CHAPTER 1

INTRODUCTION

In this modern age of industrial competition, a successful chemical engineer needs more than a knowledge and understanding of the fundamental sciences and the related engineering subjects such as thermodynamics, reaction kinetics, and computer technology. The engineer must also have the ability to apply this knowledge to practical situations for the purpose of accomplishing something that will be beneficial to society. However, in making these applications, the chemical engineer must recognize the economic implications which are involved and proceed accordingly.

Chemical engineering design of new chemical plants and the expansion or revision of existing ones require the use of engineering principles and theories combined with a practical realization of the limits imposed by industrial conditions. Development of a new plant or process from concept evaluation to profitable reality is often an enormously complex problem. A plant-design project moves to completion through a series of stages such as is shown in the following:

1. Inception
2. Preliminary evaluation of economics and market
3. Development of data necessary for final design
4. Final economic evaluation
5. Detailed engineering design
6. Procurement
7. Erection
8. Startup and trial runs
9. Production

This brief outline suggests that the plant-design project involves a wide variety of skills. Among these are research, market analysis, design of individual pieces of equipment, cost estimation, computer programming, and plant-location surveys. In fact, the services of a chemical engineer are needed in each step of the outline, either in a central creative role, or as a key advisor.

CHEMICAL ENGINEERING PLANT DESIGN

As used in this text, the general term *plant design* includes all engineering aspects involved in the development of either a new, modified, or expanded industrial plant. In this development, the chemical engineer will be making economic evaluations of new processes, designing individual pieces of equipment for the proposed new venture, or developing a plant layout for coordination of the overall operation. Because of these many design duties, the chemical engineer is many times referred to here as a *design engineer.* On the other hand, a chemical engineer specializing in the economic aspects of the design is often referred to as a *cost engineer.* In many instances, the term *process engineering* is used in connection with economic evaluation and general economic analyses of industrial processes, while *process design* refers to the actual design of the equipment and facilities necessary for carrying out the process. Similarly, the meaning of plant design is limited by some engineers to items related directly to the complete plant, such as plant layout, general service facilities, and plant location.

The purpose of this book is to present the major aspects of plant design as related to the overall design project. Although one person cannot be an expert in *all* the phases involved in plant design, it is necessary to be acquainted with the general problems and approach in each of the phases. The process engineer may not be connected directly with the final detailed design of the equipment, and the designer of the equipment may have little influence on a decision by management as to whether or not a given return on an investment is adequate to justify construction of a complete plant. Nevertheless, if the overall design project is to be successful, close teamwork is necessary among the various groups of engineers working on the different phases of the project. The most effective teamwork and coordination of efforts are obtained when each of the engineers in the specialized groups is aware of the many functions in the *overall* design project.

PROCESS DESIGN DEVELOPMENT

The development of a process design, as outlined in Chap. 2, involves many different steps. The first, of course, must be the inception of the basic idea. This idea may originate in the sales department, as a result of a customer request, or to meet a competing product. It may occur spontaneously to someone who is acquainted with the aims and needs of a particular company, or it may be the result of an orderly research program or an offshoot of such a program. The operating division of the company may develop a new or modified chemical, generally as an intermediate in the final product. The engineering department of the company may originate a new process or modify an existing process to create new products. In all these possibilities, if the initial analysis indicates that the idea may have possibilities of developing into a worthwhile project, a preliminary research or investigation program is initiated. Here, a general survey of the possibilities for a successful process is made considering the physical and chemical operations involved as well as the economic aspects. Next comes the process-research phase including preliminary market surveys, laboratory-scale experiments, and production of research samples of the final product. When the potentialities of the process are fairly well established, the project is ready for the development phase. At this point, a pilot plant or a commercial-development plant may be constructed. A pilot plant is a small-scale replica of the full-scale final plant, while a commercial-development plant is usually made from odd pieces of equipment which are already available and is not meant to duplicate the exact setup to be used in the full-scale plant.

Design data and other process information are obtained during the development stage. This information is used as the basis for carrying out the additional phases of the design project. A complete market analysis is made, and samples of the final product are sent to prospective customers to determine if the product is satisfactory and if there is a reasonable sales potential. Capital-cost estimates for the proposed plant are made. Probable returns on the required investment are determined, and a complete cost-and-profit analysis of the process is developed.

Before the final process design starts, company management normally becomes involved to decide if significant capital funds will be committed to the project. It is at this point that the engineers' preliminary design work along with the oral and written reports which are presented become particularly important because they will provide the primary basis on which management will decide if further funds should be provided for the project. When management has made a firm decision to proceed with provision of significant capital funds for a project, the engineering then involved in further work on the project is known as ***capitalized*** engineering while that which has gone on before while the consideration of the project was in the development stage is often referred to as ***expensed*** engineering. This distinction is used for tax purposes to allow capitalized engineering costs to be amortized over a period of several years.

If the economic picture is still satisfactory, the final process-design phase is ready to begin. All the design details are worked out in this phase including controls, services; piping layouts, firm price quotations, specifications and designs for individual pieces of equipment, and all the other design information necessary for the construction of the final plant. A complete construction design is then made with elevation drawings, plant-layout arrangements, and other information required for the actual construction of the plant. The final stage consists of procurement of the equipment, construction of the plant, startup of the plant, overall improvements in the operation, and development of standard operating procedures to give the best possible results.

The development of a design project proceeds in a logical, organized sequence requiring more and more time, effort, and expenditure as one phase leads into the next. It is extremely important, therefore, to stop and analyze the situation carefully before proceeding with each subsequent phase. Many projects are discarded as soon as the preliminary investigation or research on the original idea is completed. The engineer working on the project must maintain a realistic and practical attitude in advancing through the various stages of a design project and not be swayed by personal interests and desires when deciding if further work on a particular project is justifiable. Remember, if the engineer's work is continued on through the various phases of a design project, it will eventually end up in a proposal that money be invested in the process. If no tangible return can be realized from the investment, the proposal will be turned down. Therefore, the engineer should have the ability to eliminate unprofitable ventures before the design project approaches a final-proposal stage.

GENERAL OVERALL DESIGN CONSIDERATIONS

The development of the overall design project involves many different design considerations. Failure to include these considerations in the overall design project may, in many instances, alter the entire economic situation so drastically as to make the venture unprofitable. Some of the factors involved in the development of a complete plant design include plant location, plant layout, materials of construction, structural design, utilities, buildings, storage, materials handling, safety, waste disposal, federal, state, and local laws or codes, and patents. Because of their importance, these general overall design considerations are considered in detail in Chap. 3.

Various types of computer programs and techniques are used to carry out the design of individual pieces of equipment or to develop the strategy for a full plant design. This application of computer usage in design is designated as ***computer-aided design*** and is the subject of Chap. 4.

Record keeping and accounting procedures are also important factors in general design considerations, and it is necessary that the design engineer be familiar with the general terminology and approach used by accountants for cost and asset accounting. This subject is covered in Chap. 5.

COST ESTIMATION

As soon as the final process-design stage is completed, it, becomes possible to make accurate cost estimations because detailed equipmept specifications and definite plant-facility information are available. Direct price quotations based on detailed specifications can then be obtained from various manufacturers. However, as mentioned earlier, no design project should proceed to the final stages before costs are considered, and cost estimates should be made throughout all the early stages of the design when complete specifications are not available. Evaluation of costs in the preliminary design phases is sometimes called "guesstimation" but the appropriate designation is ***predesign cost estimation***. Such estimates should be capable of providing a basis for company management to decide if further capital should be invested in the project.

The chemical engineer (or cost engineer) must be certain to consider all possible factors when making a cost analysis. Fixed costs, direct production costs for raw materials, labor, maintenance, power, and utilities must all be included along with costs for plant and administrative overhead, distribution of the final products, and other miscellaneous items.

Chapter 6 presents many of the special techniques that have been developed for making predesign cost estimations. Labor and material indexes, standard cost ratios, and special multiplication factors are examples of information used when making design estimates of costs. The final test as to the validity of any cost estimation can come only when the completed plant has been put into operation. However, if the design engineer is well acquainted with the various estimation methods and their accuracy, it is possible to make remarkably close cost estimations even before the final process design gives detailed specifications.

FACTORS AFFECTING PROFITABILITY OF INVESTMENTS

A major function of the directors of a manufacturing firm is to maximize the long-term profit to the owners or the stockholders. A decision to invest in fixed facilities carries with it the burden of continuing interest, insurance, taxes, depreciation, manufacturing costs, etc., and also reduces the fluidity of the company's future actions. Capital-investment decisions, therefore, must be made with great care. Chapters 7 and 10 present guidelines for making these capital-investment decisions.

Money, or any other negotiable type of capital, has a time value. When a manufacturing enterprise invests money, it expects to receive a return during the time the money is being used. The amount of return demanded usually depends on the degree of risk that is assumed. Risks differ between projects which might otherwise seem equal on the basis of the best estimates of an overall plant design. The risk may depend upon the process used, whether it is well established or a complete innovation; on the product to be made, whether it is a stapie item or a completely new product; on the sales forecasts, whether all sales will be outside the company or whether a significant fraction is internal, etc. Since means for incorporating different levels of risk into ***profitability*** forecasts are not too well established, the most common methods are to raise the minimum acceptable ***rate*** of ***return*** for the riskier projects.

Time value of money has been integrated into investment-evaluation systems by means of ***compound-interest*** relationships. Dollars, at different times, are given different degrees of importance by means of compounding or discounting at some preselected compound-interest rate. For any assumed interest value of money, a known amount at any one time can be converted to an equivalent but different amount at a different time. As time passes, money can be invested to increase at the interest rate. If the time when money is needed for investment is in the future, the present value of that investment can be calculated by discounting from the time of investment back to the present at the assumed interest rate.

Expenses, as outlined in Chap. 8, for various types of taxes and insurance can materially affect the economic situation for any industrial process. Because modern taxes may amount to a major portion of a manufacturing firm's net earnings, it is essential that the chemical engineer be conversant with the fundamentals of taxation. For example, income taxes apply differently to projects with different proportions of fixed and working capital. Profitability, therefore, should be based on income after taxes. Insurance costs, on the other hand, are normally only a small part of the total operational expenditure of an industrial enterprise; however, before any operation can be carried out on a sound economic basis, it is necessary to determine the insurance requirements to provide adequate coverage against unpredictable emergencies or developments.

Since all physical assets of an industrial facility decrease in value with age, it is normal practice to make periodic charges against earnings so as to distribute the first cost of the facility over its expected service life. This ***depreciation*** expense as detailed in Chap. 9, unlike most other expenses, entails no current outlay of cash. Thus, in a given accounting period, a firm has available, in addition to the net profit, additional funds corresponding to the depreciation expense. This cash is ***capital recovery,*** a partial regeneration of the first cost of the physical assets.

Income-tax laws permit recovery of funds by two accelerated depreciation schedules as well as by straight-line methods. Since cash-flow timing is affected, choice of depreciation method affects profitability significantly. Depending on the ratio of depreciable to nondepreciable assets involved, two projects which look equivalent before taxes, or rank in one order, may rank entirely differently when considered after taxes. Though cash costs and sales values may be equal on two projects, their reported net incomes for tax purposes may be different, and one will show a greater net profit than the other.

OPTIMUM DESIGN

In almost every case encountered by a chemical engineer, there are several alternative methods which can be used for any given process or operation. For example, formaldehyde can be produced by catalytic dehydrogenation of methanol, by controlled oxidation of natural gas, or by direct reaction between CO and H_2 under special conditions of catalyst, temperature, and pressure. Each of these processes contains many possible alternatives involving variables such as gas-mixture composition, temperature, pressure, and choice of catalyst. It is the responsibility of the chemical engineer, in this case, to choose the best process and to incorporate into the design the equipment and methods which will give the best results. To meet this need, various aspects of chemical engineering plant-design optimization are described in Chap. 11 including presentation of design strategies which can be used to establish the desired results in the most efficient manner.

Optimum Economic Design

If there are two or more methods for obtaining exactly equivalent final results, the preferred method would be the one involving the least total cost. This is the basis of an optimum economic *design*. One typical example of an optimum economic design is determining the pipe diameter to use when pumping a given amount of fluid from one point to another. Here the same final result (i.e., a set amount of fluid pumped between two given points) can be accomplished by using an infinite number of different pipe diameters. However, an economic balance will show that one particular pipe diameter gives the least total cost. The total cost includes the cost for pumping the liquid and the cost (i.e., fixed charges) for the installed piping system.

A graphical representation showing the meaning of an optimum economic pipe diameter is presented in Fig. l-l. As shown in this figure, the pumping cost increases with decreased size of pipe diameter because of frictional effects, while the fixed charges for the pipeline become lower when smaller pipe diameters are used because of the reduced capital investment. The optimum economic diameter is located where the sum of the pumping costs and fixed costs for the pipeline becomes a minimum, since this represents the point of least total cost. In Fig. l-l, this point is represented by *E*.

The chemical engineer often selects a final design on the basis of conditions giving the least total cost. In many cases, however, alternative designs do not give final products or results that are exactly equivalent. It then becomes necessary to consider the quality of the product or the operation as well as the total cost. When the engineer speaks of an optimum economic design, it ordinarily means the cheapest one selected from a number of equivalent designs. Cost data, to assist in making these decisions, are presented in Chaps. 14 through 16.

Various types of optimum economic requirements may be encountered in design work. For example, it may be desirable to choose a design which gives the maximum profit per unit of time or the minimum total cost per unit of production.

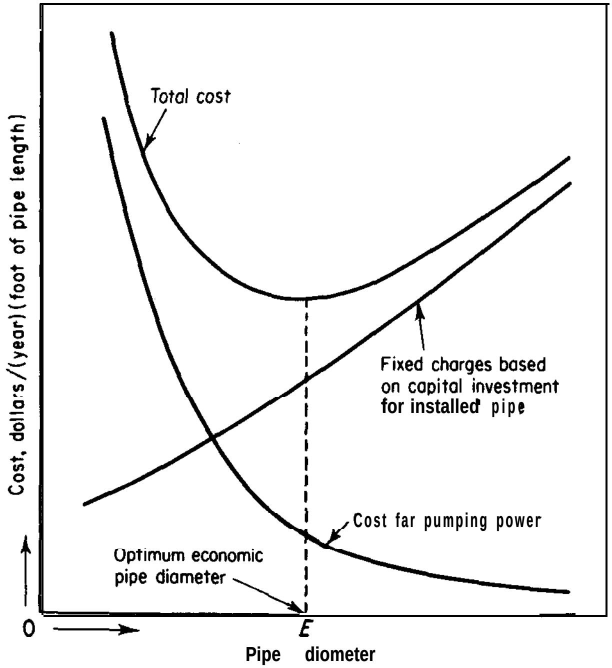


FIGURE 1-1
Determination of optimum economic pipe diameter for constant mass-throughput rate.

Optimum Operation Design

Many processes require definite conditions of temperature, pressure, contact time, or other variables if the best results are to be obtained. It is often possible to make a partial separation of these optimum conditions from direct economic considerations. In cases of this type, the best design is designated as the ***optimum operation design.*** The chemical engineer should remember, however, that economic considerations ultimately determine most quantitative decisions. Thus, the optimum operation design is usually merely a tool or step in the development of an optimum economic design.

An excellent example of an optimum operation design is the determination of operating conditions for the catalytic oxidation of sulfur dioxide to sulfur trioxide. Suppose that all the variables, such as converter size, gas rate, catalyst activity, and entering-gas concentration, are fixed and the only possible variable is the temperature at which the oxidation occurs. If the temperature is too high, the yield of SO, will be low because the equilibrium between SO,, SO,, and 0, is shifted in the direction of SO, and 0,. On the other hand, if the temperature is too low, the yield will be poor because the reaction rate between SO, and 0, will be low. Thus, there must be one temperature where the amount of sulfur trioxide formed will be a maximum. This particular temperature would give the

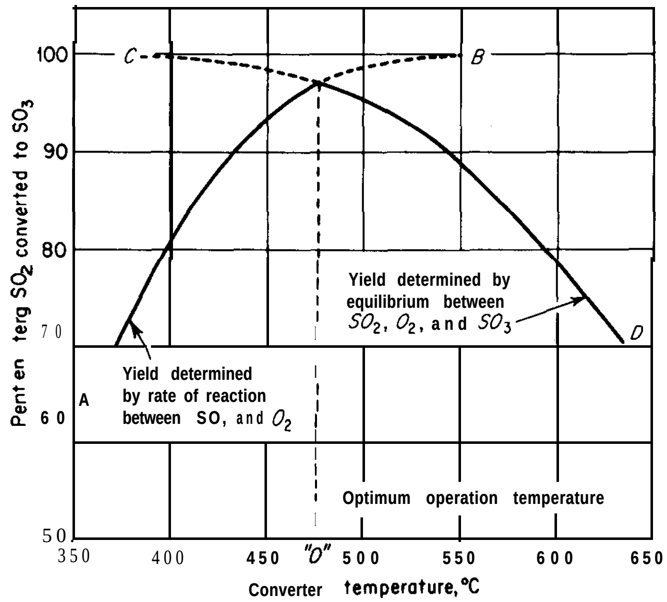


FIGURE 1-2
Determination of optimum operation temperature in sulfur dioxide converter.

optimum operation design. Figure 1-2 presents a graphical method for determining the optimum operation temperature for the sulfur dioxide converter in this example. Line AB represents the maximum yields obtainable when the reaction rate is controlling, while line *CD* indicates the maximum yields on the basis of equilibrium conditions controlling. Point 0 represents the optimum operation temperature where the maximum yield is obtained.

The preceding example is a simplified case of what an engineer might encounter in a design. In reality, it would usually be necessary to consider various converter sizes and operation with a series of different temperatures in order to arrive at the optimum operation design. Under these conditions, several equivalent designs would apply, and the final decision would be based on the optimum economic conditions for the equivalent designs.

PRACTICAL CONSIDERATIONS IN DESIGN

The chemical engineer must never lose sight of the practical limitations involved in a design. It may be possible to determine an exact pipe diameter for an optimum economic design, but this does not mean that this exact size must be used in the final design. Suppose the optimum diameter were 3.43 in. (8.71 cm). It would be impractical to have a special pipe fabricated with an inside diameter of 3.43 in. Instead, the engineer would choose a standard pipe size which could be purchased at regular market prices. In this case, the recommended pipe size would probably be a standard $3\frac{1}{2}$-in.-diameter pipe having an inside diameter of 3.55 in. (9.02 cm).

If the engineer happened to be very conscientious about getting an adequate return on all investments, he or she might say, "A standard 3-in.-diameter pipe would require less investment and would probably only increase the total cost slightly; therefore, I think we should compare the costs with a 3-in. pipe to the costs with the $3\frac{1}{2}$-in. pipe before making a final decision." Theoretically, the conscientious engineer is correct in this case. Suppose the total cost of the installed $3\frac{1}{2}$-in. pipe is $5000 and the total cost of the installed 3-in. pipe is $4500. If the total yearly savings on power and fixed charges, using the $3\frac{1}{2}$-in. pipe instead of the 3-in. pipe, were $25, the yearly percent return on the extra $500 investment would be only 5 percent. Since it should be possible to invest the extra $500 elsewhere to give more than a 5 percent return, it would appear that the 3-in.-diameter pipe would be preferred over the $3\frac{1}{2}$-in.-diameter pipe.

The logic presented in the preceding example is perfectly sound. It is a typical example of investment comparison and should be understood by all chemical engineers. Even though the optimum economic diameter was 3.43 in., the good engineer knows that this diameter is only an exact mathematical number and may vary from month to month as prices or operating conditions change. Therefore, all one expects to obtain from this particular optimum economic calculation is a good estimation as to the best diameter, and investment comparisons may not be necessary.

The practical engineer understands the physical problems which are involved in the final operation and maintenance of the designed equipment. In developing the plant layout, crucial control valves must be placed where they are easily accessible to the operators. Sufficient space must be available for maintenance personnel to check, take apart, and repair equipment. The engineer should realize that cleaning operations are simplified if a scale-forming fluid is passed through the inside of the tubes rather than on the shell side of a tube-and-shell heat exchanger. Obviously, then, sufficient plant-layout space should be made available so that the maintenance workers can remove the head of the installed exchanger and force cleaning worms or brushes through the inside of the tubes or remove the entire tube bundle when necessary.

The theoretical design of a distillation unit may indicate that the feed should be introduced on one particular tray in the tower. Instead of specifying a tower with only one feed inlet on the calculated tray, the practical engineer will include inlets on several trays above and below the calculated feed point since the actual operating conditions for the tower will vary and the assumptions included in the calculations make it impossible to guarantee absolute accuracy.

The preceding examples typify the type of practical problems the chemical engineer encounters. In design work, theoretical and economic principles must be combined with an understanding of the common practical problems that will arise when the process finally comes to life in the form of a complete plant or a complete unit.

THE DESIGN APPROACH

The chemical engineer has many tools to choose from in the development of a profitable plant design. None, when properly utilized, will probably contribute as much to the optimization of the design as the use of high-speed computers. Many problems encountered in the process development and design can be solved rapidly with a higher degree of completeness with high-speed computers and at less cost than with ordinary hand or desk calculators. Generally overdesign and safety factors can be reduced with a substantial savings in capital investment.

At no time, however, should the engineer be led to believe that plants are designed around computers. They are used to determine design data and are used as models for optimization once a design is established. They are also used to maintain operating plants on the desired operating conditions. The latter function is a part of design and supplements and follows process design.

The general approach in any plant design involves a carefully balanced combination of theory, practice, originality, and plain common sense. In original design work, the engineer must deal with many different types of experimental and empirical data. The engineer may be able to obtain accurate values of heat capacity, density, vapor-liquid equilibrium data, or other information on physical properties from the literature. In many cases, however, exact values for necessary physical properties are not available, and the engineer is forced to make approximate estimates of these values. Many approximations also must be made in carrying out theoretical design calculations. For example, even though the engineer knows that the ideal-gas law applies exactly only to simple gases at very low pressures, this law is used in many of the calculations when the gas pressure is as high as 5 or more atmospheres (507 kPa). With common gases, such as air or simple hydrocarbons, the error introduced by using the ideal gas law at ordinary pressures and temperatures is usually negligible in comparison with other uncertainties involved in design calculations. The engineer prefers to accept this error rather than to spend time determining virial coefficients or other factors to correct for ideal gas deviations.

In the engineer's approach to any design problem, it is necessary to be prepared to make many assumptions. Sometimes these assumptions are made because no absolutely accurate values or methods of calculation are available. At other times, methods involving close approximations are used because exact treatments would require long and laborious calculations giving little gain in accuracy. The good chemical engineer recognizes the need for making certain assumptions but also knows that this type of approach introduces some uncertainties into the final results. Therefore, assumptions are made only when they are necessary and essentially correct.

Another important factor in the approach to any design problem involves economic conditions and limitations. The engineer must consider costs and probable profits constantly throughout all the work. It is almost always better to sell many units of a product at a low profit per unit than a few units at a high profit per unit. Consequently, the engineer must take into account the volume of production when determining costs and total profits for various types of designs. This obviously leads to considerations of customer needs and demands. These factors may appear to be distantly removed from the development of a plant design, but they are extremely important in determining its ultimate success.

CHAPTER 2

PROCESS DESIGN DEVELOPMENT

A principle responsibility of the chemical engineer is the design, construction, and operation of chemical plants. In this responsibility, the engineer must continuously search for additional information to assist in these functions. Such information is available from numerous sources, including recent publications, operation of existing process plants, and laboratory and pilot-plant data. This collection and analysis of all pertinent information is of such importance that chemical engineers are often members, consultants, or advisors of even the basic research team which is developing a new process or improving and revising an existing one. In this capacity, the chemical engineer can frequently advise the research group on how to provide considerable amounts of valuable design data.

Subjective decisions are and must be made many times during the design of any process. What are the best methods of securing sufficient and usable data? What is sufficient and what is reliable? Can better correlations of the data be devised, particularly ones that permit more valid extrapolation?

The chemical engineer should always be willing to consider completely new designs. An attempt to understand the controlling factors of the process, whether chemical or physical, helps to suggest new or improved techniques. For example, consider the commercial processes of aromatic nitration and alkylation of isobutane with olefins to produce high-octane gasolines. Both reactions involve two immiscible liquid phases and the mass-transfer steps are essentially rate controlling. Nitro-aromatics are often produced in high yields (up to 99 percent); however, the alkylation of isobutane involves numerous side reactions and highly complex chemistry that is less well understood. Several types of reactors have been used for each reaction. Then radically new and simplified reactors were developed based on a better understanding of the chemical and physical steps involved.

DESIGN-PROJECT PROCEDURE

The development of a design project always starts with an initial idea or plan. This initial idea must be stated as clearly and concisely as possible in order to define the scope of the project. General specifications and pertinent laboratory or chemical engineering data should be presented along with the initial idea.

Types of Designs

The methods for carrying out a design project may be divided into the following classifications, depending on the accuracy and detail required:

1. Preliminary or quick-estimate designs
2. Detailed-estimate designs
3. Firm process designs or detailed designs

Preliminary designs are ordinarily used as a basis for determining whether further work should be done on the proposed process. The design is based on approximate process methods, and rough cost estimates are prepared. Few details are included, and the time spent on calculations is kept at a minimum.

If the results of the preliminary design show that further work is justified, a ***detailed-estimate design*** may be developed. In this type of design, the cost-and-profit potential of an established process is determined by detailed analyses and calculations. However, exact specifications are not given for the equipment, and drafting-room work is minimized.

When the detailed-estimate design indicates that the proposed project should be a commercial success, the final step before developing construction plans for the plant is the preparation of a firm ***process design.*** Complete specifications are presented for all components of the plant, and accurate costs based on quoted prices are obtained. The firm process design includes blueprints and sufficient information to permit immediate development of the final plans for constructing the plant.

Feasibility Survey

Before any detailed work is done on the design, the technical and economic factors of the proposed process should be examined. The various reactions and physical processes involved must be considered, along with the existing and potential market conditions for the particular product. A preliminary survey of this type gives an indication of the probable success of'the project and also shows what additional information is necessary to make a complete evaluation. Following is a list of items that should be considered in making a feasibility survey:

1. Raw materials (availability, quantity, quality, cost)
2. Thermodynamics and kinetics of chemical reactions involved (equilibrium, yields, rates, optimum conditions)
3. Facilities and equipment available at present
4. Facilities and equipment which must be purchased
5. Estimation of production costs and total investment
6. Profits (probable and optimum, per pound of product and per year, return on investment)
7. Materials of construction
8. Safety considerations
9. Markets (present and future supply and demand, present uses, new uses, present buying habits, price range for products and by-products, character, location, and number of possible customers)
10. Competition (overall production statistics, comparison of various manufacturing processes, product specifications of competitors)
11. Properties of products (chemical and physical properties, specifications, impurities, effects of storage)
12. Sales and sales service (method of selling and distributing, advertising required, technical services required)
13. Shipping restrictions and containers
14. Plant location
15. Patent situation and legal restrictions

When detailed data on the process and firm product specifications are available, a complete market analysis combined with a consideration of all sales factors should be made. This analysis can be based on a breakdown of items 9 through 15 as indicated in the preceding list.

Process Development

In many cases, the preliminary feasibility survey indicates that additional research, laboratory, or pilot-plant data are necessary, and a program to obtain this information may be initiated. Process development on a pilot-plant or semiworks scale is usually desirable in order to obtain accurate design data.

Valuable information on material and energy balances can be obtained, and process conditions can be examined to supply data on temperature and pressure variation, yields, rates, grades of raw materials and products, batch versus continuous operation, material of construction, operating characteristics, and other pertinent design variables.

Design

If sufficient information is available, a preliminary design may be developed in conjunction with the preliminary feasibility survey. In developing the preliminary design the chemical engineer must first establish a workable manufacturing process for producing the desired product. Quite often a number of alternative processes or methods may be available to manufacture the same product. Except for those processes obviously undesirable, each method should be given consideration.

The first step in preparing the preliminary design is to establish the bases for ***design.*** In addition to the known specifications for the product and availability of raw materials, the design can be controlled by such items as the expected annual operating factor (fraction of the year that the plant will be in operation), temperature of the cooling water, available steam pressures, fuel used, value of by-products, etc. The next step consists of preparing a simplified flow diagram showing the processes that are involved and deciding upon the unit operations which will be required. A preliminary material balance at this point may very quickly eliminate some the alternative cases. Flow rates and stream conditions for the remaining cases are now evaluated by complete material balances, energy balances, and a knowledge of raw-material and product specifications, yields, reaction rates, and time cycles. The temperature, pressure, and composition of every process stream is determined. Stream enthalpies, percent vapor, liquid, and solid, heat duties, etc., are included where pertinent to the process.

Unit process principles are used in the design of specific pieces of equipment. (Assistance with the design and selection of various types of process equipment is given in Chaps. 14 through 16.) Equipment specifications are generally summarized in the form of tables and included with the final design report. These tables usually include the following:

1. ***Columns (distillation).*** In addition to the number of plates and operating conditions it is also necessary to specify the column diameter, materials of construction, plate layout, etc.
2. Vessels. In addition to size, which is often dictated by the holdup time desired, materials of construction and any packing or baffling should be specified.
3. ***Reactors.*** Catalyst type and size, bed diameter and thickness, heat-interchange facilities, cycle and regeneration arrangements, materials of construction, etc., must be specified.

4. ***Heat exchangers and furnaces.*** Manufacturers are usually supplied with the duty, corrected log mean-temperature difference, percent vaporized, pressure drop desired, and materials of construction.
5. ***Pumps and compressors.*** Specify type, power requirement, pressure difference, gravities, viscosities, and working pressures.
6. ***Instruments.*** Designate the function and any particular requirement.
7. ***Special equipment.*** Specifications for mechanical separators, mixers, driers, etc.

The foregoing is not intended as a complete checklist, but rather as an illustration of the type of summary that is required. (The headings used are particularly suited for the petrochemical industry; others may be desirable for different industries.) As noted in the summary, the selection of materials is intimately connected with the design and selection of the proper equipment.

As soon as the equipment needs have been firmed up, the utilities and labor requirements can be determined and tabulated. Estimates of the capital investment and the total product cost (as outlined in Chap. 6) complete the preliminary-design calculations. Economic evaluation plays an important part in any process design. This is particularly true not only in the selection for a specific process, choice of raw materials used, operating conditions chosen, but also in the specification of equipment. No design of a piece of equipment or a process is complete without an economical evaluation. In fact, as mentioned in Chap. 1, no design project should ever proceed beyond the preliminary stages without a consideration of costs. Evaluation of costs in the preliminary-design phases greatly assists the engineer in further eliminating many of the alternative cases.

The final step, and an important one in preparing a typical process design, involves writing the report which will present the results of the design work. Unfortunately this phase of the design work quite often receives very little attention by the chemical engineer. As a consequence, untold quantities of excellent engineering calculations and ideas are sometimes discarded because of poor communications between the engineer and management.?

Finally, it is important that the preliminary design be carried out as soon as sufficient data are available from the feasibility survey or the process-development step. In this way, the preliminary design can serve its main function of eliminating an undesirable project before large amounts of money and time are expended.

The preliminary design and the process-development work gives the results necessary for a detailed-estimate design. The following factors should be

†See Chap. 13 for assistance in preparing more concise and clearer design reports.

established within narrow limits before a detailed-estimate design is developed:

1. Manufacturing process
2. Material and energy balances
3. Temperature and pressure ranges
4. Raw-material and product specifications
5. Yields, reaction rates, and time cycles
6. Materials of construction
7. Utilities requirements
8. Plant site

When the preceding information is included in the design, the result permits accurate estimation of required capital investment, manufacturing costs, and potential profits. Consideration should be given to the types of buildings, heating, ventilating, lighting, power, drainage, waste disposal, safety facilities, instrumentation, etc.

Firm process designs (or detailed designs) can be prepared for purchasing and construction from a detailed-estimate design. Detailed drawings are made for the fabrication of special equipment, and specifications are prepared for purchasing standard types of equipment and materials. A complete plant layout is prepared, and blueprints and instructions for construction are developed. Piping diagrams and other construction details are included. Specifications are given for warehouses, laboratories, guard-houses, fencing, change houses, transportation facilities, and similar items. The final firm process design must be developed with the assistance of persons skilled in various engineering fields, such as architectural, ventilating, electrical, and civil. Safety conditions and environmental-impact factors must also always be taken into account.

Construction and Operation

When a definite decision to proceed with the construction of a plant is made, there is usually an immediate demand for a quick plant startup. Timing, therefore, is particularly important in plant construction. Long delays may be encountered in the fabrication of major pieces of equipment, and deliveries often lag far behind the date of ordering. These factors must be taken into consideration when developing the final plans and may warrant the use of the Project Evaluation and Review Technique (PERT) or the Critical Path Method (CPM).† The chemical engineer should always work closely with construction personnel during the final stages of construction and purchasing designs. In this way, the design sequence can be arranged to make certain important factors

†For further discussion of these methods consult Chap. 11.

that might delay construction are given first consideration. Construction of the plant may be started long before the final design is 100 percent complete. Correct design sequence is then essential in order to avoid construction delays.

During construction of the plant, the chemical engineer should visit the plant site to assist in interpretation of the plans and learn methods for improving future designs. The engineer should also be available during the initial startup of the plant and the early phases of operation. Thus, by close teamwork between design, construction, and operations personnel, the final plant can develop from the drawing-board stage to an operating unit that can function both efficiently and effectively.

DESIGN INFORMATION FROM THE LITERATURE

A survey of the literature will often reveal general information and specific data pertinent to the development of a design project. One good method for starting a literature survey is to obtain a recent publication dealing with the subject under investigation. This publication will give additional references, and each of these references will, in turn, indicate other sources of information. This approach permits a rapid survey of the important literature.

Chemical Abstracts, published semimonthly by the American Chemical Society, can be used for comprehensive literature surveys on chemical processes and operations.† This publication presents a brief outline and the original reference of the published articles dealing with chemistry and related fields. Yearly and decennial indexes of subjects and authors permit location of articles concerning specific topics.

A primary source of information on all aspects of chemical engineering principles, design, costs, and applications is "The Chemical Engineers' Handbook" published by McGraw-Hill Book Company with R. H. Perry and D. W. Green as editors for the 6th edition as published in 1984. This reference should be in the personal library of all chemical engineers involved in the field.

Regular features on design-related aspects of equipment, costs, materials of construction, and unit processes are published in *Chemical Engineering.* In addition to this publication, there are many other periodicals that publish articles of direct interest to the design engineer. The following periodicals are suggested as valuable sources of information for the chemical engineer who wishes to keep abreast of the latest developments in the field: *American Institute of Chemical Engineers' Journal, Chemical Engineering Progress, Chemical and Engineering News, Chemical Week, Chemical Engineering Science, Industrial and Engineering Chemistry Fundamentals, Industrial and Engineering Chemistry Process Design and Development, Journal of the American Chemical Society, Journal*

†Abstracts of general engineering articles are available in the *Engineering Index*.

of Physical Chemistry, Hydrocarbon Processing, Engineering News-Record, Oil and Gas Journal, and Canadian Journal of Chemical Engineering.

A large number of textbooks covering the various aspects of chemical engineering principles and design are available.† In addition, many handbooks have been published giving physical properties and other basic data which are very useful to the design engineer.

Trade bulletins are published regularly by most manufacturing concerns, and these bulletins give much information of direct interest to the chemical engineer preparing a design. Some of the trade-bulletin information is condensed in an excellent reference book on chemical engineering equipment, products, and manufacturers. This book is known as the "Chemical Engineering Catalog,"‡ and contains a large amount of valuable descriptive material.

New information is constantly becoming available through publication in periodicals, books, trade bulletins, government reports, university bulletins, and many other sources. Many of the publications are devoted to shortcut methods for estimating physical properties or making design calculations, while others present compilations of essential data in the form of nomographs or tables.

The effective design engineer must make every attempt to keep an up-to-date knowledge of the advances in the field. Personal experience and contacts, attendance at meetings of technical societies and industrial expositions, and reference to the published literature are very helpful in giving the engineer the background information necessary for a successful design.

FLOW DIAGRAMS

The chemical engineer uses flow diagrams to show the sequence of equipment and unit operations in the overall process, to simplify visualization of the manufacturing procedures, and to indicate the quantities of materials and energy transfer. These diagrams may be divided into three general types: (1) qualitative, (2) quantitative, and (3) combined-detail.

A qualitative flow diagram indicates the flow of materials, unit operations involved, equipment necessary, and special information on operating temperatures and pressures. A quantitative flow diagram shows the quantities of materials required for the process operation. An example of a qualitative flow diagram for the production of nitric acid is shown in Fig. 2-1. Figure 2-2 presents a quantitative flow diagram for the same process.

Preliminary flow diagrams are made during the early stages of a design project. As the design proceeds toward completion, detailed information on flow quantities and equipment specifications becomes available, and combined-detail flow diagrams can be prepared. This type of diagram shows the

†For example, see the *Chemical* Engineering Series listing at the front of this text.

‡Published annually by Reinhold Publishing, Stamford, CT.

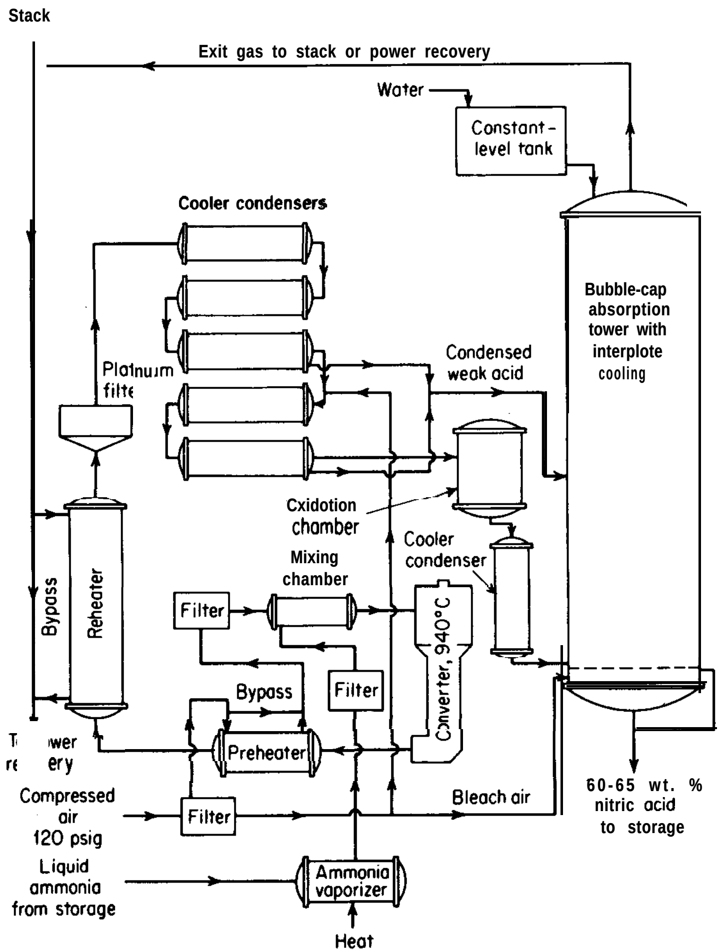


FIGURE **2-1**
Qualitative flow diagram for the manufacture of nitric acid by the ammonia-oxidation process.

qualitative flow pattern and serves as a base reference for giving equipment specifications, quantitative data, and sample calculations. Tables presenting pertinent data on the process and the equipment are cross-referenced to the drawing. In this way, qualitative information and quantitative data are combined on the basis of one flow diagram. The drawing does not lose its effectiveness by presenting too much information; yet the necessary data are readily available by direct reference to the accompanying tables.

A typical cbmbined-detail flow diagram shows the location of temperature and pressure regulators and indicators, as well as the location of critical control valves and special instruments. Each piece of equipment is shown and is designated by a defined code number. For each piece of equipment, accompany-

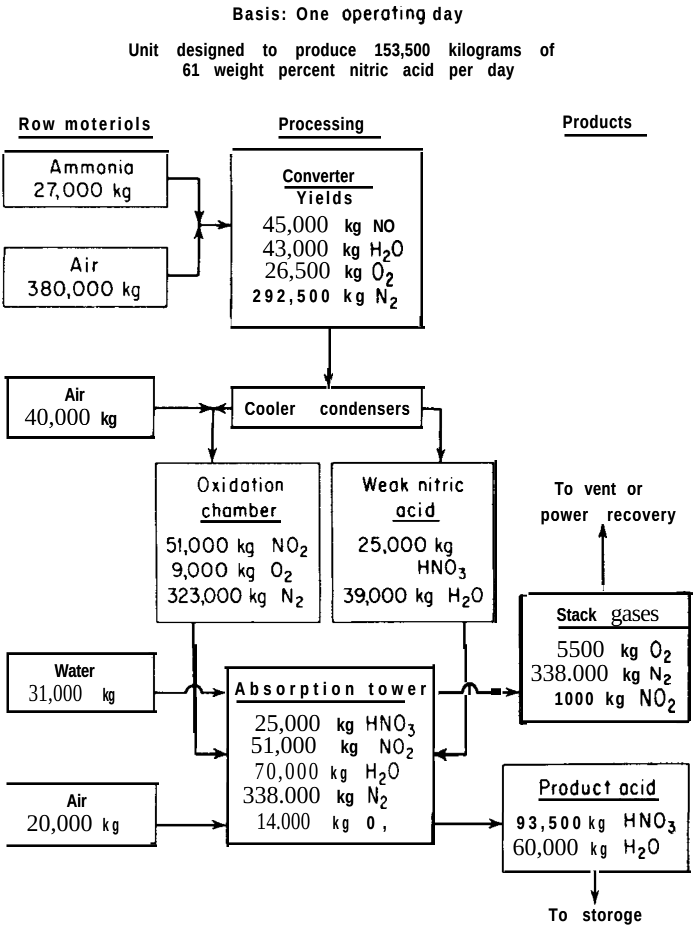


FIGURE 2-2
Quantitative flow diagram for the manufacture of nitric acid by the ammonia-oxidation process.

ing tables give essential information, such as specifications for purchasing, specifications for construction, type of fabrication, quantities and types of chemicals involved, and sample calculations.

Equipment symbols and flow-sheet symbols, particularly for detailed equipment flow sheets, are given in the Appendix.

THE PRELIMINARY DESIGN

In order to amplify the remarks made earlier in this chapter concerning the design-project procedure, it is appropriate at this time to look more closely at a specific preliminary design. Because of space limitations, only a brief presentation of the design will be attempted at this point.† However, sufficient detail will be given to outline the important steps which are necessary to prepare such a preliminary design. The problem presented is a practical one of a type frequently encountered in the chemical industry; it involves both process design and economic considerations.

Problem Statement

A conservative petroleum company has recently been reorganized and the new management has decided that the company must diversify its operations into the petrochemical field if it wishes to remain competitive. The research division of the company has suggested that a very promising area in the petrochemical field would be in the development and manufacture of biodegradable synthetic detergents using some of the hydrocarbon intermediates presently available in the refinery. A survey by the market division has indicated that the company could hope to attain 2.5 percent of the detergent market if a plant with an annual production of 15 million pounds were to be built. To provide management with an investment comparison, the design group has been instructed to proceed first with a preliminary design and an updated cost estimate for a nonbiodegradable detergent producing facility similar to ones supplanted by recent biodegradable facilities.

Literature Survey

A survey of the literature reveals that the majority of the nonbiodegradable detergents are alkylbenzene sulfonates (ABS). Theoretically, there are over 80,000 isomeric alkylbenzenes in the range of C_{10} to C_{15} for the alkyl side chain. Costs, however, generally favor the use of dodecene (propylene tetramer) as the starting material for ABS.

There are many different schemes in the manufacture of ABS. Most of the schemes are variations of the one shown in Fig. 2-3 for the production of sodium dodecylbenzene sulfonate. A brief description of the process is as follows:

This process involves reaction of dodecene with benzene in the presence of aluminum chloride catalyst; fractionation of the resulting crude mixture to recover the desired boiling range of dodecylbenzene; sulfonation of the dodecylbenzene and subsequent neutralization of the sulfonic acid with caustic soda; blending the resulting slurry with chemical "builders"; and drying.

Dodecene is charged into a reaction vessel containing benzene and aluminum chloride. The reaction mixture is agitated and cooled to maintain the reaction temperature of about 115°F maximum. An excess of benzene is used to suppress the formation of by-products. Aluminum chloride requirement is 5 to 10 wt% of dodecene.

†Completion of the design is left as an exercise for the reader.

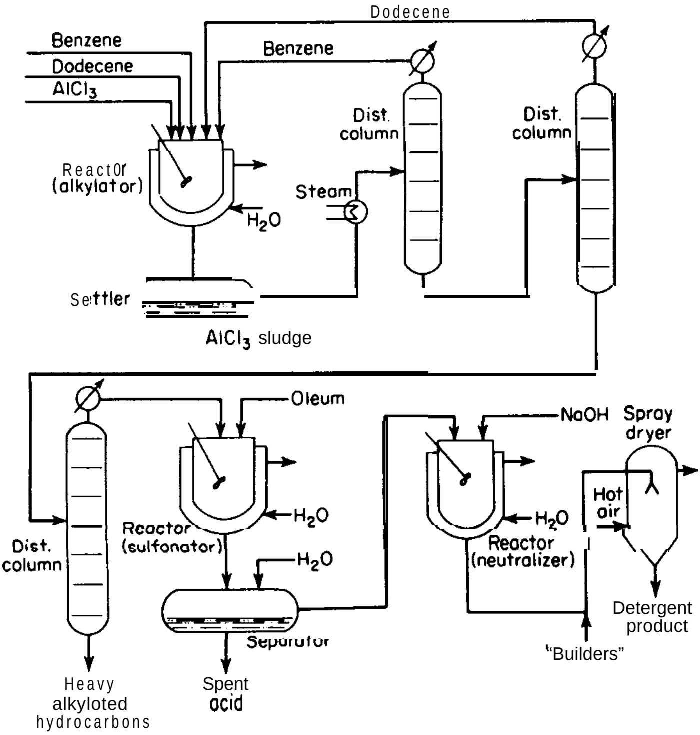


FIGURE 2-3
Qualitative flow diagram for the manufacture of sodium dodecylbenzene sulfonate.

After removal of aluminum chloride sludge, the reaction mixture is fractionated to recover excess benzene (which is recycled to the reaction vessel), a light alkylaryl hydrocarbon, dodecylbenzene, and a heavy alkylaryl hydrocarbon.

Sulfonation of the dodecylbenzene may be carried out continuously or batch-wise under a variety of operating conditions using sulfuric acid (100 percent), oleum (usually 20 percent SO,), or anhydrous sulfur trioxide. The optimum sulfonation temperature is usually in the range of 100 to 140°F depending on the strength of acid employed, mechanical design of the equipment, etc. Removal of the spent sulfuric acid from the sulfonic acid is facilitated by adding water to reduce the sulfuric acid strength to about 78 percent. This dilution prior to neutralization results in a final neutralized slurry having approximately 85 percent active agent based on the solids. The inert material in the final product is essentially Na_2SO_4.

The sulfonic acid is neutralized with 20 to 50 percent caustic soda solution to a pH of 8 at a temperature of about 125°F. Chemical "builders" such as trisodium phosphate, tetrasodium pyrophosphate, sodium silicate, sodium chloride, sodium sulfate, carboxymethyl cellulose, etc., are added to enhance the detersive, wetting, or other desired properties in the finished product. A flaked, dried product is obtained by drum drying or a bead product is obtained by spray drying.

The basic reactions which occur in the process are the following.

Alkylation:

$$C_6H_6 + C_{12}H_{24} \xrightarrow{AlCl_3} C_6H_5 \cdot C_{12}H_{25}$$

Sulfonation:

$$C_6H_5 \cdot C_{12}H_{25} + H_2SO_4 \longrightarrow C_{12}H_{25} \cdot C_6H_4 \cdot SO_3H + H_2O$$

Neutralization:

$$C_{12}H_{25} \cdot C_6H_4 \cdot SO_3H + NaOH \longrightarrow C_{12}H_{25} \cdot C_6H_4 \cdot SO_3Na + H_2O$$

A literature search indicates that yields of 85 to 95 percent have been obtained in the alkylation step, while yields for the sulfonation process are substantially 100 percent, and yields for the neutralization step are always 95 percent or greater. All three steps are exothermic and require some form of jacketed cooling around the stirred reactor to maintain isothermal reaction temperatures.

Laboratory data for the sulfonation of dodecylbenzene, described in the literature, provide additional information useful for a rapid material balance. This is summarized as follows:

1. Sulfonation is essentially complete if the ratio of 20 percent oleum to dodecylbenzene is maintained at 1.25.
2. Spent sulfuric acid removal is optimized with the addition of 0.244 lb of water to the settler for each 1.25 lb of 20 percent oleum added in the sulfonation step.
3. A 25 percent excess of 20 percent NaOH is suggested for the neutralization step.

Operating conditions for this process, as reported in the literature, vary somewhat depending upon the particular processing procedure chosen.

Material and Energy Balance

The process selected for the manufacture of the nonbiodegradable detergent is essentially continuous even though the alkylation, sulfonation, and neutralization steps are semicontinuous steps. Provisions for possible shutdowns for repairs and maintenance are incorporated into the design of the process by specifying plant operation for 300 calendar days per year. Assuming 90 percent yield in the alkylator and a sodium dodecylbenzene sulfonate product to be 85 percent active with 15 percent sodium sulfate as inert, the overall material balance is as follows:

Input components:

$$\text{Product (85\% active)} = \frac{(15 \times 10^6)(0.85)}{(300)(348.5)} = 122 \text{ lb mol/day}$$

$$C_6H_6 \text{ feed} = (122)\left(\frac{1}{0.95}\right)\left(\frac{1}{0.90}\right) = 142.7 \text{ lb mol/day}$$

$$= (142.7)(78.1) = 11{,}145 \text{ lb/day}$$

$$C_{12}H_{24} \text{ feed} = 142.7 \text{ lb mol/day}$$

$$= (142.7)(168.3) = 24{,}016 \text{ lb/day}$$

20% oleum in = (1.25)(11,145 + 24,016) = 43,951 lb/day

Dilution H_2O in = (0.244/1.25)(43,951) = 8579 lb/day

20% NaOH in = (1.25)(43,951) = 55,085 lb/day

$AlCl_3$ catalyst in = (0.05)(11,145 + 24,016) = 1758 lb/day

Alkylation process:

Alkylate yield = (0.9)(142.7)(246.4) = 31,645 lb/day

Unreacted C_6H_6 = (0.1)(11,145) = 1114 lb/day

Unreacted $C_{12}H_{24}$ = (0.1)(24,016) = 2402 lb/day

Sulfur balance:

Sulfur in = (43,951)(1.045)(32.1/98.1) = 15,029 lb/day

Sulfur out = sulfur in detergent + sulfur in spent acid

$$\text{Sulfur in detergent} = \frac{(50{,}000)(0.85)(32.1)}{(348.5)} + \frac{(50{,}000)(0.15)(32.1)}{(142)}$$

$$= 3915 + 1695 = 5610 \text{ lb/day}$$

Sulfur out in acid = 15,029 − 5610 = 9419 lb/day

$$\text{Weight of 78\% } H_2SO_4 = (9419)\left(\frac{98.1}{32.1}\right)\left(\frac{1}{0.78}\right) = 36{,}861 \text{ lb/day}$$

The weight of the heavy alkylaryl hydrocarbon is obtained by difference as 3516 lb/day.

The material balance summary made by the design group for the process shown in Fig. 2-3 is given on a daily basis in Fig. 2-4. After a complete material balance is made, the mass quantities are used to compute energy balances

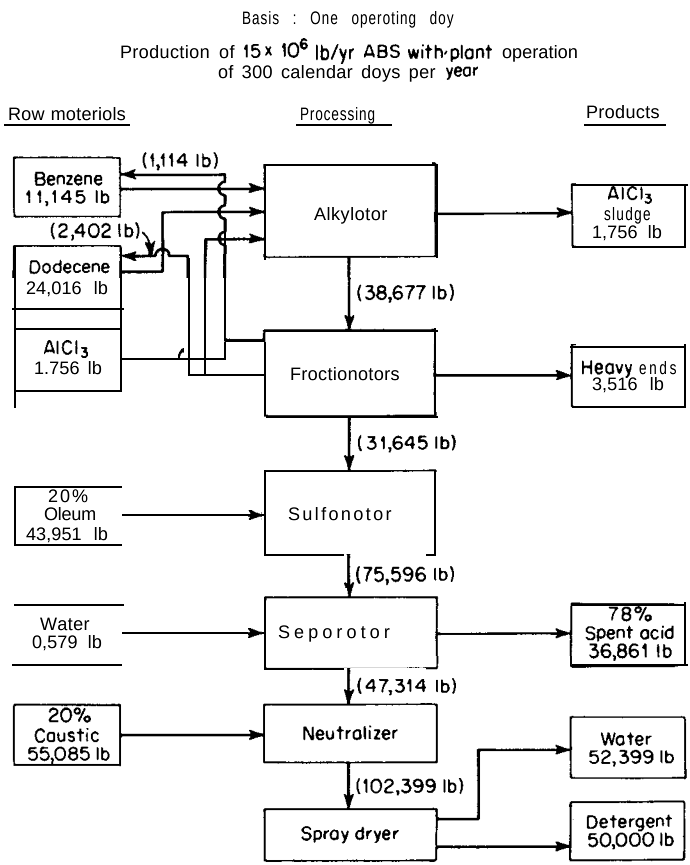


FIGURE 2-4
Quantitative flow diagram for the manufacture of sodium dodecylbenzene sulfonate.

around each piece of equipment. Temperature and pressure levels at various key points in the process, particularly at the reactors, serve as guides in making these heat balances. The complete calculations for the material and energy balances for each piece of equipment, because of their length, are not presented in this discussion.

Equipment Design and Selection

Equipment design for this preliminary process evaluation involves determining the size of the equipment in terms of the volume, flow per unit time, or surface area. Some of the calculations associated with the alkylation unit are presented in the following to indicate the extent of the calculations which are sometimes adequate for a preliminary design.

ALKYLATION UNIT EQUIPMENT DESIGN AND SELECTION

Reactor Volume

Assume a **4-h** cycle and operation of the alkylator at constant temperature and pressure of 115°F and 1 atm, respectively. The volume of reactants per day (with a 10% safety factor) is

$$V_r = \frac{(12{,}259)}{(8.34)(0.88)} + \frac{(26{,}418)}{(8.34)(0.7533)} + \frac{(1758)(7.48)}{(2.44)(62.4)}$$

$$= 1670 + 4160 + 86 = 5916 \text{ gal/day}$$

$$= \frac{5916}{6} = 986 \text{ gal/cycle}$$

If the reactor is 75 percent full on each cycle, the volume of reactor needed is

$$V_R = \frac{986}{0.75} = 1315 \text{ gal}$$

Select a **1300-gal**, glass-lined, stirred reactor.

HEAT OF REACTION CALCULATION

$$C_6H_{6(l)} + C_{12}H_{24(l)} \rightarrow C_6H_5 \cdot C_{12}H_{25(l)}$$

$$\Delta H_r = \Delta H_{f(C_6H_5 \cdot C_{12}H_{25})l} - \Delta H_{f(C_6H_6)l} - \Delta H_{f(C_{12}H_{24})l}$$

The heats of formation ΔH_f of dodecylbenzene and dodecene are evaluated using standard thermochemistry techniques outlined in most chemical engineering thermodynamic texts, The heat formation of benzene is available in the literature.

$$\Delta H_{f(C_6H_5 \cdot C_{12}H_{25})l} = -54{,}348 \text{ cal/g mol}$$

$$\Delta H_{f(C_{12}H_{24})l} = -51{,}239 \text{ cal/g mol}$$

$$\Delta H_{f(C_6H_6)l} = 11{,}717 \text{ cal/g mol}$$

Thus,

$$\Delta H_r = -54{,}348 - 11{,}717 + 51{,}239 = -14{,}826 \text{ cal/g mol}$$

$$= -26{,}687 \text{ Btu/lb mol}$$

Assume heat of reaction is liberated in 3 h of the **4-h** cycle ($\frac{1}{6}$ of an operating day):

$$Q_r = \left(\frac{11{,}145}{78.1}\right)(-26{,}687)\left(\frac{1}{6}\right)\left(\frac{1}{3}\right) = -211{,}500 \text{ Btu/h}$$

Use a 10°F temperature difference for the cooling water to find the mass of cooling water required to remove the heat of reaction.

$$m_{H_2O} = \frac{Q_r}{C_p\,\Delta T} = \frac{211{,}500}{(1)(10)} = 21{,}150 \text{ lb/h}$$

$$q_{f(H_2O)} = \frac{21{,}150}{(60)(8.33)} = 42.3 \text{ gpm}$$

The volumetric flow rate is, therefore, 42.3 gpm. Select a 45-gpm centrifugal pump, carbon steel construction.

HEAT TRANSFER AREA NEEDED TO COOL REACTOR Assume water inlet of 80°F with a 10°F temperature rise. A reasonable overall heat transfer coefficient for this type of heat transfer may be calculated as 45 Btu/(h)(ft^2)(°F).

$$\Delta T_{lm} = \frac{(115 - 80) - (115 - 90)}{2.303 \log \frac{35}{25}} = 29\ 7\text{°F}$$

$$A = \frac{Q}{U\Delta T_{lm}} = \frac{211{,}500}{(45)(29.7)} = 158 \text{ ft}^2$$

A 1300-gal stirred reactor has approximately 160 ft^2 of jacket area. Therefore, the surface area available is sufficient to maintain isothermal conditions in the reactor.

SIZING OF STORAGE TANKS. Provide benzene and dodecene storage for six days:

$$V_{\text{benzene}} = (1670)(6) = 10{,}020 \text{ gal}$$

$$V_{\text{dodecene}} = (4160)(6) = 24{,}960 \text{ gal}$$

Select a lO,OOO-gal carbon steel tank for benzene storage and a 25,000-gal carbon steel tank for dodecene storage.

Provide holding tank storage for one day:

$$V_{\text{holding}} = 5918 \text{ gal}$$

Select a 6000-gal carbon steel tank for holding tank.

SIZING OTHER PUMPS. Provide benzene and dodecene filling of reactor in 10 min:

$$q_{f(\text{benzene})} = \frac{1670}{(6)(10)} = 27.8 \text{ gpm}$$

Select a 30-gpm centrifugal pump, carbon steel construction.

$$q_{f(\text{dodecene})} = \frac{4160}{(6)(10)} = 69.3 \text{ gpm}$$

TABLE 1
Equipment specifications for alkylation unit†

No. req'd.	Item and description	Size	Mat'l. const.
1	T-l, storage tank for benzene	10,000 gal	Carbon steel
1	T-Z, storage tank for dodecene	25,000 gal	Carbon steel
1	T-3, holding tank for alkylate	6,000 gal	Carbon steel
1	P-l, pump (centrifugal) for benzene transfer from T-l to R-l	30 gpm (up to 50 psi)	Carbon steel
1	P-2, pump (centrifugal) for dodecene transfer from T-2 to R-l	70 gpm (up to 50 psi)	Carbon steel
1	P-3, pump (centrifugal) for pumping cooling water to jacket of R-l	45 gpm (up to 50 psi)	Carbon steel
1	P-4, pump (positive displacement) for alkylate transfer from T-3 to C-l	10 gpm (150 psi)	Cast iron
1	R-l, reactor (stirred) alkylator	1,300 gal	Glass-lined

†See Fig. 2-5.

Select a 70-gpm centrifugal pump, carbon steel construction. The alkylate pump used to transfer alkylate from the holding tank to the benzene fractionator must operate continuously. Thus,

$$q_{f(\text{alkylate})} = \frac{(1670 + 4160)}{(24)(60)} = 4 \text{ gpm}$$

Select a 10-gpm positive displacement pump, carbon steel construction. A summary of the equipment needs for the alkylation unit in this preliminary process design is presented in Table 1. The preparation of similar equipment lists for the other process units completes the equipment selection and design phase of the preliminary design. Figure 2-5 shows a simplified equipment diagram for the proposed process and includes the specified size or capacity of each piece of process equipment.

Economics

The purchased cost of each piece of process equipment may now be estimated from published cost data or from appropriate manufacturers' bulletins. Regardless of the source, the published purchased-cost data must always be corrected to the current cost index. This procedure is described in detail in Chap. 6.

For the alkylation unit, purchased-equipment costs may be estimated using the equipment-specification information of Table 1 and the cost data presented in Chaps. 14 through 16 of this text. Table 2 presents these costs updated to January 1, 1990. The required fixed-capital investment for the nonbiodegradable detergent manufacturing process may be estimated from the total purchased-equipment cost using the equipment-cost ratio method outlined in Table 17 of Chap. 6. The total purchased-equipment cost is, presented in

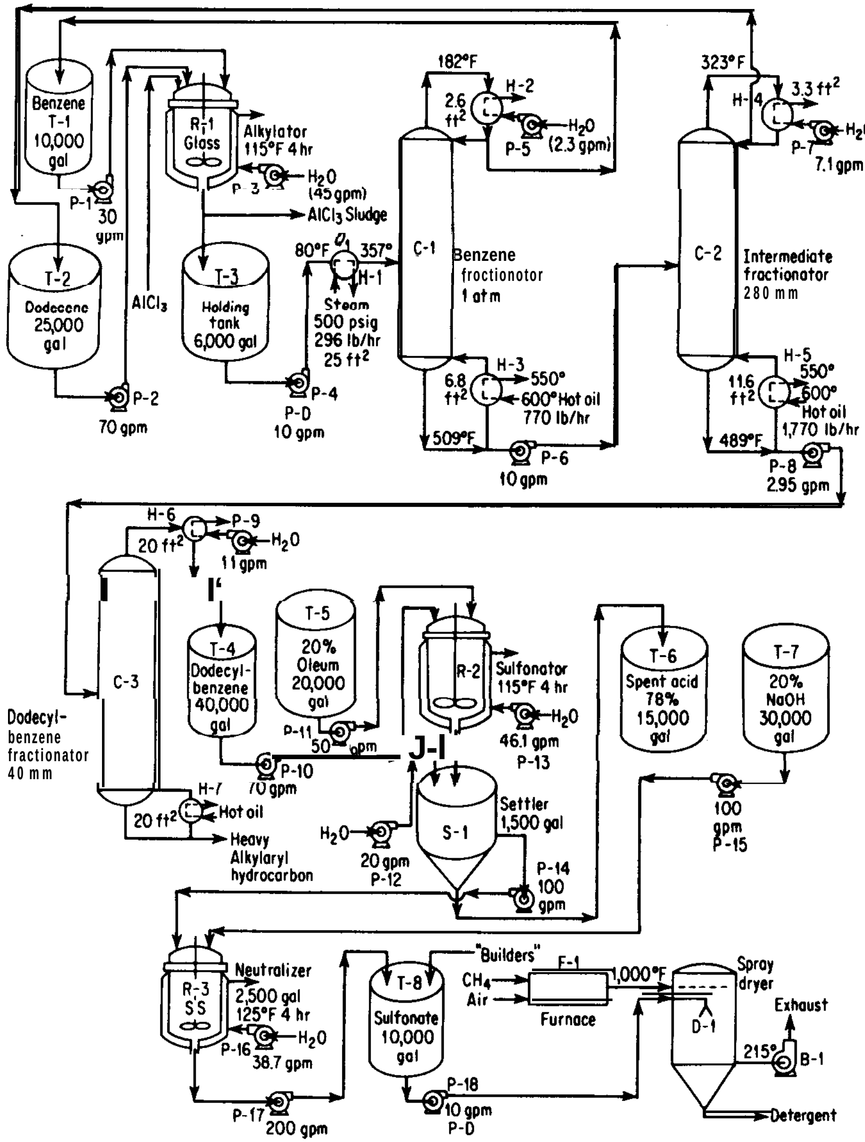


FIGURE 2-5
Simplified equipment diagram for the manufacture of sodium dodecylbenzene sulfonate.

TABLE 2
Estimated purchased-equipment cost for alkylation unit†

Designation	Item	Purchased cost
T-l	Storage tank	$ 21,800
T-2	Storage tank	36,700
T-3	Holding tank	16,200
P-l	Centrifugal pump (with motor)	1,500
P-2	Centrifugal pump (with motor)	1,700
P-3	Centrifugal pump (with motor)	1,600
P-4	Positive-displacement pump	6,200
R-l	Jacketed (stirred) reactor	58,400
		$144,100

†January 1, 1990 costs. See Fig. 2-5.

TABLE 3
Summary of purchased-equipment cost for complete process unit

Process unit	Purchased cost
Alkylation	$ 144,100
Fractionators	175,800
Sulfonation	245,100
Neutralization	163,700
Spray dryer	393,500
Auxiliary units	142,800
Total	$1,165,000

Table 3 and is the basis for the estimated fixed-capital cost tabulation given in Table 4. The probable error in this method of estimating the fixed-capital investment is as much as ± 30 percent.

An evaluation of the operating labor and utilities requirements of the process must be made before the total product cost can be estimated. Details for evaluating these direct production costs are given in Chap. 6 and Appendix B. The estimate of the total product cost for the manufacture of 15 million lb per year detergent, based on methods outlined in Chap. 6, is presented in Table 5.

Once the total product cost has been estimated, the design group is in a position to evaluate for management the attractiveness of the proposed process using such measures of profitability as rate of return, payout time, or present worth. These methods are fully outlined in Chap. 10. The design report, as mentioned previously, completes the preliminary design.

TABLE 4
Fixed-capital investment estimate†

Items	Cost
Purchased equipment	**$1,165,000**
Purchased-equipment installation	547,600
Instrumentation and controls	209,700
Piping (installed)	768,900
Electrical (installed)	128,200
Buildings (including services)	209,700
Yard improvements	116,500
Service facilities (installed)	815,500
Land (purchase not required)	
Engineering and supervision	384,500
Construction expenses	477,700
Contractor's fee	244,700
Contingency	489,300
Fixed-capital investment	**$5,557,300**
Working capital	**1,001,900**
Total capital investment	**$6,559,200**

†**Equipment-cost** ratio percentages used in Table 4 are factors applicable to a fluid-processing plant as outlined in Chap. 6.

TABLE 5
Total product cost estimate

Items	cost
Direct production costs	
Raw materials	**$2,512,200**
Operating labor	963,500
Direct supervisory and clerical labor	192,700
Utilities	567,700
Maintenance and repairs	111,100
Operating supplies	16,700
Fixed charges	
Depreciation	555,700
Local taxes	111,100
Insurance	55,600
Plant-overhead costs	760,400
General expenses	
Administration	190,100
Distribution and selling	771,900
Research and development	385,900
Financing (interest)	524,600
Annual total product cost	**$7,719,200**
Total product cost per pound	$0.515

Summary

The preliminary design presented in this section was developed to show the logical step-by-step approach which is quite often followed for each new process design. The exact procedure may vary from company to company and from one design engineer to another. Likewise, the assumptions and rule-of-thumb factors used may vary from one company to the next depending to a large extent on design experience and company policy. Nevertheless, the basic steps for a process design are those outlined in this preliminary design covering the manufacture of a common household item.

No attempt has been made to present a complete design. In fact, to minimize the length, many assumptions were made which would have been verified or justified in a normal process design. Neither were any alternative solutions considered even though some were suggested by the literature survey. The investigation of these various alternatives is left to the reader.

COMPARISON OF DIFFERENT PROCESSES

In a course of a design project it is necessary to determine the most suitable process for obtaining a desired product. Several different manufacturing methods may be available for making the same material, and various processes must be compared in order to select the one best suited to the existing conditions.

The comparison can be accomplished through the development of complete designs. In many cases, however, all but one or two of the possible processes can be eliminated by a weighted comparison of the essential variable items, and detailed design calculations for each process may not be required. The following items should be considered in a comparison of this type:

1. Technical factors
   a. Process flexibility
   b. Continuous operation
   c. Special controls involved
   d. Commercial yields
   e. Technical difficulties involved
   f. Energy requirements
   g. Special auxiliaries required
   h. Possibility of future developments
   i. Health and safety hazards involved
2. Raw materials
   a. Present and future availability
   b. Processing required
   c. Storage requirements
   d. Materials handling problems
3. Waste products and by-products
   a. Amount produced
   b. Value

   c. Potential markets and uses
   d. Manner of discard
   e. Environmental aspects
4. Equipment
   a. Availability
   b. Materials of construction
   c. Initial costs
   d. Maintenance and installation costs
   e. Replacement requirements
   f. Special designs
5. Plant location
   a. Amount of land required
   b. Transportation facilities
   c. Proximity to markets and raw-material sources
   d. Availability of service and power facilities
   e. Availability of labor
   f. Climate
   g. Legal restrictions and taxes
6. Costs
   a. Raw materials
   b. Energy
   c. Depreciation
   d. Other fixed charges
   e. Processing and overhead
   f. Special labor requirements
   g. Real estate
   h. Patent rights
   i. Environmental controls
7. Time factor
   a. Project completion deadline
   b. Process development required
   c. Market timeliness
   d. Value of money
8. Process considerations
   a. Technology availability
   b. Raw materials common with other processes
   c. Consistency of product within company
   d. General company objectives

Batch Versus Continuous Operation

When comparing different processes, consideration should always be given to the advantages of continuous operation over batch operation. In many cases, costs can be reduced by using continuous instead of batch processes. Less labor is required, and control of the equipment and grade of final product is simplified. Whereas batch operation was common in the early days of the chemical industry, most processes have been switched completely or partially to continuous operation. The advent of many new types of control instruments has made this transition possible, and the design engineer should be aware of the advantages inherent in any type of continuous operation.

EQUIPMENT DESIGN AND SPECIFICATIONS

The goal of a "plant design" is to develop and present a complete plant that can operate on an effective industrial basis. To achieve this goal, the chemical engineer must be able to combine many separate units or pieces of equipment into one smoothly operating plant. If the final plant is to be successful, each piece of equipment must be capable of performing its necessary function. The design of equipment, therefore, is an essential part of a plant design.

The engineer developing a process design must accept the responsibility of preparing the specifications for individual pieces of equipment and should be acquainted with methods for fabricating different types of equipment. The importance of choosing appropriate materials of construction in this fabrication must be recognized. Design data must be developed, giving sixes, operating conditions, number and location of openings, types of flanges and heads, codes, variation allowances, and other information. Many of the machine-design details are handled by the fabricators, but the chemical engineer must supply the basic design information.

SCALE-UPINDESIGN

When accurate data are not available in the literature or when past experience does not give an adequate design basis, pilot-plant tests may be necessary in order to design effective plant equipment. The results of these tests must be scaled up to the plant capacity. A chemical engineer, therefore, should be acquainted with the limitations of scale-up methods and should know how to select the essential design variables.

Pilot-plant data are almost always required for the design of filters unless specific information is already available for the type of materials and conditions involved. Heat exchangers, distillation columns, pumps, and many other types of conventional equipment can usually be designed adequately without using pilot-plant data.

Table 6 presents an analysis of important factors in the design of different types of equipment.? This table shows the major variables that characterize the

†Adapted from Johnstone, R. E., and M. W. Thring, "Pilot Plants, Models, and Scale-up Methods," McGraw-Hill Book Company, New York, 1957. See also Bisio, A., and R. L Kabel, "Scaleup of Chemical Processes," J. Wiley & Sons, New York, 1985.

TABLE 6
Factors in equipment scale-up and design

Type of equipment	Is pilot plant usually necessary?	Major variables for operational design (other than flow rate)	Major variables characterizing size or capacity	Maximum scale-up ratio based on indicated characterizing variable	Approximate recommended safety or over-design factor, %
Agitated batch crystallizers	Yes	Solubility-temperature relationship	Flow rate Heat transfer area	>100:1	20
Batch reactors	Yes	Reaction rate Equilibrium state	Volume Residence time	>100:1	20
Centrifugal pumps	No	Discharge head	Flow rate Power input Impeller diameter	>100:1 >100:1 10:1	10
Continuous reactors	Yes	Reaction rate Equilibrium state	Flow rate Residence time	>100:1	20
Cooling towers	No	Air humidity Temperature decrease	Flow rate Volume	>100:1 10:1	15
Cyclones	No	Particle size	Flow rate Diameter of body	10:1 3:1	10
Evaporators	No	Latent heat of vaporization Temperatures	Flow rate Heat-transfer area	>100:1 >100:1	15
Hammer mills	Yes	Size reduction	Flow rate Power input	60:1 60:1	20
Mixers	No	Mechanism of operation System geometry	Flow rate Power input	>100:1 20:1	20
Nozzle-discharge centrifuges	Yes	Discharge method	Flow rate Power input	10:1 10:1	20 20

(continued)

TABLE 6
Factors in equipment scale-up and design (Continued)

Type of equipment	Is pilot plant usually necessary?	Major variables for operational design (other than flow rate)	Major variables characterizing size or capacity	Maximum scale-up ratio based on indicated characterizing variable	Approximate recommended safety or overdesign factor, %
Packed columns	No	Equilibrium data Superficial vapor velocity	Flow rate Diameter Height to diameter ratio	>100:1 10:1	15
Plate columns	No	Equilibrium data Superficial vapor velocity	Flow rate Diameter	>100:1 10:1	15
Plate-and-frame filters	Yes	Cake resistance or permeability	Flow rate Filtration area	>100:1 >100:1	20
Reboilers	No	Temperatures Viscosities	Flow rate Heat-transfer area	>100:1 >100:1	15
Reciprocating compressors	No	Compression ratio	Flow rate Power input Piston displacement	>100:1 >100:1 >100:1	10
Rotary filters	Yes	Cake resistance or permeability	Flow rate Filtration area	>100:1 25:1	20
Screw conveyors	No	Bulk density	Flow rate Diameter Drive horsepower	90:1 8:1	20
Screw extruders	No	Shear rate	Flow rate Power input	100: 1 100: 1	20 10
Sedimentation centrifuges	No	Discharge method	Flow rate Power input	10:1 10:1	20 20
Settlers	No	Settling velocity	Volume Residence time	>100:1	15
Spray columns	No	Gas solubilities	Flow rate Power input	10:1	20

TABLE 6
Factors in equipment scale-up and design (*Continued*)

Type of equipment	Is pilot plant usually neces-sary?	Major variables for operational design (other than flow rate)	Major variables characterizing size or capacity	Maximum scale-up ratio based on indi-cated char-acterizing variable	Approxi-mate recom-mended safety or over-design factor, %
Spray condensers	No	Latent heat of vaporization Temperatures	Flow rate Height to diameter ratio	70:1 12:1	20
Tube-and-shell heat exchangers	No	Temperatures Viscosities Thermal conductivities	Flow rate Heat-transfer area	>100:1 >100:1	15

size or capacity of the equipment and the maximum scale-up ratios for these variables. Information on the need for pilot-plant data, safety factors, and essential operational data for the design is included in Table 6.

SAFETY FACTORS

Some examples of recommended safety factors for equipment design are shown in Table 6. These factors represent the amount of overdesign that would be used to account for the changes in the operating performance with time.

The indiscriminate application of safety factors can be very detrimental to a design. Each piece of equipment should be designed to carry out its necessary function. Then, if uncertainties are involved, a reasonable safety factor can be applied. The role of the particular piece of equipment in the overall operation must be considered along with the consequences of underdesign. Fouling, which may occur during operation, should never be overlooked when a design safety factor is determined. Potential increases in capacity requirements are sometimes used as an excuse for applying large safety factors. This practice, however, can result in so much overdesign that the process or equipment never has an opportunity to prove its economic value.

In general design work, the magnitudes of safety factors are dictated by economic or market considerations, the accuracy of the design data and calculations, potential changes in the operating performance, background information available on the overall process, and the amount of conservatism used in developing the individual components of the design. Each safety factor must be chosen on basis of the existing conditions, and the chemical engineer should not hesitate to use a safety factor of zero if the situation warrants it.

SPECIFICATIONS

A generalization for equipment design is that standard equipment should be selected whenever possible. If the equipment is standard, the manufacturer may have the desired size in stock. In any case, the manufacturer can usually quote a lower price and give better guarantees for standard equipment than for special equipment.

The chemical engineer cannot be an expert on all the types of equipment used in industrial plants and, therefore, should make good use of the experience of others. Much valuable information can be obtained from equipment manufacturers who specialize in particular types of equipment.

Before a manufacturer is contacted, the engineer should evaluate the design needs and prepare a preliminary specification sheet for the equipment. This preliminary specification sheet can be used by the engineer as a basis for the preparation of the final specifications, or it can be sent to a manufacturer with a request for suggestions and fabrication information. Preliminary specifications for equipment should show the following:

1. Identification
2. Function
3. Operation
4. Materials handled
5. Basic design data
6. Essential controls
7. Insulation requirements
8. Allowable tolerances
9. Special information and details pertinent to the particular equipment, such as materials of construction including gaskets, installation, necessary delivery date, supports, and special design details or comments

Final specifications can be prepared by the engineer; however, care must be exercised to avoid unnecessary restrictions. The engineer should allow the potential manufacturers or fabricators to make suggestions before preparing detailed specifications. In this way, the final design can include small changes that reduce the first cost with no decrease in the effectiveness of the equipment. For example, the tubes in standard heat exchangers are usually 8, 12, 16, or 20 ft long, and these lengths are ordinarily kept in stock by manufacturers and maintenance departments. If a design specification called. for tubes 15 ft long, the manufacturer would probably use 16-ft tubes cut off to the specified length.

HEAT EXCHANGER

Identification: Item Condenser Item No. *H-S* No. required I	Date I-I-90 By *JRL*

Function: Condense overhead *vapors from methanol fractionation column*

Operation: *Continuous*

Type: *Horizontal*
Fixed *tube sheet*
Expansion ring in shell
Duty *3,400,000* Btu/h Outside area *470* sq ft

Tube side: Fluid handled *Cooling water* Flow rate 380 *gpm* Pressure 20 psig Temperature *15°C* to 25°C Head material Carbon steel	**Tubes:** *1* in. diam. *14* BWG *1.25"* Centers A Pattern *225* Tubes each 8 ft long *2* Passes Tube material *Carbon steel*
Shell aide: Fluid handled Methanol vapor Flow rate *7000 lb/h* Pressure 0 psig Temperature 65°C to *(constant temp.)*	**Shell:** *22* in. diam. I Passes (Transverse baffles Tube *support* Req'd) (Longitudinal baffles 0 Req'd) Shell material *Carbon steel*

Utilities: *Untreated cooling water*
Controls: *Cooling-water* rare *controlled by vapor temperature in vent* line
Insulation: *2-in. rock cork or equivalent; weatherproofed*
Tolerances: *Tubular Exchangers Manufacturers* Association *(TEMA) standards*
Comments **and drawings:** Location and sizes *of inlets* and *outlets are shown* on drawing

FIGURE 2-6
Specification sheet for heat exchangers using U.S. customary units.

Thus, an increase from 15 to 16 ft for the specified tube length could cause a reduction in the total cost for the unit, because the labor charge for cutting the standard-length tubes would be eliminated. In addition, replacement of tubes might become necessary after the heat exchanger has been in use, and the replacement costs with 16-ft tubes would probably be less than with 15-ft tubes.

Figures 2-6 and 2-7 show typical types of specification sheets for equipment. These sheets apply for the normal type of equipment encountered by a chemical engineer in design work. The details of mechanical design, such as shell or head thicknesses, are not included, since they do not have a direct effect on the performance of the equipment. However, for certain types of of equipment involving unusual or extreme operating conditions, the engineer may need

SIEVE-TRAY COLUMN

Identification: Item ______ Date ______
Item No. ______
No. required ______ By ______

Function:

Operation:

Materials handled:

	Feed	*Overhead*	*Reflux*	*Bottoms*
Quantity	______	______	______	______
Composition	______	______	______	______
Temperature	______	______	______	______

Design data: No. of trays ______ Reflux ratio ______
Pressure ______ Tray spacing ______
Functional height ______ Skirt height ______
Material of construction ______
Diameter: Liquid density ______ lb/ft^3 (___ kg/m^3)
Vapor density ______ lb/ft^3 (___ kg/m^3)
Maximum allowable vapor velocity (superficial) ______ ft/s (___ *m/s*)
Maximum vapor flow rate ______ ft^3/s (___ m^3/s)
Recommended inside diameter ______
Hole size and arrangement ______
Tray thickness ______

Utilities:
Controls:
Insulation:
Tolerances:
Comments and drawings:

FIGURE 2-7
Specification sheet for sieve-tray distillation column.

to extend the specifications to include additional details of the mechanical design. Locations and sizes of outlets, supports, and other essential fabrication information can be presented with the specifications in the form of comments or drawings.

MATERIALS OF CONSTRUCTION

The effects of corrosion and erosion must be considered in the design of chemical plants and equipment. Chemical resistance and physical properties of constructional materials, therefore, are important factors in the choice and design of equipment. The materials of construction may be resistant to the corrosive action of any chemicals that may contact the exposed surfaces. Possible erosion caused by flowing fluids or other types of moving substances must be considered, even though the materials of construction may have adequate chemical resistance. Structural strength, resistance to physical or thermal shock, cost, ease of fabrication, necessary maintenance, and general type of service required, including operating temperatures and pressures, are additional factors that influence the final choice of constructional materials.

If there is any doubt concerning suitable materials for construction of equipment, reference should be made to the literature,† or laboratory tests should be carried out under conditions similar to the final operating conditions. The results from the laboratory tests indicate the corrosion resistance of the material and also the effects on the product caused by contact with the particular material. Further tests on a pilot-plant scale may be desirable in order to determine the amount of erosion resistance or the effects of other operational factors.

PROBLEMS

1. Using ***Chemical Abstracts*** as a basis, list the original source, title, author, and brief abstract of three published articles dealing with three different processes for producing formaldehyde.
2. Prepare, in the form of a flow sheet, an outline showing the sequence of steps in the complete development of a plant for producing formaldehyde. A detailed analysis of the points to be considered at each step should be included. The outline should take the project from the initial idea to the stage where the plant is in efficient operation.
3. A process for making a single product involves reacting two liquids in a continuously agitated reactor and distilling the resulting mixture. Unused reactants are recovered as overhead and are recycled. The product is obtained in sufficiently pure form as bottoms from the distillation tower.
   (a) Prepare a qualitative flow sheet for the process, showing all pieces of equipment.
   (b) With cross reference to the qualitative flow sheet, list each piece of equipment and tabulate for each the information needed concerning chemicals and the process in order to design the equipment.
4. Figure 2-1 presents a qualitative flow diagram for the manufacture of nitric acid by the ammonia-oxidation process. Figure 2-2 presents a quantitative flow diagram for the same process. With the information from these two figures, prepare a quantitative energy balance for the process and size the equipment in sufficient detail for a preliminary cost estimate.
5. A search of the literature reveals many different processes for the production of acetylene. Select four different processes, prepare qualitative flow sheets for each, and discuss the essential differences between each process. When would one process be more desirable than the others? What are the main design problems which would

†Detailed information on materials of construction is presented in Chap. 12.

require additional information? What approximations would be necessary if data are not available to resolve these questions?

6. Ethylene is produced commercially in a variety of different processes. Feed stocks for these various processes range from refinery gas, ethane, propane, butane, natural gasoline, light and heavy naphthas to gas and oil and heavier fractions. Prepare three different qualitative flow sheets to handle a majority of these feed stocks. What are the advantages and disadvantages of each selected process?
7. Gather all the available information on one of the ethylene processes for which a flow sheet was prepared in the preceding problem and make a preliminary material balance for the production of 50 million lb/yr of ethylene. Assume an operating factor of 90 percent.
8. One method of preparing acetaldehyde is by the direct oxidation of ethylene. The process employs a catalytic solution of copper chloride containing small quantities of palladium chloride. The reactions may be summarized as follows:

$$C_2H_4 + 2CuCl_2 + H_2O \xrightarrow{PdCl_2} CH_3CHO + 2HCl + 2CuCl$$

$$2CuCl + 2HCl + \tfrac{1}{2}O_2 \longrightarrow 2CuCl_2 + H_2O$$

In the reaction, $PdCl_2$ is reduced to elemental palladium and HCl, and is reoxidized by $CuCl_2$. During catalyst regeneration the CuCl is reoxidized with oxygen. The reaction and regeneration steps can be conducted separately or together.

In the process, 99.8 percent ethylene, 99.5 percent oxygen, and recycle gas are directed to a vertical reactor and are contacted with the catalyst solution under slight pressure. The water evaporated during the reaction absorbs the exothermic heat evolved, and make-up water is fed as necessary to maintain the catalytic solution concentration. The reacted gases are water-scrubbed and the resulting acetaldehyde solution is fed to a distillation column. The tail gas from the scrubber is recycled to the reactor. Inerts are eliminated from the recycle gas in a bleed stream which flows to an auxiliary reactor for additional ethylene conversion.

Prepare, in the form of a flow sheet, the sequence of steps in the development of a plant to produce acetaldehyde by this process. An analysis of the points to be considered at each step should be included. List the additional information that will be needed to complete the preliminary design evaluation.
9. Prepare a simplified equipment flow sheet for the acetaldehyde process outlined in Prob. 8. Identify temperature, pressure, and composition, wherever possible, at each piece of equipment.
10. Prepare a material balance and a qualitative flow sheet for the production of 7800 kg/h of acetaldehyde using the process described in the previous problem. Assume an operating factor of 90 percent and a 95 percent yield on the ethylene feed. Both ethylene and oxygen enter the process at 930 kPa.
11. Using the information developed in Prob. 10, make a basic energy balance around each piece of equipment and for the entire process. Prepare, a quantitative flow sheet to outline the results of the basic energy balance.
12. Prepare a material balance for the production of 7800 kg/h of acetaldehyde using the process described in Prob. 8. However, because 99.5 percent oxygen is unavailable, it will be necessary to use 830 kPa air as one of the raw materials. What steps of the process will be affected by this substitution in feed stocks? Assume an operating factor of 90 percent and a 95 percent yield on the ethylene feed.

13. Synthesis gas may be prepared by a continuous, noncatalytic conversion of any hydrocarbon by means of controlled partial combustion in a fire-brick lined reactor. In the basic form of this process, the hydrocarbon and oxidant (oxygen or air) are separately preheated and charged to the reactor. Before entering the reaction zone, the two feed stocks are intimately mixed in a combustion chamber. The heat produced by combustion of part. of the hydrocarbon pyrolyzes the remaining hydrocarbons into gas and a small amount of carbon in the reaction zone. The reactor effluent then passes through a waste-heat boiler, a water-wash carbon-removal unit, and a water cooler-scrubber. Carbon is recovered in equipment of simple design in a form which can be used as fuel or in ordinary carbon products.

    Prepare a simplified equipment flow sheet for the process, with temperatures and pressure conditions at each piece of equipment.

14. Make a material balance and a qualitative flow sheet for the synthesis gas process described in Prob. 13. Assume an operating factor of 95 percent and a feed stock with an analysis of 84.6 percent C, 11.3 percent H_2, 3.5 percent S, 0.13 percent O_2, 0.4 percent N_2, and 0.07 percent ash (all on a weight basis). The oxidant in this process will be oxygen having a purity of 95 percent. Production is to be 8.2 m^3/s.

15. Prepare an energy balance and a suitable flow sheet for the synthesis gas production requested in Prob. 14.

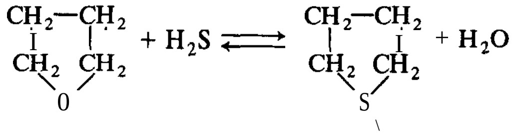
16. Size the equipment that is necessary for the synthesis gas production outlined in Probs. 13 and 14.

17. Estimate the required utilities for the synthesis gas plant described in the previous four problems.

18. Repeat the calculations of Probs. 14 to 17 by substituting air as the oxidant in place of the 95 percent purity oxygen.

19. In the face of world food shortages accompanying an exploding world population, many engineers have suggested that the world look to crude oil as a new source of food. Explore this possibility and prepare a flow sheet which utilizes the conversion of petroleum to food by organic microorganisms. What are the problems that must be overcome to make this possibility an economic reality?

20. A chemical engineering consultant for a large refinery complex has been asked to investigate the feasibility of manufacturing 1.44 x 10^{-2} kg/s of thiophane, an odorant made from a combination of tetrahydrofuran (THF) and hydragen sulfide. The essential reaction is given below:



The process consists essentially of the following steps:

(*a*) THF is vaporized and mixed with H_2S in a ratio of 1.5 moles H_2S to one mole of THF and reacted over an alumina catalyst at an average temperature of 672 K and 207 kPa.

(*b*) Reactor vapors are cooled to 300 K and phase separated.

(*c*) The noncondensable gases are removed and burned in a fume furnace while the crude thiophane is caustic washed in a batch operation.

(*d*) The caustic treated thiophane is then batch distilled in a packed tower and sent to storage before eventual shipment to commerical use.
(*e*) Recoverable THF is recycled back to the reactors from the batch column.
(*f*) The aqueous bottoms stream is stored for further processing in the plant.
(*g*) Carbon deposition on the catalyst is heavy (4 percent of THF feed) and therefore provision for regeneration of the catalyst must be made.

Assist the consultant in analyzing this process with a complete flow sheet and material balance, assuming 85 percent operating factor, 80 percent conversion in the reactor, and 90 percent recovery after the reactor. Outline the types of equipment necessary for the process. Determine approximate duties of heat exchangers and list overall heat balances *on* the plant. It is known that the heat of formation of THF is -59.4 kcal/g mol, H_2S is -4.77 kcal/g mol, and thiophane is – 17.1 kcal/g mol.

What additional information would be required in order to complete the project analysis?

Physical properties:

THF **MW = 72** sp gr = 0.887 Boiling pt. = 65°C

Vap. press. at 25°C = 176 mm Hg

Thiophane, MW = 88 Boiling pt. = 121°C