1.
OVERALL PROCESS SYSTEM DESIGN

1.1 INTRODUCTION

The chemical process industries (CPI), petroleum and allied industries apply physical as well as chemical methods to the conversion of raw feedstock materials into salable products. Because of the diversity of products, process conditions and requirements, equipment design is often unique, or case specific. The prime requirement of any piece of equipment is that it performs the function for which it was designed under the intended process operating conditions, and do so in a continuous and reliable manner. Equipment must have mechanical reliability, which is characterized by strength, rigidness, steadiness, durability and tightness. Any one or combination of these characteristics may be needed for a particular piece of equipment.

The cost of equipment determines the capital investment for a process operation. However, there is no direct relationship to profits. That is, more expensive equipment may mean better quality, more durability and, hence, longer service and maintenance factors. These characteristics can produce higher operating efficiencies, fewer consumption coefficients and operational expenses and, thus, fewer net production costs. The net cost of production characterizes the perfection rate of the total technological process and reflects the influences of design indices. Therefore, it is possible to compare different pieces of equipment when they are used in the manufacture of these same products.

The desirable operating characteristics of equipment include simplicity, convenience and low cost of maintenance; simplicity, convenience and low cost of assembly and disassembly; convenience in replacing worn or damaged components; ability to control during operation and test before permanent installation; continuous operation and steady-state processing of materials without excessive noise, vibration or upset conditions; a minimum of personnel for its operation; and, finally, safe operation. Low maintenance often

is associated with more complex designs as well as cost. Automation of production is the most complete solution to problems associated with maintaining steady operation, easy maintenance and a minimum of operating personnel. The addition of control devices must be considered as part of the overall design and a factor that adds to the capital investment of the project. Increased automation through the use of controls increases the degree of sophistication in equipment design but lowers operational expenditures while increasing production quality. The use of automatic devices influences the form and dimensional proportions of the equipment as well as imposing additional constraints on the design. It is justified by increased production efficiencies and added security during normal and emergency operations.

Design practices often are neglected in engineering curricula. In fact, most textbooks stress conceptual design fundamentals and leave the detailed design principles to job experience and training. Consequently, equipment design is often treated as an art rather than as an exact science that applies rigorous engineering principles. This deficiency exists not only in many engineering undergraduate curricula, but also in the industrial published sector in that few texts present detailed design practices and guidelines. It is the intent of the authors to fill this void, at least in part, by organizing standard industrial design practices for equipment used throughout the CPI and other major industries. This work will take the form of a series of textbooks that provide detailed design and calculation procedures for sizing and selecting equipment. We shall depart from the standard unit operations textbooks, of which there are several classical works, by not stressing theory. Rather, we will concentrate on specific design practices, computational methods and working formulas. Hence, we hope the reader of principal interest will be the practicing engineer.

This first volume presents fundamental design principles that may be applied to all equipment. Emphasis is placed on process system peripherals, particularly vessels and their associated components. Design principles for all types of vessels, and selection, sizing and design criteria for piping system components are presented. Because practices rather than theory are stressed, only the final working formulas are presented; further, since we intend this to be a designer's guide, numerous example problems are included throughout the book.

The first chapter provides an overview of process design strategies. Fundamental definitions and a brief review of preparing process flow plans are included.

1.2. PLANNING PROJECTS AND EQUIPMENT DESIGN

There are numerous stages of activities that must be conducted before an actual process, plant or even small-scale pilot system reaches its operational

stage. Figure 1.1 is a simplified flow diagram illustrating some of the major activities and their normal sequence. From the initial idea the engineer is directed to prepare a preliminary design basis. This includes a rough flow plan, a review of the potential hazards of the process and an assimilation of all available technical, economic and socioeconomic information and data. At this stage of a project often the engineer or engineers are not the final equipment designers, but merely play the devil's advocate, by establishing the equipment requirements. Dialog established between the conceptual design engineer and the process designer results in an initial process flow plan. From the flow plan, a preliminary cost estimate is prepared, many times by a different engineer whose expertise is cost estimating. Once management approval is received, the design engineer's work begins. In the initial stages the design engineer will help prepare a preliminary engineering flow plan, select the site and establish safety requirements.

This initial project stage is often considered a "predesign" period, which constitutes the basis of the conceptual design. Usually a collection of individuals are involved in discussions and planning. The cast of characters includes the project engineer, who oversees the entire project, the design engineer (with whom we are most concerned), safety engineer, environmental engineer and, perhaps, a representative from management and additional support personnel.

Once the overall process has been designed conceptually, a more detailed engineering flow plan is prepared. This flow plan serves two purposes; (1) to document the logic behind the process operation, and (2) to identify in detail major process equipment, including all control devices. A complete flow plan also will identify potential hazards and their consequences, in addition to how they are handled. After the environmental and safety engineers have reviewed all potential hazards related to handling toxic materials, noise, radiation, etc., recommendations are outlined for safe and standard handling and disposal practices. These recommendations often affect the overall system design, resulting in revised plans.

The next stage is the actual construction of the unit according to the revised plans. By now, the design engineer is totally involved and has selected, sized and designed most of the equipment and process piping, based (hopefully) on the standard practices outlined in this book. During the actual construction phase, the design engineer will list and review the plans with the project engineer.

At the completion of the unit or system construction, a prestartup review is conducted by the designer and his support personnel. This should include a review of all operating, as well as emergency and shutdown, procedures. The prestartup review normally involves the following personnel in addition to the designer: project engineer, trained operating personnel, operations foreman, the company environmental engineer, the division and company safety engineers and representatives from management. At this point, any

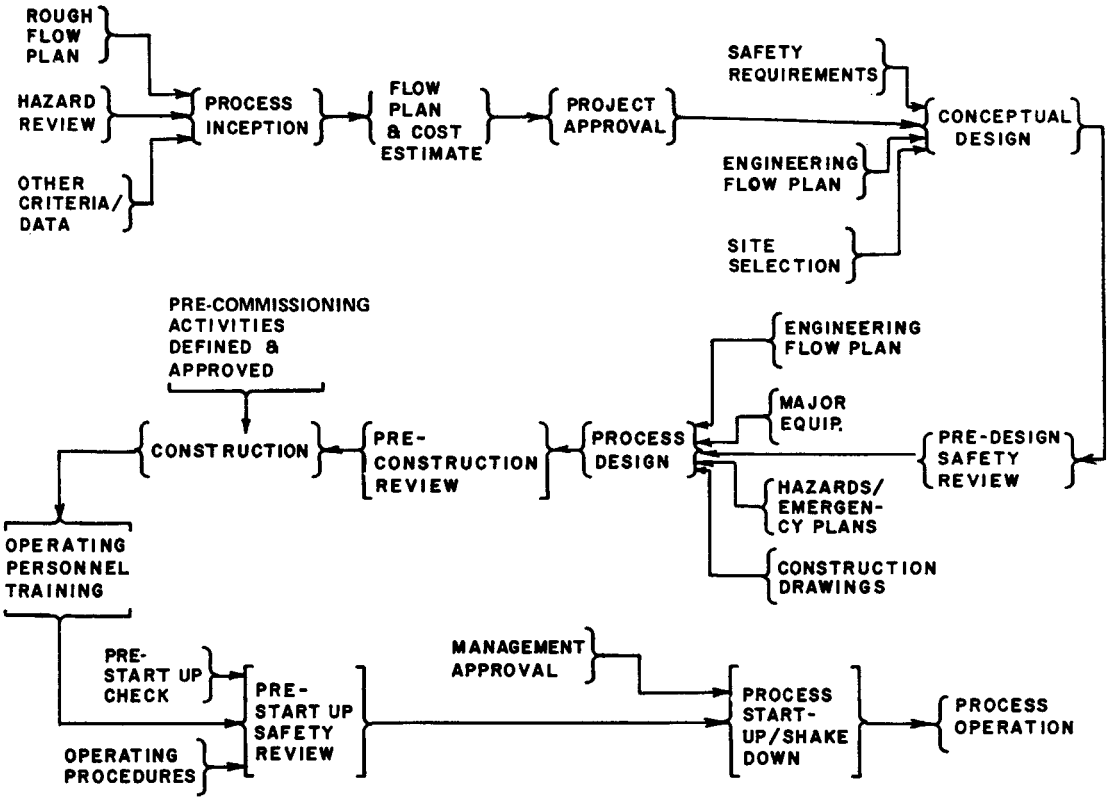


Figure 1.1. Simplified flow diagram of activities in planning and implementing process and plant design projects.

additional changes or recommendations to the process design are made. Major process revisions may be requested by the operations foreman, project engineers, design engineer, safety and environmental coordinators and/or plant operating personnel. Table 1.1 summarizes major items that are considered in the operating procedures planning.

The project planning activities may be much more complex than illustrated

Table 1.1. Major Items in Operating Guidelines Planning

PURPOSE OF PROCESS OR OPERATION

- General Discussion of Process
  - What will be done (brief summary)
  - Chemistry involved
  - Major unit operations
- Personnel Protection
  - Hazards involved–severity
  - Protective equipment–what, where, when
  - Area restrictions–what, where, when
  - Ventilation
- Startup
  - Preparation and handling
    - Feedstocks
    - Catalysts
    - Equipment
- Step-by-Step Description
  - Flow plans
  - Sketches
  - Labelled parts of units
  - Position of valves, control settings, etc.
- Sampling and Final Product Form
  - Description of equipment
  - Actions required
- Shutdown Procedure
  - Step-by-step description
    - Flow plans
    - Sketches
    - Labelled parts of unit
    - Position of valves, control settings, etc.
- Emergency Shutdown Procedure
  - Action required
  - Followup required
  - Emergency personnel/outside organizations
- Unit Cleaning Procedures
  - Description
  - Hazards or precautions
- Product or Waste Disposal

by the simple flow diagram of Figure 1.1. This depends, of course, on the magnitude of the project. Often, large complex system planning has numerous checkpoints at various stages where a continuous review of technical and revised economic forecasts is performed. Also not shown in this flow diagram is the legal framework for obtaining construction and operating permits as well as preparing the environmental impact statement and meeting local, state and federal regulations.

1.3. EQUIPMENT AND INSTRUMENTATION CODES

Process and instrumentation flow diagrams (P & I diagrams) essentially define the control and operating logic behind a process as well as provide a visual record to management and potential users. In addition, P & I diagrams are useful at various stages of a project's development by providing:

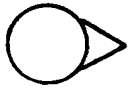
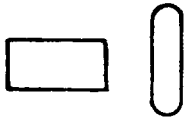
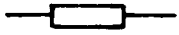
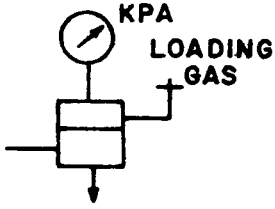
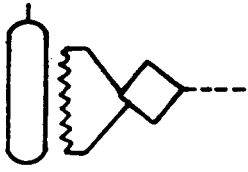
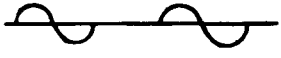
- the opportunity for safety analysis before construction begins;
- a tabulation of equipment and instrumentation for cost estimating purposes;
- guidelines for mechanics and construction personnel during the plant assembly stage;
- guidance in analyzing startup problems;
- assistance in training operating personnel; and
- assistance in solving daily operating and sometimes emergency problems.

P & I diagrams contain four important pieces of information, namely, all vessels, valves and piping, along with a brief description and identifying specifications of each; all sensors, instruments and control devices, along with a brief description of each; the control logic used in the process; and, finally, additional references where more detailed information can be obtained.

Information normally excluded from P & I diagrams includes electrical wiring (normally separate electrical diagrams must be consulted), nonprocess equipment (e.g., hoist, support structures, foundations, etc.) and scale drawings of individual components.

There are basically two parts to the diagram: the first provides a schematic of equipment and the second details the instrumentation and control devices. The P & I diagram provides a clear picture of what each piece of equipment is, including identifying specifications, the size of various equipment, materials of construction, pressure vessel numbers and ratings, and drawing numbers. Equipment and instrumentation are defined in terms of a code consisting of symbols, letters and a numbering system. That is, each piece of equipment is assigned its own symbol; a letter is used to identify each type of equipment and to assist in clarifying symbols, and numbers are used to identify individually each piece of equipment within a given equipment type. Table 1.2 illustrates common equipment symbols and corresponding letter codes.

Table 1.2. Common Equipment Symbols and Letter Codes

Equipment	Symbol	Code	Information Needs
Control valve		CV	Size, maximum flowrate, pressure drop
Piping			Material, size, wall thickness
Valves			Type: ball (B), globe (G), needle (N), etc.
Centrifugal Pump		P	Inlet/outlet pressure, flowrate
Rotameter		R	Tube, float, body, maximum flowrate
Reactor		R	Pressure vessel no., drawing no., size
Filter		FIL	Pore size
Back Pressure Regulator			Range of gauge and loading source
Electric Heater			Shown on vessel with power pack and control signal
Tracing			Type: steam (S)/ electric (E)
Spring-Loaded Relief Valve		PR	Relief pressure, orifice size

When denoting instrumentation it is important that definitions be understood clearly. Terms for instruments and controls most often included on P & I diagrams are given below:

Instrument Loop—A combination of one or more interconnected instruments arranged to measure or control a process variable.

Final Control Element—A device that directly changes the value of the variable used to control a process condition.

Transducer (Converter)—A device that receives a signal from one power source and outputs a proportional signal in another power system. A transducer can act as a primary element, transmitter or other device.

Fail Closed (usually normally closed)—An instrument that will go to the closed position on loss of power (pneumatic, electric, etc.).

Fail Open (usually normally open)—An instrument that will go to the open position on loss of power (pneumatic, electric, etc.).

Fail Safe—An instrument that on loss of power (pneumatic, electric, etc.) will go to a position that cannot create a safety hazard.

Process Variable—A physical property or condition in a fluid or system.

Instrument—A device that measures or controls a variable.

Local—An instrument located on the equipment.

Remote—An instrument located away from the equipment (normally a control cabinet).

Primary Element—A device that measures a process variable.

Indicator—A device that measures a process variable and displays that variable at the point of measurement.

Transmitter—A device that senses a process variable through a primary element and puts out a signal proportional to that variable to a remotely located instrument.

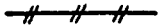
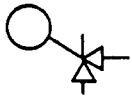
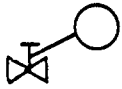
Controller—A device that varies its output automatically in response to changes in a measured process variable to maintain that variable at a desired value (setpoint).

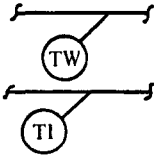
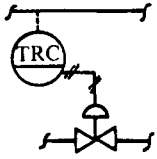
Instrumentation normally is denoted by a circle in which the variable being measured or controlled is denoted by an appropriate letter symbol inside the circle. When the control device is to be located remotely, the circle is divided in half with a horizontal line. Table 1.3 gives various instrumentation symbols and corresponding letter codes. The specific operating details and selection criteria for various process instrumentation are not discussed in this book. The reader is referred to earlier works by Cheremisinoff [1,2] for discussions on essential control and measurement instrumentation.

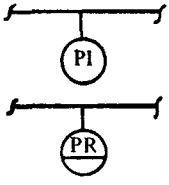
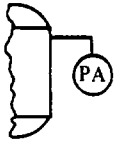
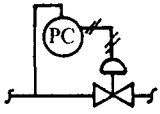
Piping normally is denoted by solid lines. Piping lines on the P & I diagram should be accompanied by the following identifying information:

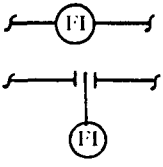
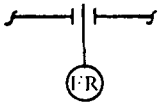
1. line number,
2. nominal pipe size and wall thickness,

Table 1.3. Typical Instrument Codes and Examples

General Symbols			
	Instrument process piping		Electrically operated valve (solenoid or motor)
	Instrument air lines		Piston-operated valve (hydraulic or pneumatic)
	Electrical leads		3-way body for any valve
	Capillary tubing		Safety (relief) valve
	Locally mounted instrument (single service)		Manually operated control valve
	Locally mounted transmitter		
	Board-mounted transmitter		
	Diaphragm motor valve		

Temperature Symbols			
	Temperature well Temperature indicator		Temperature recording controller

Pressure Symbols			
	Pressure indicator (locally mounted) Pressure recorder (board mounted)		Pressure alarm
			Pressure controller (blind type)

Flow Symbols			
	Displacement-type flowmeter Flow indicator, differential type		Flow recorder

3. origin and termination,
4. design temperature and pressure,
5. specified corrosion allowance,
6. winterizing or process protection requirements (i.e., heat tracing via steam or electric),
7. insulation type and thickness,
8. test pressure (indicate hydrostatic or pneumatic), and
9. piping flexibility range (e.g., the maximum or minimum operating temperature).

1.4. VESSEL CODES AND FLANGE RATINGS

In this first volume we shall direct much of our attention to vessel design. In the United States, the primary standard for pressure vessel design is that of the American Society of Mechanical Engineers (ASME). (In subsequent chapters information on European codes for vessels shall be reviewed.) The ASME code is essentially a legal requirement. It provides the minimum construction requirements for the design, fabrication, inspection and certification of pressure vessels. The ASME code does not cover: (1) vessels subject to federal control; (2) certain water and hot water tanks, (3) vessels with an internal operating pressure not exceeding 15 psig with no limitation on size; and (4) vessels having an inside diameter not exceeding 6 inches with no limitation on pressure.

Flange ratings are also specified by the ASME. Table 1.4 gives the various flange ratings in terms of the strength of materials, as based on ASME standards. Table 1.5 gives data on flange pressure-temperature ratings. Finally, Figure 1.2 gives data on allowable stress at different temperatures for carbon steel pipe and 304 stainless steel plate.

All pressure vessels must pass appropriate hydrostatic testing before approval for service. For safety reasons, hydrostatic pressure testing is almost always recommended over a pneumatic test. The recommended

Table 1.4. Flange Ratings for Different Materials

	Strength of Materials	
	Carbon Steel	Stainless Steel
150 lb	@ 500°F	@ 500°F
300 lb 600 lb 900 lb 1500 lb 2500 lb	@ 850°F	@ 1000°F

Table 1.5. Typical Flange Pressure-Temperature Data

	Carbon Steel		304 SS	
°F	150 psia	300 psia	150 psia	300 psia
100	275	720	275	615
200	240	700	240	550
300	210	680	210	495
400	180	665	180	450
500	150	625	150	410
600	130	555	130	380
700	110	470	110	355
800	92	365	92	330
900	70	225	70	310
1000	40	85	40	300
1100	-	-	-	255
1200	-	-	-	155

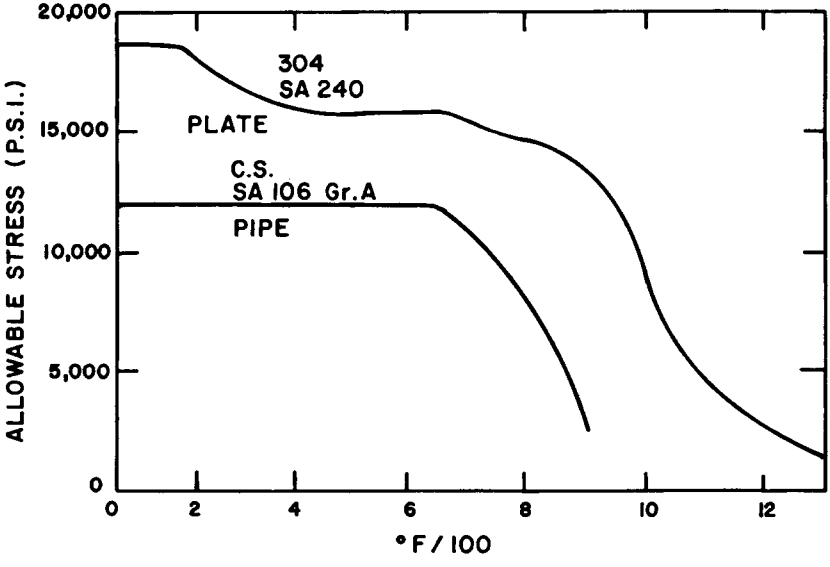


Figure 1.2. Allowable stress for different materials.

hydrostatic test is typically 150% of the temperature corrected design. The pneumatic test is typically 125% of design, as recommended by ASME. A "proof-test" is used when calculations are not possible. This requires at least twice the maximum allowable pressure and employs a brittle coat on the vessel to indicate overstress.

REFERENCES

1. Cheremisinoff, N. P. *Applied Fluid Flow Measurement* (New York: Marcel Dekker, Inc., 1979).
2. Cheremisinoff, N. P. *Process Level Instrumentation and Control* (New York: Marcel Dekker, Inc., 1981).