW = 106$). For our purposes here we will assume that equal amounts of o-x and p-x are produced so that the reaction proceeds as follows:

$$2\text{m-x} \rightarrow \text{o-x} + \text{p-x}$$

This liquid phase reaction is assumed to be irreversible and is approximated by first-order kinetics with a rate constant of $k_r = 0.133\ min^{-1}$. The reaction is slightly endothermic ($\Delta\hat{H}_{react,m-x} = 295\ cal/gmol\ of\ m\text{-}x\ reacted$). The simplified process is described in the following paragraphs.

A liquid feed stream will enter the process at atmospheric pressure and a temperature of $77°F$ at a rate of 1 million kg/day. The mass fractions of that feed stream are

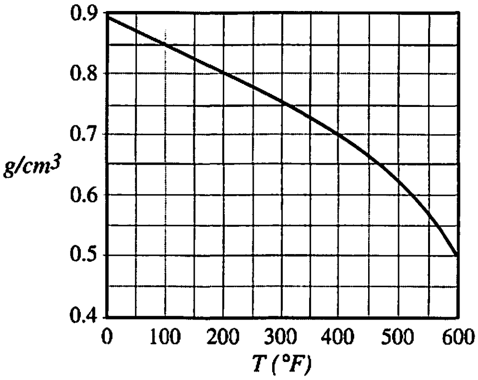
Feed Stream	o-x	m-x	p-x
	0.29	0.48	0.23

A centrifugal pump will be used to increase the pressure of the stream sufficiently to overcome the pressure drop due to friction in each of the components of the process (see the additional information given below). Following the pump, the stream will pass through a shell-and-tube heat exchanger where the temperature will be increased to $500°F$ using steam. The hot pressurized stream will then be fed into a well-mixed isothermal reactor (maintained with a steam jacket around the reactor) where 70% of the m-x will be reacted to form products. The product stream from the reactor will be cooled as much as possible with cooling water in another exchanger before entering the separation system. The separation system will yield three streams with the following mass fractions and that are all at the same temperature:

Outlet Stream	o-x	m-x	p-x
1	1.00	0.00	0.00
2	0.00	0.03	0.97
3	0.00	0.70	0.30

Technical Details

1. Assume that the separation system is isothermal (operates at constant temperature).
2. The separation system uses a complex scheme of multiple steps. For this preliminary design, simply represent the separation system by a box labeled "Separation System."
3. Assume countercurrent, single-pass heat exchangers
4. The heat capacity ($\bar{C}_p$) is essentially the same for all xylene streams and can be approximated for this preliminary estimate by an average value of $35\ Btu/lbmol°F$.
5. The density of xylenes varies as follows:



Case Study 2 *Manufacture of Xylenes (continued)*

6. Saturated steam is available at 545°F (1000 $psig$), and $\Delta\hat{H}_{vap} = 650\ Btu/lb_m$. When used for a heater or a reactor, the amount of steam that is used is only that which is condensed, and the condensate leaves as saturated liquid.
7. Cooling water is available at 90°F and has a maximum return temperature of 120°F. In selecting the actual return cooling water temperature, assume that you want to minimize the cost of cooling water (even though this will affect the size and cost of the heat exchanger). Also, the heat capacity of water is 1.0 $cal/g°C$.
8. In selecting the temperature of the process stream leaving the cooler, observe the rule of thumb that the minimum temperature difference (either ΔT_1 or ΔT_2, see Figure 10.11) for a heat exchanger is 10°F.
9. The pressure drop due to friction in each of the units is estimated to be as follows:

heat exchanger	15 *psi*
reactor	5 *psi*
product cooler	15 *psi*
separation system	165 *psi*

The outlet pressure from the separation system is atmospheric pressure. For this preliminary design, the pressure drops in the pipes between the major components may be neglected. The pipes are all the same diameter, and there are no significant elevation changes. You may also ignore the changes in kinetic energy associated with having one inlet and three outlets in the separation system (it would be instructive for you to think about how large such kinetic energy terms would be, say, with a 6-*in* ID pipe, compared with the large pressure drop term for the separation system).

10. The direct capital costs for the reactor, heat exchangers, and pump can be estimated from the formulas in Table 13.2 and using the current value of the *M&S* Index (look in the back of a current issue of the magazine *Chemical Engineering*[2]).
11. The following utility costs apply:

steam:	\$5.20/1000 lb_m
cooling water:	\$0.03/1000 *gal*
electricity:	\$0.05/*kW-hr*

12. The following market values/costs apply:

feed stream:	\$0.88/*gal*
ortho-xylene product stream:	\$0.22/lb_m
para-xylene product stream:	\$0.22/lb_m
byproduct (70% meta-xylene) stream:	\$0.12/lb_m

13. The cost of the separation system can be approximated as \$6.5 million (delivered price).
14. The total operating cost per year can be estimated as 1.5 times the sum of the feed cost, steam costs, cooling water costs, and electricity costs (excluding the separation system, for which these values are not known). In other words:

Operating cost = 1.5(*Feed cost* + *Steam cost* + *Cooling water cost* + *Electricity cost*)

15. The current tax rate is 35%; we are allowed to depreciate our equipment over 10 years; and our company requires a minimum *ROI* of 0.15. In our case, 85% of the capital investment can be depreciated.

Assignment

1. Draw a PFD for the process.
2. Perform material balances on the process, one unit at a time, to determine the component flows for each stream.
3. Perform energy balances to determine the unknown temperatures of the streams and/or the heat duties for the heat exchangers and reactor.
4. Calculate the amount of steam and cooling water needed for the heat exchangers and reactor.
5. Design the reactor(s) – determine the reactor volume(s) needed to achieve the specified conversion.

Case Study 2 *Manufacture of Xylenes (continued)*

6. Determine the work required for the pump assuming that the pump is 85% efficient (only 85% of the energy added to the pump is transferred to the fluid).
7. Size all heat exchangers using approximate values of U_o from Table 10.4.
8. Complete a stream table showing, for each stream, the mass flow rates of all components, the temperature, and the pressure. The stream table would be as follows:

	Process Feed	Pump Outlet	Reactor Feed	Reactor Outlet	Separator Feed	Separator Outlet		
						#1	#2	#3
Flows (lb_m/hr):								
m-xylene								
o-xylene								
p-xylene								
Total								
Temp. ($^\circ F$)								
Pressure ($psig$)								

9. Complete an equipment specification list, containing the following kinds of information:

   Pumps: Provide the required horsepower

   Heat exchangers: For each exchanger, provide the heat duty (Btu/hr), area, A_o (ft^2), and required steam flow rate (lb_m/hr) or cooling water flow rate (lb_m/hr)

   Reactor: Provide the volume (*liters*), heat duty for the heating jacket (Btu/hr), and required steam flow rate (lb_m/hr) for the jacket.

10. Determine the *ROI* for this project.
11. Suggest three ways to potentially improve the economics of this process. Explain why you believe your suggestions may make a significant improvement.

REFERENCES

1. Johnson D.W., R.T. Johnson, and K.A. Smith, *Active Learning: Cooperation in the College Classroom*, Edina, MN: Interaction Book Company, 1991.
2. *Chemical Engineering*, publication of McGraw-Hill Co., New York.