# Chemical Plant Design and Construction

ULLMANN'S ENCYCLOPEDIA OF INDUSTRIAL CHEMISTRY

**S. Moran,** Expertise Limited, Wirksworth, Matlock, United Kingdom




10.1002/14356007.b04_477.pub2

# 1. Introduction to Plant Design

## 1.1. General

Chemical plants (also called process plants) are used to produce a specified product, largely by a combination of mixing and/or separation of mixtures and by chemical, biological, or nuclear reaction. They manufacture a wide variety of products, such as bulk chemicals, drinking water, pharmaceuticals, cosmetics, paraffin, and electricity.

The key point is that chemical plants make a specified *quantity* of a substance or substances to a specified *quality*.

Those designing and constructing such plants need to make sure that the product is made cost-effectively, safely, and reliably [1].

## 1.2. Plant Lifecycle

The details of project lifecycles vary between industries, but there is a common core. For example, the following list summarizes the key stages in the product lifecycle for a pharmaceutical project:

1. Identify the problem to be addressed
2. Define the problem in business, engineering, and science terms
3. Generate options providing potential solutions to the problem
4. Evaluate and eliminate the options that do not meet agreed selection criteria
5. Generate a conceptual process design for the selected options
6. In parallel:
    a. Commence development work at the laboratory scale to provide more data to refine the business, engineering, and science basis of the options
    b. Commence conceptual design study to evaluate the possible locations, project timescale, and order of magnitude of cost
    c. Develop the business case at the strategic level
7. Based on the outcomes of step 6, reduce the number of options to those carried forward to the next level of detail
8. In parallel:
    a. Continue the development work at the pilot plant scale
    b. Based initially on data from the laboratory scale, develop the design of the remaining options to allow a front end engineering design (FEED) study to be undertaken

   c. Continue to develop the business scale leading to a project sanction request at the appropriate corporate level
9. Based on the outcomes of step 8, select the lead option to be designed and installed
10. In parallel:
   a. Continue the development work at pilot scale
   b. Carry out the detailed design of the lead option
11. Construct the required infrastructure and install the required equipment
12. Commission the equipment
13. Commission the process and verify that the plant performs as designed
14. Commence routine production
15. Improve process efficiency based on the data and experience gained during routine production
16. Increase the plant capacity based on data and experience gained
17. Decommission the plant at the end of the product life cycle

The pharmaceutical industry operates more stages in parallel than other industries and uses more laboratory and pilot plant work, but this is the general model followed in all industries and countries [1].

Different design activities are undertaken throughout the plant's life. In the early stages, the plant to be designed is very poorly specified, and as the lifetime of the plant continues, more and more is known about the plant.

In addition, a situation in which the plant is essentially underspecified prevails throughout most of its lifecycle. A substantial body of data on the plant has only developed by stage 15 at which point it is possible to create a highly accurate model. This allows the effect of a modification to be known with some certainty in advance.

Therefore, during the majority of a plant's lifecycle, finding reliable, just creative enough solutions to ill-defined problems is the essence of plant design.

## 1.3. Plant Design

Those designing process plants need to ensure that their design produces the desired product reliably, safely and cost-effectively and meets the specified composition and quantity.

Plants are designed in a commercial environment. Thus, the ultimate objective of plant design is to generate a profit for both the designer and the plant owner (which are nearly always separate entities) rather than for research purposes. This has a key influence on the way in which plants are designed [2]:

- Engineering design is always based in heuristics, professional judgment, and reliance on approaches that are known from the designer's experience to be highly likely to work.
- First-principles design is avoided as much as possible by professional engineers, because an initial design based on first principles almost always has some unforeseen problem.
- Process plants are too complex to be completely understood, but the designer does not need to completely understand the plant. It is only necessary to understand it well enough to have a high degree of certainty that it meets reliably its specification.

### 1.3.1. Stages of Plant Design

The design of a chemical plant is an expensive process and many designs do not prove practical. Therefore potential designs are often developed to the extent necessary to establish whether they are sufficiently promising to warrant further development.

This has resulted in a staged approach to design, which essentially proceeds from an inexpensive initial and conceptual evaluation of options through to a detailed design stage that accounts for a significant proportion of the build cost of the plant, via intermediate evaluations.

This formal staged design process is followed by two further stages, i.e., modification of the as-built design during the commissioning stage and the post-handover redesign by the plant owners' engineers, which are usually not undertaken by the original plant design team.

The design process might therefore be split into six stages as follows [1]:

- Feasibility or conceptual design
- Basic design or front end engineering design (FEED)
- Detailed design
- Design for construction
- Site-level redesign
- Post-handover redesign or optimization

Procurement and construction of the plant proceed along its design to varying degrees. Orders for long lead-time items, for example, are commonly placed as early as the detailed design stage.

Various types of companies are involved in the design process. Conceptual design usually involves some combination of an operating company and design consultant and possibly an engineering, procurement, construction (EPC) company.

***An Operating Company*** is a company whose business is the operation of process plants. Such companies are usually the ultimate clients of the companies who design and construct process plants.

***Consultant.*** Consulting companies offer a range of services, usually mainly centering on design, project management, or a combination of the two. They may be single-discipline (especially if they are design focused) or multidisciplinary. It is rare for consultants to take on contractual responsibility for whether the design works, and their design input is usually at a conceptual level.

***Contracting or EPC Company.*** Contracting companies engineer, procure, and construct process plants. EPC is one of many common contractual arrangements including EPCM (engineering, procurement, construction, management) and EPCI (engineering, procurement, construction, installation). Contracting companies design and build plants and usually offer a guarantee that the process works.

FEED, detailed design, and design for construction design are mostly completed by EPC companies, possibly with some assistance from design consultants and ideally with operating company input.

Site-level redesign is led by the commissioning team of the EPC companies.

Process optimization is led by process engineers in the operating company, possibly with assistance from design consultants and EPC companies or equipment suppliers [1].

### 1.3.2. Elements of Process Plant Design

Process plant design has a number of integrated elements [1]:

- Analysis of needs, data, specifications, etc., to generate a clear description of the design envelope of the plant
- System level design, which is concerned with making all of the unit operations work together
- Process control, as specified by documents, such as the functional design specification (FDS) for software
- Design and specification of the individual processing steps, such as reactors and distillation columns (known as unit operations in chemical engineering, see below)
- Hydraulic design (concerned with moving fluids around the plant) and the associated specification of pumps, compressors, etc.
- Plant layout, in which the equipment and buildings are laid out on the site in such a way as to produce a cost-effective, safe, operable, aesthetically pleasing whole
- Risk and safety analysis using techniques, such as HAZOP (hazard operability) [3]
- Economic analysis, which uses tools, such as costing and sensitivity analysis
- Project programming
- Production of key project deliverables defining the design, such as mass and energy balances, layout drawings, piping and instrumentation diagrams, process flow diagrams, Gantt charts, and various schedules.

***Unit Operation [1].*** The development of the concept of unit operations is agreed to be the foundation of the discipline of chemical engineering. This concept is simple but powerful. A unit operation is a stage of processing, such as reaction, mixing, separation, or heat exchange, where a single significant change is made. By splitting the process into unit operations, it is possible to analyze it more readily, using tools, such as mass and energy balance.

#### 1.3.3. Disciplines Involved in Process Plant Design

The key skill of the process designer is to make all of the parts of the plant (and indeed the associated design process) work together properly.

Process designers are, generally speaking, chemical engineers, but there are other disciplines that need to be involved in the plant design process. As a minimum, electrical, software, and civil engineers are required to design their respective aspects of the plant.

There is an exchange of ideas between the various disciplines as the design progresses. The common language of the various parties to the design is engineering drawings, most notably a line drawing of the plant laid out in space known as a plot plan or general arrangement drawing.

All these disciplines seek to optimize the design from their point of view. The lead designer needs to manage this to produce the best design.

In most industries, the chemistry used is generally selected from available proprietary technologies that have previously been successfully operated at the proposed scale of operation.

Scale-up from bench scale to full scale is no trivial matter and process plant designers place far greater emphasis on the reliability, safety, and cost-effectiveness of the design than on novelty.

## 2. Feasibility and Conceptual Design

### 2.1. Introduction

The key questions to consider at the earliest stage of design are:

- Is it economically viable?
- Is it reliably possible to meet the specification?
- Is it publically acceptable?
- Is it safe?

It is not possible to answer these questions with the required degree of certainty unless a rough design (or, more likely, multiple designs) has been carried out. However, for the conceptual designer, the required degree of certainty to allow design to progress to the next stage is far lower than that produced by a rigorous (but expensive and time-consuming) scientific analysis.

Therefore engineering is not applied science, but professional art informed by science [1].

### 2.2. The Design Envelope

The first task in the conceptual design of a process plant is the analysis of the available design data to establish the design envelope i.e., the multi-dimensional set of constraints on the design.

External constraints determine which designs are possible. The proposed design must be physically and chemically possible. However, designs are commonly far less directly constrained by scientific considerations than by man-made ones, the effects of which only diminish as new commercially-proven technologies become available. This, taken with the innate conservatism of professional engineers, means that the practice of design has a slow rate of change.

Because the aim of design is to produce a plant that generates a profit throughout its lifetime, it must work within the economic and other resources available. The resources differ over time and between countries and sectors.

All designs must also be compliant with national and international safety legislation, relevant industry and statutory standards, codes, and controls. Some of these constraints may vary from country to country.

Internal constraints determine which designs are plausible. The companies carrying out a design have access to just a subset of all design and construction methods, knowledge and experience, licensed processes, process equipment, and materials. There are also finance, time, and personnel constraints on what can be delivered.

Operating companies and designers both have preferences for one process over another based on their experience. Operating company staff has experience of a limited number of processes, and there are costs associated with training them on a new process.

The more novel a process is, the more likely there are to be unforeseen problems after a period of operation. Plant designers and operators tend therefore to favor just novel enough processes and to be more conservative at the earliest design stage in order not to over-commit resources in developing a design which proves impractical at a later stage [1].

## 2.3. Risk and Safety Analysis

Safety first! Before progressing with a design, chemical engineers must consider whether the proposed chemistry and processing steps are inherently safe [4]. The key principles of the concept are:

- Minimize: Reduce stocks of hazardous chemicals
- Substitute: Replace hazardous chemicals with less hazardous ones
- Moderate: Reduce the energy of the system
- Simplify: Simple processes are easier to understand, operate, and control hazards within

Rather than using, for example, a highly flammable solvent and subsequently putting in place the requisite protection measures, consideration should be given to employing a less flammable (and therefore less inherently dangerous) solvent in the first instance.

This is one of the most important parts of conceptual design, because it builds passive safety into the design at the earliest stage.

## 2.4. System-Level Design

Process plant design seeks to make a collection of unit operations work together as a well-controlled and unified whole.

Chemical engineers are trained to address this at the earliest stages of design mainly with two tools, namely the mass and energy balance and the associated process flow diagram.

***Mass and Energy Balance.*** The law of conservation of mass states that (unless a nuclear reactor is being designed) mass is neither created nor destroyed in chemical reactions. By extension, this law holds true in a chemical plant. It may be that chemical reaction causes the chemical elements in the process to be rearranged into new compounds, but the masses of elements in and out are always equal.

This principle forms the basis of a simple but powerful tool known as a mass balance. This is a calculation in which the masses of all of the substances going into the plant and each of its unit operations are determined.

An assumption of steady state is probably made at the earliest stage of design, such that the mass balance is calculated only under the normally envisaged operating condition. This is a simplifying assumption, which takes no account of even the most foreseeable excursions from the ideal operating conditions [1].

One important feature of the mass balance is that it is common in plant design to recycle materials from the end of a process back to the start for reprocessing. This can make a large difference to the required size of equipment between the point at which the materials are withdrawn and that at which they are reintroduced. Failure to account for such recycle streams can consequently have a significant impact upon the size, price, and practicality of the plant as a whole; thus they should be considered even at this early stage of design.

Beside conservation of mass, energy is also conserved. This allows an energy balance to be constructed by a similar method based upon the mass balance and the laws of thermodynamics.

***Process Flow Diagram.*** The process flow diagram (PFD) is used to show the inter-relationship of the main unit operations in the envisaged plant, and the flows of mass and energy between them. Unlike some other engineering drawings (see Sections 3.5 and 3.8), there is consensus agreement within the engineering profession on the nature (and name) of the PFD.

Standards used in PFDs vary from country to country but, internationally, the most commonly used standard is ISO 10628 [5]. There is also a commonly used (though now withdrawn) U.S. standard, ANSI Y32.11 [6].

There can be no valid design of unit operations before a mass balance and PFD have been produced, since flows to individual unit operations are not necessarily obvious from whole-plant throughput, largely due to the presence of recycle streams in the plant.

Chemical or process engineers (the terms are almost interchangeable) therefore tend to produce at least a rough PFD as part of their initial deliberations on the various potential process options.

At this earliest stage of design, the rough PFD is likely to be hand sketched on paper or shown in the spreadsheet or other computer program used to produce the mass balance rather than developed into a proper engineering CAD drawing. However, a properly CAD-drafted version of the rough PFD may be produced at the earliest stage of design to illustrate proposals to the client. In this manner, engineering drawings serve as tools for explanation and review as much as they are tools for thinking [1].

## 2.5. Unit Operation Level Design

It is usually necessary to design unit operations to some extent at the earliest stage, if only to provide a rough approximation of their physical size and cost. This can be completed relatively quickly by experienced engineers, based upon approximate heuristics. These heuristics may take the form of rules of thumb, design guides, or manuals, or they may be built into specialist black-box computer software. Thus, even at conceptual design stage, it is helpful to be able to size rectangles, circles, etc., representing the footprint on the site of the unit operations that are the heart of the plant [1].

Frequently, reaction and separation processes of the plant do not represent a significant proportion of the whole-plant footprint. The required separation (for safety and operational reasons) between these processes as well as the pumps, compressors, buildings, etc., probably accounts for far more of the site than the unit operations. In addition, ancillary processes, such as steam-raising plant and pollution abatement measures can account for a considerable amount of space.

It is therefore good practice to allow space for these additional requirements when estimating plant footprint. This is achieved by multiplying the footprint for the key unit operations by a factor of four or more. Alternatively, it is possible to estimate the sizes of these key items, an approach that is especially worthwhile if the client wishes to have some idea of what the plant will look like on the site at the earliest stage of design.

If pumps or compressors are to take up a significant proportion of the site, it is best to size them approximately even at the earliest stage, using the roughest kind of hydraulic design techniques (see Section 2.6). Similarly, in some industries heat exchangers can have a very significant capital and running cost as well as site footprint, and consequently an initial heat exchanger design is undertaken at conceptual design stage.

The inherent conservatism of professional engineers screens out many options at the conceptual design stage in a way that may be frustrating to neophiles. Much of professional engineering know-how however, consists of knowing what is not likely to work.

***Erring on the Side of Caution: The Conservatism of Engineers.***

- A general rule in plant design is to err very much on the side of caution at earlier stages of design.
- Plants are always bigger, cost more, and have more design challenges than seemed likely before embarking upon the detailed stages of design.
- The urge to optimize a plant design at the conceptual design stage should therefore be strongly resisted [1].

## 2.6. Hydraulic Design

When sizing the pumps for liquids or the compressors for gases used to transfer fluids around a process plant, there are three key information requirements:

- Composition of the fluid to be moved
- Required flow
- Pressure required to move it

The composition and flow of the fluid to be moved come from the mass balance and its temperature from the energy balance. The required pressure, however, has to be determined by hydraulic calculations [1].

It is essentially impossible to calculate this pressure rigorously from first principles, and it is in any case pointless to attempt to generate a precise value for a calculation based upon very vague information. Engineers therefore employ a range of techniques that facilitate the rapid generation of approximate values for the pressure required of pumps and compressors.

Even at conceptual design stage, approximate pipe internal sizes can be established using a rule of thumb based on average velocity of fluid through the pipe. For example, velocities of 1.5 m/s for water-like liquids, and 15 m/s for air-like gases can be used to generate approximate pipe sizes.

The key pumps and compressors can then be sized approximately, using charts which give the amount of pressure required per meter of pipeline to transfer a given flow of material through a pipe of a given diameter.

The flow and pressure estimate can then be used to determine the number and size of the required pumps and compressors, with the aid of manufacturers' product catalogues (frequently available online).

The above would be the most rigorous calculation employed at conceptual design stage, and it would be common for even such rough calculations not to be used at this early stage. They are, however, necessary to generate an initial plant layout.

## 2.7. Plant Layout [7]

Laying a process plant out in space is not a trivial matter, and the process or chemical engineer is always involved. Most obviously, the relative positions of equipment affects the pressure requirements for pumps and compressors, but there is also a series of complex considerations associated with safety and operability, aesthetics, etc.

It is unusual for engineer-led design to give substantial consideration to plant layout at the conceptual design stage, but there is a growing trend for architects to be involved in plant design at an early stage resulting in an increased early consideration of layout issues.

Even an initial layout might show that the plant envisaged cannot fit on the proposed site resulting in a need to return to the very earliest stage of design definition and reconsider the choices made there [1].

## 2.8. Economic Analysis

The fundamental objective of conceptual design is to generate an idea of how much it costs to build and operate a plant. Around 98% of conceptual designs prove uneconomic, which is why engineers develop potential designs only to the extent necessary to generate a sufficiently robust cost estimate allowing a decision to be made on whether to proceed further.

At conceptual design stage, professional engineers often price the main plant items (roughly analogous to the unit operations) and then calculate the whole plant cost by multiplying the total main plant items cost by a factor.

The most established factorial costing method is that of Lang [8], which offers a factor to multiply main plant item costs to account for costs of:

- Design and engineering costs
- Contractors' fees
- Contingency
- Equipment erection
- Piping
- Electrical
- Instrumentation
- Structures and buildings
- Storage
- Utilities
- Site preparation
- Site work

There are other sets of factors (for example Guthrie's [9]), but the ratio of the main plant items to the cost of the complete working plant cost is approximately 1 : 5.

Alternatively, if the plant designer has access to whole plant costs, they might adjust these costs for the size of the proposed plant using the 0.6 rule [10], which holds that the ratio of the cost of the proposed plant to the known one is the ratio of the production volumes of the two plants raised to the power of 0.6. The same approach can be used to extrapolate from known equipment costs to unknown ones.

### 2.9. Project Programming

If a more accurate costing is required, the likely duration of the project needs to be known, and it can be useful to have an idea of project program length even at the earliest stages of design evaluation. Thus, engineers need to estimate how long it takes to build a plant as part of their consideration of whether it is worth building, and to choose between the different design possibilities. Experienced engineers can usually generate a reliable estimate based on experience of how long it takes to procure an item of equipment, deliver it to site, erect, and commission it.

Formally, the duration and interrelationship of all the individual activities which form the project of designing and building a process plant is often expressed using a Gantt chart, also known as a project program or schedule. The project program shows the start and finish dates and duration of tasks, such as site preparation, dependencies between tasks as links, and key events as milestones. The program is quite simple at the conceptual design stage.

However, the interrelationships between tasks are particularly important; for example, some items can be installed concurrently, whereas others are reliant on other activities, which have already taken place before they can be erected [1].

### 2.10. Deliverables

The deliverables for a conceptual design study normally include a narrative report, setting out the considered design, the technology options possible at the plant, and a comparison of those options from the perspective of cost, safety, and practicality.

The report usually identifies any options worthy of further design development and is supported by process flow diagrams and possibly by drawings of the appearance of the plant on site.

In some cases, piping, instrumentation, and general arrangement drawings might also be included, though these are indicative only, intended for explanatory purposes rather than as contractually binding design deliverables.

## 3. Basic Design or Front End Engineering Design (FEED)

### 3.1. Introduction

Only around 2% of projects progress beyond the conceptual design stage. The next stage for those progressing is the basic design or front end engineering design FEED study [1].

Design consultants or EPC companies work with operating companies to produce a FEED study, though the lead organization may vary. At FEED stage, the operating company needs to be involved in the process to ensure that the proposed design meets their specific situation and needs. Design consultants may not be required, but if they are used, they assist the operating company to manage the EPC company, carry out some high-level design activities, and/or contribute some proprietary process or technology. The EPC company has the detailed design and construction know-how and access to accurate pricing data to ascertain that the design and pricing aspects of the study are realistic [1].

### 3.2. The Design Envelope

Whereas, during the conceptual design stage, a first rough consideration of the constraints on the system design has been undertaken, at FEED stage, these assumptions are investigated in more detail, and design philosophies are clearly set out in writing. If the design proceeds further, those responsible for the next stage of design have a clear statement of the design basis of the plant, which minimizes the risk of wasting resources on redesign based on a different set of assumptions or a different design philosophy [1].

The FEED designers should record their choice of standards and philosophies, together with any underlying assumptions and justifications for their design selection. This record should include items, such as:

- Overpressure, vent, flare, and blowdown philosophies (how the designer has handled the residual possibility of overpressurization of equipment after inherent safety has been applied)
- Isolation philosophies (how the designer has designed in safe access to equipment during maintenance activities as well as the assumptions made in that design)
- Safety and loss prevention philosophy (the way in which the designer has addressed the safety and loss prevention aspects of the design and the underlying assumptions)
- Operating and environmental conditions (the range of internal and external conditions under which the plant is designed to operate, including foreseeable accident or incident conditions)
- Feedstock and product qualities (the specification of the feedstocks and product, which the plant will work with)
- Acceptable range of technologies (the list of technologies which were considered at conceptual and FEED stage, with cost, safety, or robustness justifications for the exclusion of other technologies)

## 3.3. Risk and Safety Analysis (→ Plant and Process Safety, 6. Risk Analysis)

By the end of the FEED stage, there is enough information to allow formal risk analysis tools, such as HAZID (hazard identification), risk matrices, and HAZOP (hazard operability) to be used, in addition to checking whether inherent safety has been properly applied [3].

HAZID techniques are quick, early stage, relatively informal techniques that require examination of the proposed design from the point of view of operation, maintenance, construction, and commissioning to identify which hazards it presents. The hazards identified can be prioritized by risk matrices.

HAZOP studies are highly rigorous, detailed, time-consuming reviews of the design undertaken by a panel of engineers intended to identify possible hazards arising due to unforeseen interaction of parts of a process plant.

There are various degrees of resolution in risk matrices, but they all permutate the probability (the risk) of an adverse event occurring (a hazard) with the severity of consequences if it does occur. Figure 1 gives a typical example of a risk matrix.

Using the matrix in Figure 1, it is common to design out any hazards considered intolerable. It would be desirable to design out those considered moderate. Any remaining moderate hazards, plus any tolerable hazards are then controlled through standard operating procedures and/or passive safety devices. Trivial

| | | Potential severity of harm | | |
|---|---|---|---|---|
| | | slightly harmful 1 | harmful 2 | extremely harmful 3 |
| Likelihood of harm occurring | highly unlikely 1 | trivial 1 | tolerable 2 | moderate 3 |
| | unlikely 2 | tolerable 2 | moderate 4 | substantial 3 |
| | likely 3 | moderate 2 | substantial 6 | intolerable 9 |

**Figure 1.** Example of a risk matrix [11]

hazards may be numerous, but do not generally necessitate special measures.

## 3.4. System-Level Design

At FEED stage the tools of mass and energy balance are used again, but they are applied at a higher resolution. Smaller streams are considered as well as the design of pollution abatement measures that have been left out of the conceptual stage design. Significant design problems that had previously been identified but not resolved are addressed.

The mathematical model of the mass and energy balance is most commonly produced using a spreadsheet program, such as Microsoft Excel, but process simulation packages, such as Aspen Hysys are increasingly applied [1].

## 3.5. Process Control

Although process control is a complex subject in its own right, the key issue is to control the processes either manually or (more commonly) automatically to maximize profitability while maintaining safety.

Irrespective of the control mode, the conditions inside the process need to be measured, and depending on the measurements, the operation of the process may need to be adjusted.

For example, a plant designer needs to produce a stream of water at around pH 7 from a water feed stream with a variable pH. The pH of the outgoing water can be measured with an in-line pH probe. If the pH is higher than 7, a metering pump can be used to add acid. If it is lower than 7, a similar pump can be used to add alkali.

The addition of the acid or alkali moves the pH towards the desired value (set point), which the pH probe registers. The signal from the probe goes into the controller, which sends out a control signal to an actuator (in this case a metering pump) to dose a little less of the acid or alkali.

This process, whereby feedback is taken by an instrument of a parameter to control an actuator, which modifies the parameter, is known as feedback control [1].

Measurements are normally taken using online instruments, inserted into the process equipment (in-line) and taking continuous readings. Off-line measurement may also be used, which involves taking a sample from the process and carrying out some field or laboratory analysis and measurement of parameters. Online measurement is generally preferred so that systems can be updated with the status of the measured parameter as often as it is useful to obtain the required degree of control.

Both the measuring devices and the control devices may be referred to as instrumentation, but it is common and less confusing, to refer to the measuring instruments alone as instrumentation and the control devices as actuators [1].

The most commonly used online instrumentation measures pressure, flow, and temperature. Many other parameters can, however, be measured using online instruments.

The most common actuator on a process plant is some kind of control valve. There are many types of valve, some more suited for on/off control, and some more suited for more precise modulating control. The valve can be moved using an electrical, pneumatic, or steam power supply, and the control signal itself is almost always electrical or electronic nowadays.

The process designers develop the control philosophy of the plant using two key documents, the piping and instrumentation diagram (most commonly known as P+ID) and the functional design specification (FDS).

Numerous standards are used in P+ID production but ISO 14617-6:2002 [12] and ANSI/ISA 5.1 (2009) [13] are those most commonly employed.

The functional design specification [also called URS (user requirement specification) or a control philosophy, though all of these terms may also be used for other documents] is a description in words of how the process designer wants the control system to work. This document and the P+ID tell the software engineer what is required of the software.

## 3.6. Unit Operation Level Design

At FEED stage, it is usual to send procurement enquiries out to specialist suppliers for any significant items of equipment. Although plant designers may well have a basic knowledge of the design of such items, they do not have the specialist knowledge required to design them sufficiently realistic. The plant designer's role is therefore to specify unit operations rather than to design them.

The plant designer may, however, use heuristics to produce a rough design for such items while awaiting supplier information. An approximate idea of the power, utility and control requirements, physical size and mass of these items is required to allow design to progress. The plant designer may therefore be required to make such estimates in anticipation of more accurate information from the supplier.

## 3.7. Hydraulic Design

Whereas hydraulic design is relatively unusual at the conceptual stage, it is mandatory at the FEED stage. Since the completion of hydraulic design calculations requires knowledge of the size, length, and shape of pipework, a layout drawing must first be produced [1].

Hydraulic design progresses iteratively by increasing the degree of rigor. The next most rigorous approach (after the average velocity method outlined in Section 2.6) is as follows:

The equipment is laid out in space and connected by pipes on a layout drawing (as described in Section 3.8). For each of these pipes, the designer needs to know:

- Any vertical height difference, pipe lengths, number of bends, tees, etc. (which can be taken from the layout drawing)
- Number of valves, constrictions, etc. (which can be taken from the P+ID)
- The pressure in process vessels (which can be taken from the PFD)

Once this information and the range of flows required through each pipe is known, the designer can calculate the three components of the required pressure to push flow through the pipe:

1. Dynamic head due to straight run pipe: The pressure drop due to friction while fluid is flowing in straight pipe per meter of pipe can be estimated using various charts and tables, such as the nomogram reproduced in Figure 2, which are available from process pipe suppliers
2. Dynamic head due to fittings: The pressure drop due to friction while fluid is flowing from bends, tees, valves, etc., can be estimated using the $K$-value method:

   Loss of head due to fittings $= K\, v^2\, 2^{-1}\, g^{-1}$

   Where
   $v$ = average velocity of fluid
   $g$ = acceleration due to gravity (9.81 m/s$^2$)
   $K$ = sum of $K$-values

   The $K$-values for a number of common fittings are provided in Table 1.
3. The static head: Independent of fluid flow, there is a pressure in the line from any pressurized process vessels attached to it, as well as a pressure exerted by the fluid uphill of the entry point to the pipe. These two components are added together to form the static head.

The designer calculates the amount of pressure required at the inlet of the pipe to give a certain flow as the sum of these three components.

Since length and internal diameter of the pipe, number of fittings, and vertical height difference between process vessels are key variables, the designer can to some extent choose between flows through the plant being driven purely by gravity or using smaller or larger pumps to generate flow.

There is an interplay between hydraulic design, economics, and plant layout.

## 3.8. Plant Layout [7]

Regardless of whether plant layout has been considered at the conceptual design stage, it is always considered at FEED stage, where layout drawings, known as general arrangement (GA) or plot plan drawings are produced. As a minimum, these drawings show, in plan and elevation, the unit operations, pipes, pumps, buildings, roadways, and other access arrangements of the proposed plant.

These layout drawings are given to civil and electrical engineering designers to allow them to

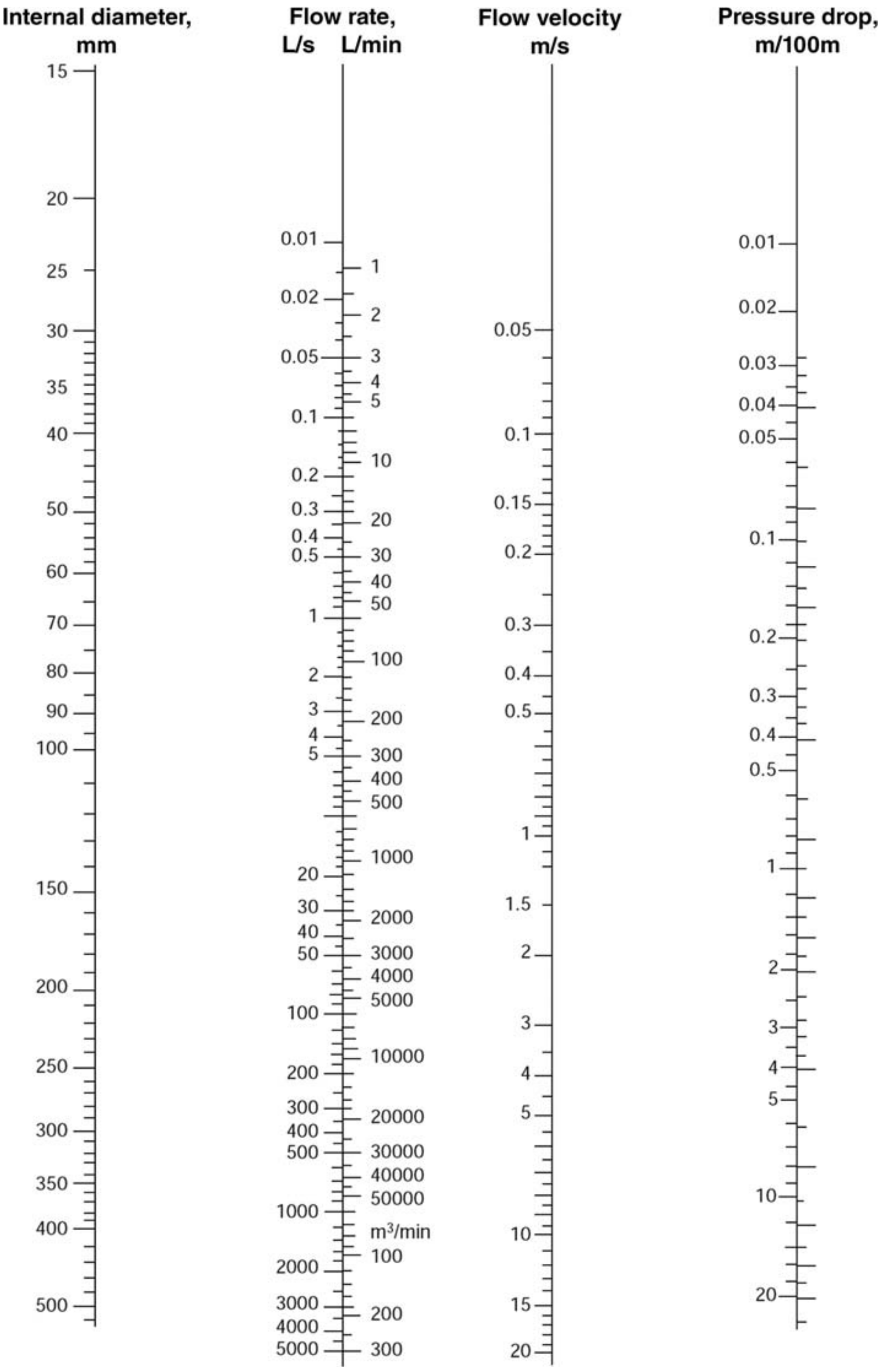


**Figure 2.** ABS pipe nomogram for water at 10°C (approximate values only). (Reproduced with permission of Durapipe ABS)

**Table 1**. *K*-values for common fittings [8]

| Fitting type | Bend radius, ° | *K*-Value |
|---|---|---|
| Short radius bends | 22.5 | 0.2 |
| | 45 | 0.4 |
| | 90 | 0.8 |
| Long radius bends | 22.5 | 0.1 |
| | 45 | 0.2 |
| | 90 | 0.4 |
| Open isolation valve | | 0.4 |
| Open control valve | | 10.8 |
| Side entry tee | | 1.2 |
| Through tee | | 0.1 |
| Swing check NRV | | 1 |
| Sharp entry | | 0.5 |

progress their own layout drawings and the design of buildings, slabs, cabling, etc. This is, however, not a one-way information transfer. The civil and electrical engineers may return with suggestions on how the design could be improved to save costs or facilitate construction in their areas. The plant designer needs then to take an overall view of such suggestions and decide if the process design can be modified to incorporate them in such a way that the overall design is improved. However, experienced designers use well-established mutual arrangements of equipment with inbuilt consideration of hydraulics, civil, and electrical implications in their design. Therefore they usually encounter far less redesign at this stage than less experienced designers [1].

## 3.9. Economic Analysis

The preceding two stages generate a wide range of choices, and even the most experienced designers need to make a rapid selection. The key benefit of experience is knowledge of what does not work and of where good design compromises are likely to lie.

Even the most experienced engineer generates numerous plausible alternatives to achieve a design objective. A choice must be quickly made between these on the grounds of cost, safety, and process robustness.

In particular, the cost element of this selection process needs to be sufficiently accurate to serve as a tool to differentiate between options. Thus it is necessarily more rigorous than the main plant items method described in Section 2.8.

Professional engineers normally refer to current supplier quotations for the cost of main plant items. During evaluation, it is important that the engineer has an understanding of the accuracy of their cost estimates, so that he/she can assess the significance (or otherwise) of any apparent differences in price.

In addition, the engineer considers estimates of time and other resources required for site installation, generated by someone who is experienced in such matters. Thus, the time required to procure and install the equipment can also be determined. If the project program is tight, required equipment may not be available in time to meet it.

This stage of the design process might loop back to several previous points in the process. It certainly involves iteration through the previous two stages of FEED, and often involves reconsideration of unit operation level design.

If the conceptual design stage was not well articulated, iteration may even revert back to reconsideration of design envelope. This iterative process, with its loops within loops, is characteristic of all design and is particularly common in process plant design due to its great complexity [1].

The design activities described so far have largely required preceding stages for completion. However, this gives a misleadingly linear impression of the design process. There are many points in the process where a problem can only be resolved by going back a few stages in the process to redefine the design being considered.

This process of iteration is more characteristic of the design process than any linear model.

## 3.10. Project Programming

There may be options which would be viable, but for the fact that they cannot be delivered within the available timescale. Such options need to be identified and eliminated at FEED stage.

To be accurate, the costing of the plant needs also to take into consideration indirect, time-dependent costs. For example, costs associated with the provision of the site compound used during construction accrue on a weekly basis, irrespective of how much progress is made with construction.

For these reasons, it is common to produce at least an outline project program at FEED stage, with input from the civil, electrical, and process engineers involved in the design development.

Projects are usually programmed using software, such as Microsoft Project or, more commonly, Oracle's Primavera, and a project programming specialist often joins the project team at this stage. MS Project is, however, sufficiently intuitive that most engineers can produce a simple program for themselves at FEED stage.

### 3.11. Deliverables

From a technical perspective, a FEED document package usually includes as a minimum PFDs, P+IDs, GAs, project program, detailed costing, and specifications for the main plant items, pumps, pipework, valves, and instrumentation. There are also corresponding civil and electrical drawings and documentation.

Usually there are also contractual documentation as well as safety and quality assurance scheme details and other certifications.

FEED studies can be produced by consultants, in which case they are almost entirely technical in nature, and their costing basis may be less reliable.

Alternatively, design and build-capable contracting companies can produce competitive tenders incorporating a FEED study. Such tenders are likely to include detailed legal documentation but may be less forthcoming in their articulation of the design due to commercial confidentiality [1].

### 3.12. Design Reviews

Engineering is a team activity, and the design work is always checked before it is considered reliable enough to act upon.

The costs associated with formal design reviews are sufficiently high that, at FEED stage, oversight by more senior engineers and/or managers is all that is usually undertaken [1].

### 3.13. Site Selection [1]

FEED stage would usually be the first point at which site selection is seriously considered. Any proposed plant, whether it is an extension of an existing plant or an all-new grassroots design, needs to be able to fit onto the available land.

Since this consideration can affect such basic factors as choice of technology, it is wise to consider site selection at an early stage, along with factors, such as proximity of housing, utilities, etc.

For more detailed listing of the factors that should be considered see Section 4.13.

## 4. Detailed Design

### 4.1. Introduction

Detailed design of process plants is an expensive process, which can cost up to 10% of the whole value of the plant as constructed. It is therefore only undertaken for projects identified by the FEED study as strongly viable [1].

The detailed design stage produces deliverables close to the design for construction documents, involving in depth discussion with equipment suppliers, construction companies, planning authorities, operating companies, and consultants.

New disciplines, such as architects, software, and piping engineers not involved in earlier stages, may be introduced, and the management of the design team starts to become a significant task in itself.

The requirement for a close link between detailed design and design for construction means that this stage of design always involves construction companies, and if the FEED study was undertaken as part of a competitive tendering exercise, it takes place almost entirely within an EPC company.

### 4.2. Design Envelope

At detailed design stage, the design envelope needs to cover all foreseeable circumstances. This includes environmental conditions, variations in feedstock, utility quality, and availability, etc. The interactions between the main process and ancillaries also need to be fully considered at this stage.

By the end of it, there should be no significant design issues left unresolved. Significance, in this context, means having serious safety implications, the potential to incur additional costs in excess of the permitted contingency, the potential to miss project program milestones, and, most importantly, the potential to prevent the plant meeting its performance specification [1].

### 4.3. Risk and Safety Analysis (→ Plant and Process Safety, 6. Risk Analysis)

A HAZOP study on the detailed design documentation is almost certainly undertaken (although different industries may employ other analyses, such as hazard area zoning, safety integrity levels (SIL) for instrumentation, etc.). Although HAZOP is not intended as a design review, it should identify any unintended safety consequences of design choices that make it through to the final design.

There may also be statutory considerations, such as control of major accident hazards (COMAH) legislation [14] that need to be integrated into the design at this stage as well as a numerous safety related design codes. Experienced designers should have automatically considered much of this at earlier stages, but there should be explicit consideration at this stage.

### 4.4. System-Level Design

Detailed system level design is undertaken using some kind of computer program. This is most commonly a bespoke Microsoft Excel spreadsheet created by the process engineer [1].

Although it is reasonably commonplace in many industries for process simulation and modeling programs to be used at this stage (if not sooner) to ensure the whole system design works, it is by no means universal practice and is still more common in consultancies than in EPC companies.

It is both easy and quick to use simulation programs badly; expensive, and time consuming for anyone other than the most expert users. It is better to have a simpler model (e.g., an Excel model) that the designers understand than to have a more complex one which they do not.

Whichever software is used, there needs to be a detailed mass and energy balance, integrated with less detailed unit operation design. The detailed design of unit operations is undertaken by equipment suppliers, which are normally different companies from the process plant design company.

The detailed whole-plant design yields detailed specifications for unit operation design companies to work from, though the system-level design is checked to make sure that the approximate unit operation designs within it are similar to commercially available unit operation designs. It is always better to use a commercially available unit operation in a design, because a model from a supplier's standard range is both cheaper and more likely to be well-characterized than a one-off special design [1].

### 4.5. Process Control [15]

Process control is always considered at detailed design stage, and a detailed FDS is produced by the process engineer in conjunction with the P+ID. Instrumentation and actuators to be used are specified down to the level of a particular manufacturer's model at this stage.

The highest level of control is usually achieved by some kind of industrial computer. These are usually programmable logic controllers (PLCs), or personal computers (PCs). PLCs run a simple operating system, with a somewhat basic input and output screen known as a human machine interface (HMI). PCs are essentially the familiar desktop computers running Microsoft Windows, as well as specialized system control and data acquisition (SCADA) or distributed control system (DCS) software. Often both PLCs and PCs are used together in various ways across a site.

There can also be field-mounted local control by various means ranging from smart instruments that carry out control actions to field-mounted PLCs.

Software engineers are frequently involved at this stage to comment on the implications of the chosen control philosophy for the price and practicality of the control system.

Choosing between the numerous possible options to give a cost effective, robust, and safe control system is best done in conjunction with software control and instrumentation specialists [1].

## 4.6. Unit Operation Level Design

The detailed design of the whole plant involves advice from equipment suppliers about their standard range of units. Ideally, more than one equipment supplier is able to supply the specified unit, so that competitive quotations may be obtained at design for construction stage.

While it may be possible for whole plant designers to design unit operations from first principles, these designs are bespoke one-off units. It is often as much as three times as costly to purchase a one-off special item as it is to buy a stock item. Furthermore, a special item does not have the supplier's know-how built into it, nor do they have prior experience with it.

Stock items are usually available in an overlapping range of sizes, with minimum and maximum unit sizes. Thus the designer may be constrained as to the number of units to be specified.

There is a further consideration in this respect. Process-critical unit operations need to be duplicated, such that there are duty and standby units. If the required duty cannot be achieved by a single unit, duty–duty–standby, duty–assist–standby (and so on) arrangements are needed [1].

## 4.7. Hydraulic Design

The layout drawing shows the actual equipment to be used at an accuracy of around $\pm 100$ mm in this stage. With this greater accuracy of the detailed design it is now possible to complete more precise hydraulic calculations.

The main methodological difference is that straight-run headloss is calculated rather than estimated less precisely from charts. This is normally done using Excel spreadsheets purpose-written by the plant designer or by the company's process engineering department.

The pipe lengths, elevations, number of fittings, etc., are known more accurately, but the design methodology is the same as that used in previous stages. The pumps, compressors, etc., needed to deliver the required flows are specified as described in Section 4.6. At this stage, consideration may be given to the effects of pipe networks with their numerous entry and exit points [1].

## 4.8. Plant Layout [7]

The layout drawings at the detailed design stage need to be highly detailed, with accurate placement and dimensioning of all equipment in three dimensions. It is increasingly common to use 3D modeling software, especially if architects are involved in the design.

The importance of buildings to the overall design predicts to some extent whether architects are involved at this stage. Pharmaceutical processes, for example, are often indoors for containment and confidentiality reasons, which puts them at the forefront of this trend.

## 4.9. Economic Analysis

A very accurate estimate of costs is possible at the detailed design stage. Equipment has been specified down to the manufacturer's model number, and it is therefore possible to obtain three firm fixed quotations for every item.

The civil and electrical engineering design should also have progressed to the point where firm prices and timescales can be obtained from potential civil and electrical partner companies.

The discipline managers in the EPC company should now be able to produce firm estimates of how many man-hours of each discipline are required for design of construction, procurement, site installation, site supervision, commissioning, etc.

In addition, a program, fed with this information, can be produced in enough detail such that an accurate estimate of the costs associated with the setup of office- and site-based teams can be established.

It should therefore be possible to produce an estimate to AACE Class 2, $\pm 5\%$ accuracy (see Table 3). This estimate should be in line with those produced at earlier stages, otherwise a project which appeared promising at the

FEED stage might yet prove unviable at the detailed design stage [1].

### 4.10. Project Programming

The information on delivery periods for equipment, man-hours estimates, etc., available at detailed design stage means that a detailed and accurate project program can now be constructed [1].

There may well be a need for iteration involving programming, design, and costing to resolve design issues that become apparent when the details of design are considered, such as accommodating long-delivery items or allowing for any temporary works required.

At detailed design stage, the use of more sophisticated tools, such as critical path analysis becomes worthwhile. Critical path analysis is useful for showing project managers, which parts of a project are most important for maintaining project deadlines:

- Once a project program has been constructed, showing the dependencies of tasks on those preceding them, it is possible to establish the critical path of the project, the longest linked chain of dependencies. This, in turn, determines the minimum possible time in which the project can be completed.
- Items which are not on the critical path are said to be float. They can be fitted in anywhere without delaying the project.

### 4.11. Deliverables

Deliverables packages for detailed design include more detailed versions of the PFDs, P+IDs, GAs, etc. Because of the greater level of details each of these drawings needs to be drawn on multiple sheets to maintain clarity. There are also detailed FDS as well as data sheets and schedules:

- To facilitate purchasing and project management, the complete technical specification of the equipment to be purchased has to be reliably transferred from designer to the supplier company via the project engineer or buyer. This is done using a data sheet similar to that illustrated in Figure 3.
- Schedules serve a similar function, but check for completeness and cross referencing. The design team produces drive schedules listing all motors on the design used primarily to transfer information to electrical equipment suppliers, valve schedules used to check that all valves shown on the drawings are being purchased, etc.

There may also be a number of written technical documents, addressing the planning, safety, environmental, and other studies required to progress the document to this stage.

Since the design has now been progressed to the point where it is sufficiently well characterized that it is ready to be built, deliverables will include the documentation, costing, etc., used to define an offer to build the plant to a purchaser.

### 4.12. Design Reviews

At the detailed stage of design, more formal design reviews are required. These basically involve a set of experienced engineers reviewing what has been designed based on their collective experience.

A typical review may involve as many as eight senior engineers and may take many hours or days. Reviews are expensive, but they are essential at later stages of design to ensure that as much know-how as possible is built into the design.

There are three main kinds of technical review. Value engineering reviews address costs, safety reviews, such as HAZOP, address safety and operability issues, and design reviews usually center on process robustness and technical feasibility.

If this stage of design is associated with the production of a commercial bid, there may be a tender-settling meeting before signing off the tender documents. Such a meeting touches upon cost, safety, and robustness issues, but often focuses on risk issues based in company-specific constraints and the quality of supporting documentation [1].

| **Equipment Schedule and Pricing** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| Supplier | | | | | | | | |
| | | | | | | | | |
| Client | | Prepared by | STM | | Date | Nov-03 | | |
| Site | | Checked by | | | Date | | | |
| Project | Example | Contract ref | | C2265 | C2295 | Rev | 0 | |
| Section | Skid mounted pumps | Section | X | of | Y | | | Rev |
| Compressor | | | | | | Item | P16,P17 | |
| One air compressor, pressurised air storage reservoir and associated controls and ancellaries to provide air for oil water separator (if required) continuous sand filter {if required}, DAF unit {if required}, air actuated valves, and instruments. Current duty is estimated from preliminary calculations, Suppliers should satisfy themselves that the duty specified is correct and make any adjustments as necessary to the sizing. Supply should be for complete, free standing unit. Dryer to be provided if supplier considers this to be beneficial. System will be located inside control building | | | | | | | | |
| | | | | | | | | |
| Any infromation not requested which the supplier believes will add to his offer to be provided on separate sheets | | | | | | | | |
| Performance parameter | Description | Pipework | Valves | Option1 | Option2 | Option3 | Option4 | |
| | | | | | | | | |
| Min flow {Nm3/hr) | | | | 30 | 10 | 10 | 10 | |
| Max flow {Nm3/hr) | | | | 90 | 20 | 25 | 35 | |
| Pressure (bar) | | | | 8 | 8 | 8 | 8 | |
| | | | | | | | | |
| Compressor | | | | | | | | |
| Manufacturer | | | | | | | | |
| Model | | | | | | | | |
| Type | | | | | | | | |
| Materials of construction | | | | | | | | |
| Noise levels (dBA) | | | | | | | | |
| | | | | | | | | |
| Length (mm) | | | | | | | | |
| Width (mm) | | | | | | | | |
| Height (mm) | | | | | | | | |
| Weight (kg) | | | | | | | | |
| | | | | | | | | |
| Inlet connection (mm dia) | | | | | | | | |
| Outlet connection (mm dia) | | | | | | | | |
| Motor type | | | | | | | | |
| Enclosure class (IEC 34-5) | | | | | | | | |
| Insulation Class (IEC 85) | | | | | | | | |
| Motor Speed {rpm) | | | | | | | | |
| Rated power {kW} | | | | | | | | |
| Efficiency at design duty (%) | | | | | | | | |
| Mains frequency {Hz} | 50 | | | | | | | |
| Rated voltage | 415 | | | | | | | |
| Rated current {amp) | | | | | | | | |
| Strating (Star delta/DoL) | | | | | | | | |
| Strating current (amp) | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| Price for comlete system, delivered Manchester | | | | | | | | |
| Delivery period for complete, tested system (weeks) | | Target < 10 weeks | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| Enter here any additional notes, details of additional equipment or facilities required | | | | | | | | |

**Figure 3.** Example of an equipment datasheet

## 4.13. Site Selection [7]

It may be that the site is fixed by the operating company at the very start of the design process, but there is often a process of evaluation of possible sites for grassroots designs at a later stage. In considering possible sites, account must be taken of layout factors, such as:

- Desired layout of the proposed complex
- Cost, size, shape, and contours of the land available
- Degree of leveling and filling needed to meet process requirements
- Load-bearing qualities and acidity of the soil

- Water table, flooding history, and natural drainage patterns of the site and surroundings
- Direction and maximum velocity of prevailing winds and aspect
- Seismic activity
- Existence of old mineshafts and workings, culverts, pipelines, or old chemical dumps
- Ease of obtaining planning permission
- Nature of adjacent land and activities
- Any future developments being considered by other bodies adjacent to the proposed site that could have beneficial or harmful interactions.

However, some important criteria for site selection are independent of the layout within the site boundary. These reflect, instead, the relationship of the site to its surroundings. Some key examples of such criteria include the proximity of the site to raw material supplies and product markets and the available means of transport to and from of the site.

An optimum combination of distance, difficulty, or reliability of transport should be sought, bearing in mind any legal requirements for transport of materials, particularly hazardous or flammable ones.

The availability of suitably-skilled local labor and the existence of local subcontractors should be considered. In addition, the nature of the local community and the quality of local infrastructure (e.g., schools, housing, etc.) may influence the willingness of key staff to move to the new site.

Attitudes of local authorities and pressure groups can affect the responses of both the local community and society to the new site. The most immediately measurable negative impacts of the site are probably its consumption of public utilities and its generation of process and sanitary waste, odor, and noise nuisance. Local services must be checked for their capacity to cope with the new demand and for their standards of quality and tolerance. Fears of major plant accidents impinging on the community may also arise. In addition, if the site development requires a large temporary influx of construction workers, their impact on a community can be considerable. Other nuisance effects of construction, such as noise and dust should be minimized.

Consideration must be given to any adjacent fire hazards, such as buildings, factories, plants, tips, and vegetation. Adequacy of local or regional firefighting and other emergency services must be checked against foreseeable major accidents.

Government incentives for investment and employment in certain areas, assistance with buildings and developments of the social infrastructure, such as roads, airports, and railways may be available. Their value is directly calculable, but their tangible benefits to site investment prospects must not be allowed to override less tangible negative considerations. The AIChE or IChemE sustainability metrics (see Section 8.3) [16] may be of use in such situations.

It is crucial to enter into consultation with planning and other local authorities as well as any other key stakeholders as early as possible, possibly with the assistance of professional consultants with expert knowledge of the local legal, safety, environmental, and social practices. Such discussions should not only establish which effects the site may have on the locality but also should reveal if the planning authorities have any other plans or proposals that may affect or even inhibit future expansion.

## 5. Design for Construction

### 5.1. Introduction

Design for construction is always completed within the organization constructing the plant. This stage is controlled by the EPC company's project managers, as it is an integral part of the construction activity.

This final stage of design is the least forgiving and usually starts late from the point of view of the critical path, due to the delays which have almost always accrued in earlier stages. It therefore often takes place concurrently with purchasing and construction activities.

Design for construction involves applying the organization's knowledge of what works and what does not. Small design changes, based on experience, can have a large impact on the robustness of a process. The management of the internal handover to the construction teams thus has to be well handled to limit modifications to the design to those absolutely necessary. Those responsible for construction have different priorities from those in design and proposals departments, and their mutual information transfer may often be poor, so this issue may require active management.

The design for construction stage produces new documentation, which allows site construction teams without process design skills to build the designed process plant.

### 5.2. The Design Envelope

The design envelope should have been completely and accurately set by the end of the detailed design stage and no rethink should be required or permissible at design for construction stage other than in extremis.

The documentation of the design envelope, design philosophies, etc., should make it clear that this is the case. This is not the time for the design to be re-engineered to suit the preferences of the construction team, unless their very detailed design shows that the design envelope which formed the basis of earlier stages contains a fundamental error.

The use of quality assurance, document, and change control procedures become extremely important at this stage to ensure that this is the case.

### 5.3. Risk and Safety Analysis

The design is often subjected to HAZOP at this stage, which can cause programming problems, since HAZOP brings together a number of key people who often operate under time pressure for an extended period.

Because HAZOP is not a design review, and the design should have been well reviewed and fixed by this stage, design and procurement can proceed alongside the HAZOP process. HAZOP should ideally show that there are no problems with the design of any significance. It should, therefore, be a due diligence exercise at this stage, rather than an opportunity to modify the design.

### 5.4. System-Level Design

The emphasis of design for construction is on a very detailed design, often at a level below unit operation level design rather than on whole system design.

There is also more time pressure than in previous stages of design, and even though the very detailed design could be entered into a simulation program and optimized, there is rarely time to do so.

However, 3D walk-through models of the plant layout might be used to evaluate operability. In this instance, staff operates the plant on a virtual basis, identifying any small design details, which can be addressed to maximize safety and ease of correct operation.

### 5.5. Process Control

The process control software has probably been compiled during the detailed design stage, and there is, at the very least, a detailed questioning of the FDS, as software engineers produce their own detailed description of exactly how the software needs to work.

There are hardware implications to this process, as the software engineer establishes exactly how many inputs and outputs to the PLC there need to be to accommodate the envisaged control actions.

If previous stages of design were insufficiently rigorous, new input and output modules are required on the PLC, or the PLC needs to be upgraded to a more sophisticated model. However, with good software or control and instrumentation engineers, design for construction may yield savings over what was envisaged at the detailed design stage.

### 5.6. Unit Operation Level Design

The exact items of equipment to be used are selected and the design revised, if required, to reflect this. However, this is not just a matter of placing a different item of equipment on the GA drawing.

Design for construction involves the detailed design of items, such as pipe supports and hangers, the production of isometric drawings of pipework for fabricators, and the completion of associated stress analyses. Thus, moving items at this stage involves significant additional work.

The delivery time needs also to be considered. The design is often progressed in a direction and to the point where long-delivery items, such as large gas compressors, can be ordered preferentially.

It is an essential part of process plant design that the specification of every part depends to some extent on the specification of other parts. Fixing the part of the design surrounding these long delivery items with a design freeze is therefore done as late as possible, since reversing an unwise design freeze, or revising the specification of equipment already on order, costs time and money.

## 5.7. Hydraulic Design

There should be very little change to the layout at design for construction stage, so any hydraulic design activity should mostly be a checking operation.

However, occasionally a particularly complex element of hydraulic design requiring an expensive computational flow dynamics (CFD) study (→ Computational Fluid Dynamics) by a third party expert consultant is left until this final stage.

## 5.8. Plant Layout

In many industries the very detailed layout required at this stage is undertaken by specialist piping engineers with loose oversight by process designers.

It is relatively common for such engineers, or, in some industries, specialized process architects, to use 3D modeling software and building information modeling (BIM) systems.

## 5.9. Economic Analysis

Discussions with suppliers at this stage are largely final negotiations on price, delivery, and specification with a view to purchase rather than a pricing exercise. Purchasing may well be integrated with design at this stage, and long lead-time items may be purchased while final design continues.

## 5.10. Project Programming

The programs produced at this stage are more project management tools than design aids. The project manager is therefore far more likely to be driving their production than any design leader.

Specific resources are allocated to each task, and tasks are split into sub-tasks, knowing which staff members are available, and how much of their time is allocated to the project, as well as an accurate start and finish date, equipment delivery, and installation timetables, etc.

## 5.11. Deliverables

There are large quantities of deliverables at this stage, and the version of the design approved for construction has to be right. Good document change control and QA therefore becomes essential:

- Each deliverable item (drawing, schedule etc.) depends upon others. If an instrument on a P+ID is changed, this requires the modification of instrument schedules, the PLC I/O schedule, FDS, etc., to suit.
- In the past, the drawings were stored in a drawing chest to which access was controlled. Now that drawings are kept in electronic format, new techniques have been developed to ensure that everyone is working from the same, current, set of drawings and other deliverables.
- At this stage of design, QA and change control systems usually mandate that any changes to drawings are sanctioned via the signature of one or more key staff. Deliverables are marked with a revision number and cross-referenced to the revision number of other deliverables upon which they rely to avoid confusion.

### 5.12. Design Reviews

At design for construction stage, the design is reviewed by those who have to build and commission it. In a company with experienced designers and good internal communications, the design is not subject to significant changes.

It is, however, commonplace for the addition of a range of small items, which would facilitate construction and commissioning, to be proposed at the stage. Good change control procedures are required to limit their inclusion to the absolute minimum necessary after giving due consideration to the wishes of the installation and commissioning teams.

### 5.13. Site Selection

The site has been selected by this stage, but there is ongoing liaison with planning and other authorities which can affect the details of site selection.

## 6. Site Level Redesign

Even with well-controlled design processes, there can be a lack of feedback from construction and commissioning staff to design teams about some aspects of design important to installation and commission stages.

Frequently some residual errors in the design have to be corrected by redesign. Examples of such minor errors and/or omissions include missing valves, instruments, sample points, and connections for temporary services.

## 7. Post-Handover Redesign and Optimization

Once a plant is in full operation, it is commonplace for a plant operator to wish to reduce its production costs per unit of product to increase profits. This may entail a partial redesign of the plant to optimize production efficiency.

The design of modifications to an existing plant is very different to grassroots design of a complete new plant because there is a substantial body of information on plant operation and performance that can be taken into consideration. There is consequently far less uncertainty; furthermore, the data can be used in conjunction with modeling and simulation programs to create an accurate model of the plant. This validated model can then be used to carry out virtual trials of proposed modifications to the plant.

The use of modeling and simulation programs in support of design becomes very important in this application. This is the stage at which such tools can be used realistically to optimize operations, such as heat exchanger networks and, to a lesser extent, utility usage.

## 8. Health, Safety, Environmental and Sustainability Issues in Design

### 8.1. General

Although this section deals with health, safety, environmental, and sustainability issues, these issues are not separate from design. Consideration of these issues should be embedded in design from the earliest stages, as described in previous sections, and any abatement processes should be designed alongside the main process.

### 8.2. Pollution Control

The best way to control waste would be not to generate any in the main process. However, it is not possible to have a zero-waste process. Preventing the waste products from becoming avoidable pollution is, thus, a matter of containing them, removing them from emissions to air, water, or land, and converting the retained pollution into harmless substances.

#### 8.2.1. Air Pollution Control

In addition to limits on the release to atmosphere of poisonous and obnoxious gases, most countries have strict controls on the release of acid gases, such as sulfur oxides ($SO_x$) and nitrogen oxides ($NO_x$) to prevent acid rain. Most also restrict greenhouse gases, such as $CO_2$, and volatile organic compounds (VOCs).

$SO_x$, $NO_x$, and $CO_2$ are scrubbed out by water or alkali. VOCs are removed by scrubbing with an aqueous oxidizing agent, by adsorption, or by removal with catalytic oxidation (→ Air, 7. Waste Gases, Separation and Purification).

### 8.2.2. Water Pollution Control

Large quantities of water are used in process plants in various grades as a solvent, heat transfer medium, etc. Water may also be produced as a reaction product. It is also used by the staff in sanitary and food applications, and any rainwater falling on the site needs to be managed and often treated prior to discharge.

Industrial effluent treatment has a number of key design problems.

***Batching.*** Many processes, especially in the pharmaceutical and fine chemical sectors, utilize a batch production process. Effluents are therefore also produced batchwise. This can be overcome by either providing a large in-line buffer capacity prior to the treatment plant or by treating the wastes on a batch-by-batch basis as they are produced.

***Toxic Shocks.*** There may be wide variations, such as production of certain substances, processes that are carried out infrequently, or emergency situations, which might lead to the occasional release of high concentrations of toxic materials to the effluent treatment plant. Such situations may be handled in different ways. The operation can be designed with (online or off-line) buffering capacity; the process selected can be designed to handle the full loading; or alternative arrangements can be made for dealing with the toxic shock.

***Nutrient Balance.*** Although industrial effluents may have very high BOD (biological oxygen demand) levels, nutrients may be limited. Appropriate levels of N, P, S, etc., are needed for biological processes to work. Various proprietary formulations are available, but it is questionable whether the majority of them offer significant advantages over commercially available agricultural fertilizers.

***Sludge Consistency.*** Industrial process plants frequently experience problems with obtaining consistent sludges. There may be a greater proportion of chemical sludges, and there may be a greater number of different sludge types. There is almost certainly less sludge inventory to smooth out any inconsistencies. As a result, it may be necessary to design consolidation and thickening facilities to even out or otherwise cope with greater inconsistency.

***Changes in Main Process.*** Not only may the main process or processes be highly variable, but the processes carried out might also occur on a seasonal or campaign basis. The effluent produced may thus vary widely in composition and strength throughout the year. Such changes may be on a timescale too long to handle by buffering capacity. In such cases, it is therefore advisable to consider operation of the effluent treatment plant as part of the preparations for changes to be made. In the case of campaign manufacture, where there may be unique events and contaminants, pilot trials may be advisable.

### 8.2.3. Ground Pollution Control

Ground pollution is often of lesser concern than the groundwater pollution that it can cause. Liquid wastes or liquids leached from solid wastes by rain or groundwater can be transferred a long way from the site and enter drinking water supplies with adverse effects on human health.

The disposal of solid wastes by burial is therefore highly regulated in most countries, and the disposal of wastes containing free liquids by burial is banned in the European Union, United States, and many other countries.

Control measures (other than prohibiting the on-site burial of waste, and permitting its disposal only via suitable carriers to licensed disposal facilities) therefore consist of keeping potential pollutants away from the ground by keeping liquid storage tanks on impermeable standing and within secondary bunds.

In some cases, liquid and solid wastes are disposed of on-site by incineration, but this is a highly regulated (and publicly unpopular) process in most countries. Incineration therefore tends only to be a worthwhile option if the site is located far from human habitation, or if the volumes of waste are very significant.

### 8.2.4. Noise and Odor Nuisance Control (→ Noise and Vibration)

Nuisance differs from the preceding categories of pollution because it is subjective. Different people have different tolerances, certain types of noise and odor can be far more annoying to people than other equally loud noises and emotional factors all come into play.

Noise pollution can be controlled by specifying low-noise equipment, by fitting noise abatement measures to equipment, or by locating noisy equipment as far as possible from the potential complaints. In addition, night-time noise levels should be considered, because a noise level acceptable against a high background level may not be acceptable against a lower night-time baseline.

Odor nuisance, even when it is entirely harmless, can cause great perceived nuisance even at very low concentrations. Odors can be treated like VOCs, which they mostly comprise, by scrubbing, catalytic, or biological oxidation.

## 8.3. Sustainability in Chemical Plant Design

Sustainability is a highly contested term, the meaning of which can be subject to political influence. To a plant designer, however, sustainability issues entails consideration of the environmental indicators outlined in the UK IChemE's sustainability metrics [16], which are divided into three main areas:

1. Resource usage (energy, material, water, land)
   - Percentage of total net primary energy sourced from renewables
   - Total net primary energy usage per kilogram product
   - Total net primary energy usage per unit value added
   - Total raw materials used per kilogram product
   - Total raw materials used per unit value added
   - Fraction of raw materials recycled within company
   - Fraction of raw materials recycled from consumers
   - Hazardous raw material per kilogram product
   - Net water consumed per unit mass of product
   - Net water consumed per unit value added
   - Total land occupied and affected for value added
   - Rate of land restoration (restored per year/total)
2. Emissions, effluents, and waste (impact on atmosphere, water, and land)
   - Atmospheric acidification burden per unit value added
   - Global warming burden per unit value added
   - Human health burden per unit value added
   - Ozone depletion burden per unit value added
   - Photochemical ozone burden per unit value added
   - Aquatic acidification per unit value added
   - Aquatic oxygen demand per unit value added
   - Ecotoxicity to aquatic life per unit value added
   - Eutrophication per unit value added
   - Hazardous solid waste per unit value added
   - Nonhazardous solid waste per unit value added
3. Additional environmental items
   - Duty of care with respect to products and services produced. Environmental impact and mitigating steps taken, including issues concerning long-term environmental or health problems arising from process or product, for which the solution is not yet known.
   - Issues concerning environmental impact of plant construction and decommissioning.
   - Compliance: Magnitude and nature of penalties for noncompliance with any local, national, or international environmental regulations or agreements.
   - Impacts on protected areas (sites of special scientific interest, proposed special areas of conservation, national parks). Impacts on local biodiversity or important habitats.
   - Issues concerning long-term supply of raw materials from nonrenewable resources.
   - Other possible relevant metrics

# 9. Mechanical Engineering Aspects of Chemical Plant Design

## 9.1. General

The selection of the basic subcomponents of process plants is an essential part of what plant designers do. Certain types of materials, for example, are more suited to a given range of pressures, temperatures, chemical, and physical compositions than others.

Matching the ranges of these parameters in the plant design envelope to suitable materials is usually considered to be the responsibility of the process plant designer. Similarly, so is the selection of pumps, heat exchangers, instrumentation, valves, etc.

At conceptual design stage it is often important to know, at a category level, what kinds of components are likely to be used. For example, process plant designers usually know whether to use rotodynamic or positive displacement pumps; membranes or distillation; globe or butterfly valves; carbon steel or plastic, etc., by the time their initial drawings are complete. All of these decisions affect the fundamental characteristics of the design and have implications for cost, safety, and robustness.

At the detailed design stage, selection is at the level of particular specific commercially-available items of equipment. Datasheets are produced setting out the detailed specification of the item and taking account of the selected materials of construction. Manufacturers may, on sight of these datasheets, provide feedback that may lead to refinement or reconsideration of the selection.

Design for construction generates significantly more detailed documentation, and experienced engineers are likely to review the design choices before they are finalized. This may lead to a requirement to modify selections, based on their experience of what may or may not work.

## 9.2. Materials Selection

Plant designers need to know which materials are suitable for the plant's intended duty, as well as the duties to which the plant might (intentionally or unintentionally) be put.

This is not determined so much by material science as by practical experience, together with a broad qualitative knowledge of available materials and their strengths and limitations.

There are also traditional default positions in various process sectors. For example, the generic pipe material in the oil and gas industry is carbon steel, whereas plastics are specified within the water industry; highly corrosive water is transported in carbon steel piping in the oil and gas industry.

Although this may seem unusual to a water specialist, this selection is not wrong, per se, as long as suitable corrosion allowances are made, and the consequent increased metal ion content of the water is acceptable from a process point of view.

## 9.3. Mechanical Design

Process designers probably only address the materials selection aspect of the mechanical design of process plants. Piping engineers, mechanical engineers, mechanical installers, and equipment suppliers carry out the mechanical design of process plant and interconnections.

The items requiring design and those usually responsible for designing them are shown in Table 2.

**Table 2**. Responsibilities of mechanical design

| Item | Responsibility |
|---|---|
| Pressure vessels | Suppliers of pressure equipment |
| Steel and plastic open-topped tanks | Suppliers of tanks |
| Above-ground pipework, pipework supports, thrust blocks, and bracketry | Piping engineers, mechanical installers |
| Below-ground pipework and thrust blocks, wall penetrations | Civil and structural engineers |

## 10. Civil Engineering Aspects of Chemical Plant Design

Civil engineering design is frequently the work of specialist civil and structural engineering design companies and consultants. Such companies design the reinforced concrete slabs on which process plants sit as well as water retaining concrete tanks, buildings, etc.

Civil engineers may also have environmental engineering skills allowing them to design water and pollution abatement equipment, although such design falls increasingly into the main plant design.

The key aspects of civil design are the selection of type and thickness of concrete and sizing of required reinforcing steel to construct slabs and tanks. The determination of these selections is dependent on:

- The ability of the ground at the proposed location to resist applied forces
- The weight of the items of the process plant
- Whether their weight is constant or variable
- The type of process fluid or water that the concrete is in contact with
- The height of the water table at the site

As these factors vary not only between possible sites but also across sites, an optimal design must take into consideration the civil engineering implications of placement of process equipment.

## 11. Plant Layout [7]

Plant layout considers the spatial arrangement of items, such as process vessels and equipment, together with their connection by pipes, ducts, conveyors, or vehicles. When developing a layout, engineers have to satisfy several criteria in their designs:

- Efficient, reliable, and safe plant operations
- Safe and convenient maintenance of process equipment by removal or in situ repair
- Acceptable levels of hazard and nuisance to the public
- Safe and efficient construction
- Effective and economical use of space

On a new or greenfield plant, the site layout needs to reflect the known needs of the process plant to be constructed. Alternatively, a plant may have to be laid out on an existing site where the requirements of a future plant may not have been foreseen at the time of the original site layout. In this second case, at least some of the access arrangements that would normally be provided on a new site have to be provided by the plant layout engineers.

There are three main elements to layout:

1. Site layout: Consideration of plots in relation to each other within the site and to activities outside the site
2. Plot layout: Consideration of process units in relation to each other within a plot
3. Equipment layout: Consideration of accessories around a process unit

A complete set of process units (i.e., a plant) fits onto a plot, although bigger plants may need two or more plots.

The initial layout is usually based upon the PFD sequence, with process units arranged in the order of processing. Physically adjacent vessels and equipment are separated by distances that are sufficient to permit access for satisfactory operation and maintenance without wasting space.

The layout of some plants may follow the process flow sequence closely through to the final stages, but in practice there are several common features that require the layout sequence to differ from this default sequence. These include:

- Process requirements
- Economics
- Ease of operation, maintenance, construction, and commissioning
- Ease of future expansion and extension
- Ease of escape and firefighting
- Operator safety
- Hazard containment
- Environmental impact

**Table 3**. AACE classes of cost estimate

| Estimate class | Name | Purpose | Project definition level, % |
|---|---|---|---|
| Class 5 | order of magnitude | screening or feasibility | 0–2 |
| Class 4 | intermediate | concept study or feasibility | 1–15 |
| Class 3 | preliminary | budget, authorization, or control | 10–40 |
| Class 2 | substantive | control or bid/tender | 30–70 |
| Class 1 | definitive | check estimate or bid/tender | 50–100 |

Any change to the initial layout as a result of these considerations may result in extra pipework or transportation costs and additional site or building areas. The changes must therefore be economically justifiable. Repeated checks should be made to ensure that layout changes do not adversely affect another requirement.

A detailed knowledge of the characteristics of process materials is needed to determine the requirements of hazard containment. This evaluation must therefore be carried out by experienced process engineers. In particular, they must be able to identify and use appropriate statutory and in-house regulations, design standards and codes of practice; appreciate the needs of operation, maintenance and construction; and apply engineering experience and common sense.

Alternatively, this work may be carried out by designers and piping engineers supervised by engineers experienced in plant layout. Exactly how this is done varies from sector to sector.

Arriving at an optimal layout thus involves close cooperation between the process and layout engineers. It also requires good cooperation between all the technical and engineering disciplines to incorporate all relevant factors correctly in the layout design.

## 12. Costing [17, 18]

### 12.1. General

Engineering is a commercial activity. Engineers consider the cost, safety, and robustness implications of every choice at every stage of a project to allow rational decision making whether to proceed to the next stage.

At the conceptual design stage, it is possible to get a budget estimate of costs. A budget estimate from a contractor is probably accurate to $\pm 30\%$ and is based on a body of data from equipment suppliers as well as key experience on the true costs of plant construction.

Professionals working in contracting companies complete a very detailed design and price all the goods and services required to supply it, taking into consideration risks, margins, contingency, etc.

Engineers have quantified this process into five classes of estimates (Table 3). These are used by public bodies in the United States and worldwide [19].

The degree of confidence in the performance of the technical design thus reflects the maximum degree of confidence which may be placed in a costing. In addition, to develop a robust pricing, consideration needs to be given to a number of risk factors:

- Process risks: The more novel the process, the greater the chance it underperforms or fails to perform. If the plant fails its performance test, the construction company incurs daily penalties until the issues are rectified. It is possible to purchase performance bonds, which insure process risks, the cost of which are directly related to the novelty of the design.
- Financial risks: Contracts may be subject to fluctuations in foreign exchange, market volatility (particularly in the cost of raw materials), and changes in inflation and taxation.
- Political risks: Political relations between nations can affect the price and import of raw materials, industries may be privatized or nationalized without compensation and changes in regulations, particularly in the environmental field, may lead to certain design options becoming illegal or prohibitively expensive.

Sensitivity analysis is the key to understanding these risks and deciding how to account for them in pricing, but a competitive tender is unlikely to succeed if all risks are considered to have 100% probability of occurrence.

As a rough guide, a reasonable method of pricing risk would be the probability of occurrence, multiplied by the consequential cost of occurrence. However, some commercial players may be willing to undercut this considerably to gain competitive advantage.

At the detailed design stage all of the risk factors are considered, and a price accurate to a few percent is produced. This price needs to be based upon a design, which is optimized to meet the client evaluation criteria, whether that is the lowest price that meets the specification, lowest whole-life cost, best net present value, or fastest payback period, each of which affects every aspect of competitive design.

### 12.2. Price Indices

A number of price indices are produced commercially to allow sector specific inflation and cost escalation to be accounted for in cost estimation.

In all cases, there is a baseline date at which costs are set at 100%, and cost indices at specific dates, which are multiples of 100%. To apply cost escalation to a historical quotation, the quotation value is multiplied by the ratio of the cost index at the date of the quotation and the current cost index.

The best known and most widely used process plant specific index in the field of chemical plant design is the chemical engineering plant cost index (CEPCI) [20].

### 12.3. Electronic Data Processing Approaches

Modeling and simulation programs may offer integrated costing facilities though these may represent, at best, no more than very coarse budgetary estimates. There are also commercially available spreadsheet based approaches.

However, these programs have two disadvantages for the engineering practitioner. Firstly, there is a necessary limit to the realism of the programs. They are reliant on curve fitting algorithms, but equipment prices are not a continuous variable. Such prices proceed stepwise from model to model, and it is usual to specify the next size model up. There are also maximum and minimum commercially-available unit sizes, affecting the decision on the appropriate quantity of units.

Secondly, there is an issue of the authority of a price estimate generated by software. A firm fixed price quotation is offered with a legally enforceable guarantee that the equipment is available at the quoted price. Computer software vendors may offer no such guarantee.

### 12.4. Availability Analysis

In deciding the required quantity of each unit operation, some kind of availability analysis is necessary to determine the probability if any given unit operation is available when required.

In an operational environment, sophisticated tools, such as fault tree analysis and reliability block diagrams are used alongside process simulation software to arrive at very certain estimates of availability.

In the costing stage, only the required standby, assist, and duty units need to be determined. It is common to ensure a higher availability for equipment on the main process stream than for less process-critical side-streams.

### 12.5. Accountancy

A number of accountancy techniques are particularly useful in the economic appraisal of plant design because of the long-term nature of such projects: a new process plant requires significant investment in the present but cash inflows generated by the project will not arrive until well into the future. Two key techniques for the appraisal of such projects are payback period and discounted cash flow analyses [21].

***Payback period*** works by comparing the known initial costs of a project with its estimated future cash flows (or savings). The length of time it takes for the cash flows (or savings) to cover the initial expenditure is the payback period. For example, a project with an initial cost of $10 000 000, which generates cash flows of $2 000 000 in year one and every year thereafter would have a payback period of five years.

Payback period has the advantage of simplicity, and it is widely used in project appraisal. It is readily understood by management, who may set internal payback time limits. However, payback period analysis relies heavily on assumptions and overlooks the often critical issue of when exactly cash flows are received within the payback period time limit. It also fails to take the inflation of money into account.

***Discounted Cash Flows.*** Discounted cash flow techniques are more sophisticated than simple payback period analysis, because they account for the inflation of money, allowing future cash flows to be compared with present-day monetary values on a like-for-like basis.

Discounted cash flows work on the basis that it is preferable to receive a sum of money today rather than an equal sum in the future; this is due to three reasons. Firstly, there is a risk that the future sum will not materialize; secondly, receiving the money now creates an investment opportunity (and will thus become a greater sum in a year's time), and thirdly, due to inflation, the original sum may be worth less in real terms in a year's time.

They are calculated by taking the projected cash flows for a project and applying a discount factor to each. The sum of the resulting discounted cash flows can then be compared to the total costs of the project, giving the net present value of a project. If the net present value is positive, then the project is financially viable because, the inflows of cash will exceed the outflows.

## 13. Simulation and Modeling

Modeling and simulation programs allow an approximate computer model of a process plant to be assembled and operated on a virtual basis.

The realism of this virtual plant depends on three factors:

- The skill and experience of the person setting up the model
- Whether the model has been programmed properly (validation)
- Whether the model matches the real world plant it is intended to simulate (verification)

Modern simulation and modeling programs are very powerful, but there is a high potential for misuse by all but the most skilled users. The dividing line between use and misuse of simulation and modeling programs tends to reflect whether the IChemE computer aided process engineering (CAPE) guidelines [22] are followed, and particularly whether model verification and validation have been undertaken.

In situations where a body of applicable data on the exact plant to be designed already exists, and many similar plants are to be designed, it may be worthwhile to invest resources in creating a verified model of the proposed plant, together with models of the unit operations. Plant design then becomes a question of linking these blocks into an integrated model, and optimization of the model can serve as a valid proxy for optimizing the plant.

If, however, a single one-off plant is designed, there is usually insufficient data available on the plant to produce anything but an unverified model using generic data. The considerable margin of error would thus render such a model worthless.

In general, plant operators are the staff most likely to hold the information necessary to verify and tune modeling software. The contracting companies, who design the majority of process plants, do not have this information, and consequently make less use of modeling. Therefore, the most commonly-used modeling software is employed in the oil and gas industry, because these companies are best placed to invest the data, time, and effort needed to verify the accuracy of modeling software.

## 14. Design Optimization, Synthesis, Intensification, and Similar Techniques

### 14.1. General

The majority of real-world plant optimization takes place after plant construction, during exercises, such as debottlenecking. These exercises are aspects of plant operation rather than plant design.

The availability of detailed information on plant and unit operation performance collected from the real plant makes it possible to develop a plant-specific verified, validated process model. The effect of various modifications and improvements can thus be assessed in advance using this model. The effects of modifications suggested by applying various optimization techniques, such as pinch analysis [23, 24], may then be applied to the model, and assessed for cost-effectiveness, robustness and safety.

***Pinch Analysis (→ Pinch Technology)*** Originally developed to allow optimization of heat exchanger networks in the 1970s, pinch analysis, network analysis, or process integration is used widely in academia but far less in professional engineering practice.

Pinch analysis techniques have been expanded to allow the possibility of recovery of water and hydrogen, but these techniques have three major flaws in all applications: They are very time consuming; they do optimize the issues that are most relevant to engineers, and they require too much information input to be of use during the design stage.

However, process synthesis or integration (making the parts of the plant work together as a unified whole) occurs automatically as part of process plant design. It is in fact the essence of process design.

Process intensification (→ Process Intensification, 4. Plant Level), in the sense of making equipment as small as is practical and sometimes combining unit operations is also a feature of standard process design approaches.

In academia these terms are used to describe the approaches of academic researchers and modelers, enumerated by, e.g., the NTNU (Norwegian University of Science and Technology) which are applied to versions of process design problems lacking the uncertainty and lack of definition which make their real world counterparts genuinely problematic.

Such approaches do not properly consider the cost, safety, and robustness implications of design choices (improper trade-off handling) and are consequently of very limited relevance to engineering practitioners.

# 15. Project Management during Plant Construction

## 15.1. Project Team

Once the operating company has accepted the offer by the EPC company to build the designed plant, the project is handed over to a new team within the EPC company, responsible for plant construction, commissioning, and handover to the client.

The focus of the project now changes from design to management of resources. There are a number of engineering disciplines within the EPC company's project team as well as interfaces with civil and electrical engineering companies and possibly design houses and various specialist consultants.

## 15.2. Project Manager

There is usually an overall project manager, with project engineers working under them. Generally, project management positions are occupied by graduate engineers, though their skills are usually deployed in people and process management rather than design or technical issues.

The project manager has the key responsibility for managing a complex range of resources to ensure that the overall objectives of the project are met. These are usually expressed in three main criteria:

- Time: The project must be delivered within a specified timeframe, with key interim deadlines (milestones) to meet contractual requirements
- Cost: The project must be delivered within budget if it is to be a profitable activity for the EPC
- Specification: The finished project must meet its contractual performance specifications

Therefore, the project managers have responsibility for management and deployment of staff, equipment, and raw materials as well as any other resources. They also need to manage and control the risks associated with project delivery, monitor and report on progress, and control change as the project moves through its delivery milestones. In addition, a good project manager needs to be able to see beyond the project itself and has a sound commercial awareness, including an appreciation of the project's impact on the business of the EPC company as a whole.

The project managers have various tools and techniques at their disposal including specialist software for managing each resource and reporting. In addition, many project managers now have professional qualifications in the field.

### 15.3. Technical Support

Project management engineers are usually provided with technical support either by in-house or bought-in process and electrical engineers as well as software, civil, and mechanical engineers.

Bought-in staff resources may come from external design houses, or more commonly, they may be freelance individuals, allowing companies to staff up rapidly to meet demands.

### 15.4. Project Progression

A plant construction project normally progresses through the activities as shown in Table 4.

The chronological order given in Table 4 is only approximate because, by the time an order is awarded to construct a plant, less time is available than originally envisaged. Some degree of project acceleration, achieved by running activities concurrently, is therefore the norm. Similarly, the office-based activities always take longer than envisaged, so commissioning is performed under great time pressure. Commissioning engineers often commence work on site having already missed key deadlines.

This time pressure is responsible for a very different style of management in commissioning teams. Commissioning teams, led by a project commissioning engineer, have a very high degree of aim orientation. Commissioning is a short, intensive high-pressure campaign usually undertaken by a team assembled solely for the purposes of the particular project.

**Table 4**. Summary of construction project activities

| Location | Activity |
|---|---|
| **Office based: Project team** | Finalization of design |
| | Obtaining planning and other permissions |
| | Procurement of equipment |
| | Project programming and subsequent tracking |
| | Appointment of mechanical, electrical, civil and software subcontractors |
| **Site based: Project team** | Establishment of site compound |
| | Site preparatory civil works |
| | Mechanical and electrical installation |
| | Mechanical and electrical completion |
| | Snagging |
| **Site based: Commissioning team** | Mechanical and electrical commissioning |
| | Process commissioning |
| | Snagging |
| | Performance trials |
| | Production of operating and maintenance manuals |
| | Operator training |
| | Plant acceptance |
| | Plant handover |

## 16. Legal Issues

Process plant construction is usually controlled by a formal contract between vendor and purchaser. Even if it is not, there is an implied contract, whose terms are far more expensive to establish if a problem arises.

As well as the provisions of commercial contracts, plants have to be built in accordance with the laws of the jurisdiction in which they are built and in compliance with national and international codes and standards, which may or may not be specifically referenced in contract documentation.

### 16.1. Regulatory Framework

National regulatory frameworks vary from country to country, but the requirements of international trade and other considerations tend to result in some convergence of regulation, especially with respect to health, safety, and environmental requirements.

One notable exception is the application of the precautionary principle. Originally only applied to Health Safety and Environmental (HSE) legislation, it has become a general guiding principle of lawmaking in the European Union [25]. However, the United States do not accept the precautionary principle, and consequently there is a greater disparity between some aspects of HSE law and regulation in the United States and European Union than in other areas.

There are also differences in the degree of prescription. The United States tend to require strict compliance with design codes, whereas the European Union tends to offer guidance and place the onus on the designer to ensure a safe plant has been designed.

## 16.2. Contract Writing and Forms of Contracts

A number of bodies have produced standard terms or model forms of contract commonly used in process plant construction.

The IChemE produces standard terms for three types of process plant construction contract [26]:

- In a *lump sum contract*, the contractor contracts to achieve compliance with the design and performance specifications and deliver the finished plant on time. In return, the contractor receives a firm fixed price.

  In this scenario any unforeseen costs diminish the contractor's profits, but any cost savings are enjoyed by the contractor alone. The pricing of lump sum contracts, therefore, requires careful consideration of risk and the inclusion of an appropriate contingency allowance.
- In a *cost-reimbursable contract*, the contractor is reimbursed at agreed rates for all of the costs incurred in meeting their contractual obligations. Specific contractual provision is made for the cost of any corrective works, depending on how these arise.
- In a *target cost contract*, the contractor also works on a cost-reimbursable basis but there is contractual provision for both the purchaser and the contractor to share either any additional unforeseen costs (pain share) or any unforeseen savings (gain share).

Other contract names commonly used in the process industries are:

- *Turnkey projects*: A project which is handed over to the client in a fully complete and operational state and able to generate cash flows immediately. In the case of a process plant, a turnkey project would be one where all the client needs to do is turn the plant on.
- *Design, build and operate contracts*: In this type of contract, a contractor has full responsibility for the design and construction of a plant, and also operates it for a specified period of time before handover to the ultimate client.

  There are several variants on this type of contract, including for example build, operate, maintain; build, operate, transfer; and design, build, finance, operate. Such contracts are often used for public sector projects where the contractor has the ability to raise the significant levels of finance required, together with appropriate expertise in facilities management and construction.

All standard forms of contract contain similar elements. To take the IChemE Red Book as an exemplar:

- Description of the works
- Documentation
- Responsibilities of purchaser
- Health and safety
- Environmental protection and waste disposal
- Quality assurance and validation
- Subcontracting
- Contractor's named personnel
- Training by contractor
- Parts with limited working life and spare parts
- Times of completion
- Liquidated damages for delay
- Preinstallation tests and procedures
- Criteria for the completion of construction
- Take over procedures
- Performance tests and procedures

- Performance guarantees and damages for failure
- Valuation of variations and claims
- Contract price and payment
- Contract coordination
- Reports and records

The essence of the contract is that the parties have decided prior to commencement of works how they are going to work together, whether the project proceeds smoothly or not. They have agreed their roles and responsibilities as well as the penalties and procedures in the event of noncompliance.

Business culture varies from country to country and so does the ease of enforcing agreed contract conditions. In some countries, (e.g., India) the time and effort involved in initiating court action to enforce a contract may be so onerous that the signing of a contract may have very little practical significance. In others, the goodwill and friendship between parties may be considered more important than the precise details of the contract which has been signed.

These considerations are also important in countries where contract enforcement is relatively well-defined, since business culture may interpret strict enforcement of every aspect of the letter of the contract as sharp practice and a breach of goodwill. Contracts may thus be considered as guidance rather than prescription and if a project is proceeding well then minor breaches may well be overlooked.

The UK's IChemE has a set of color-coded terms specifically intended for use in process plant construction (Table 5).

Each of the IChemE standard forms of contract also has a corresponding international version.

With the possible exception of the Brown Book, all the forms of contract explicitly recognize that a process plant is not just a collection of equipment, but has a specifically defined purpose and a minimum required performance.

The UK Institute of Engineering and Technology (IET) produce the MF/1 model form of contract [27], which is arguably more suited to mechanical and electrical equipment without specified process performance requirements than the IChemE Forms.

The International Federation of Consulting Engineers (FIDIC) [28] produces standard terms, which are commonly used in international construction contracts but are less suited to process plant construction. They also have a color-coded selection:

- Red Book: Conditions of contract for construction for building and engineering works designed by the employer

**Table 5**. IChemE standard forms of contract

| Title | Features |
|---|---|
| Red Book for lump sum contracts | Used in a wide range of process industries<br>Used for fixed-sum contracts<br>Particularly useful for turnkey projects with significant technical elements in design and construction and where a performance specification has been set for the finished plant |
| Green Book for reimbursable contracts | Used for similar projects to the Red Book but where the contract is cost-reimbursable rather than fixed-sum |
| Burgundy Book for target cost contracts | Used for projects where a target cost is defined<br>Target costs may be defined either at the outset or at a later date once there is more clarity on the scope of works |
| Orange Book for minor works contracts | Used for modifications to existing plant<br>Less detailed than the Red, Green and Burgundy Books |
| Yellow Book for subcontracts | Used to govern mechanical electrical or process subcontract relationships in the design and construction of process plant<br>Design to work in concert with the Red, Green or Burgundy Books for main contracts |
| Brown Book subcontract for civil engineering works | Used to govern subcontract relationships for any necessary civil engineering works that precede the construction of process plant (e.g., laying slabs, access ways, etc.)<br>Design to work in concert with the Red, Green or Burgundy Books for main contracts |

- Yellow Book: Conditions of contract for plant and design-build
- Silver Book: Conditions of contract for EPC and turnkey projects
- Green Book: Conditions of short form of contract
- Blue Book: Contract for dredging and reclamation works; MDB/FIDIC contract: FIDIC conditions incorporated in the standard bidding documents of multilateral development banks
- White Book: Client and consultant model services agreement
- Gold Book: FIDIC design, build, and operate projects

## 17. Quality Assurance and Management Systems

### 17.1. Introduction

The ISO standards are the most commonly used international standards, although there are other standards in use worldwide, most notably in the United States.

The three most popular international standards covering the management and control of quality, environment, and occupational health and safety are soon to be produced to a common ISO format as follows:

- Scope
- Normative references
- Terms and definitions
- Context of the organization
- Leadership
- Planning
- Support
- Operation
- Performance evaluation
- Improvement

### 17.2. ISO 9000 Series

The ISO 9000 [29] series of international quality assurance and quality management systems are derived from a British Standard, BS5750, itself based on 1960s U.S. military standards. The 9000 series are the most popular standard of this type, with over one million subscribers worldwide.

The concept of ISO 9000 systems is to set out how a company intends to control its design or product quality, and how it intends to monitor and correct and deviations from the plan.

ISO 9000 series systems are not necessarily benchmarked against an external quality standard. They ensure consistency with a predetermined internally-set standard rather than an absolute standard.

When well written and administered, ISO 9000 systems can ensure the production of a consistently good design and product. However, they have therefore been criticized for overlooking continuous improvement considerations and for their resource-intensive nature.

The series comprises:

- ISO 9001 Model for quality assurance in design, development, production, installation, and servicing
- ISO 9002 Model for quality assurance in production, installation, and servicing
- ISO 9003 Model for quality assurance in final inspection and test

### 17.3. ISO 14000 [30]

The ISO 14000 series was developed from ISO 9000 as an environmental management system. Unlike ISO 9000, ISO 14000 defines both absolute minimum standards and a commitment to continuous improvement. The series comprises:

- ISO 14001: Environmental management systems—requirements
- ISO 14004: Environmental management systems—principles, systems and support techniques
- ISO 14006: Environmental management systems—incorporating eco-design
- ISO 14015: Environmental assessment of sites and organizations
- ISO 14020 series (14020 to 14025): Environmental labels and declarations
- ISO 14030: Post-production environmental assessment

- ISO 14031: Environmental performance evaluation
- ISO 14040 series (14040 to 14049): Life Cycle Assessment
- ISO 14046: Requirements for water footprint assessments

### 17.4. OHSAS 18001/ISO 45001 [31]

British Standard OHSAS 180001 is an internationally-applied British standard for the management of occupational health and safety. A version of OHSAS, restyled to match ISO 9000 and ISO 14000, is due to be published as ISO 45001 in October 2016.

## 18. Plant Start-up and Performance Testing

A process plant is more than a loose collection of equipment. It is a single integrated working machine, which reliably and safely produces a given quantity of a specified product.

This integrated whole is not achieved by completing mechanical and electrical installation alone. At this point, there exists only a collection of equipment fixed to a slab and interconnected with pipes and cables. This collection is not yet a single integrated working machine, and it is not safe to operate.

Thus, before the plant can be handed over there must be a phase of commissioning and performance trials, which converts the collection of equipment into a single integrated operational plant functioning in accordance with its specification.

### 18.1. Safety During Plant Start-up and Commissioning

Plant start-up is dangerous, because the safety measures which protect operators during normal operation are not in place. Risk assessments are undertaken, and detailed descriptions of how the plant is started up (known as method statements) are written to control these risks.

The plant is probably filled, initially, with a less harmful fluid than the process materials. Acids and alkalis are for example often replaced by water. The fluid is often a liquid, even if the systems are eventually filled with gas when in service. This is because a leak or rupture in a liquid-containing vessel or pipe is far less hazardous than a pressurized gas-containing one, since liquids do not have the stored energy of pressurized gases. The liquid might be water, or it might be a less-flammable hydrocarbon, such as fuel oil, depending on the nature and materials of construction of the plant.

Where gases are charged in start-up and commissioning exercises, less hazardous gases are often used initially in place of any flammable or toxic ones used when the process is running.

### 18.2. Stages of Plant Start-up and Commissioning

There are a number of discrete and consecutive stages of process plant commissioning. This area is well covered in the IChemE's Chemical and Process Plant Commissioning Handbook [32] but an outline is provided in Table 6.

## 19. Operating and Maintenance Manuals

Operating and maintenance (O & M) manuals are produced by those responsible for plant construction. O & M manuals are written for the plant as a single integrated machine rather than as if it was a collection of independent equipment.

Thus, they usually contain detailed explanations of what the objectives of the plant are, the limits on its performance, how the automatic controls systems work, and how operators should operate maintain and troubleshoot the plant as a whole.

A generic O & M manual has usually the following sections in the approximate order given:

- Introduction
- Emergency procedures and contact numbers
- HSE information
- General description of the process and plant including design and operating envelope
- Standard operating procedures for routine operation
- Faultfinding guidance
- Maintenance schedule and procedures

**Table 6**. Summary of commissioning tasks

| Task | Notes |
|---|---|
| **Phase A Construction and precommissioning** | |
| Ensure adequate safety precautions and services available for activities in this and ensuing phases: Risk assessment and method statement in place, all safety equipment available. | Completed by mechanical installers before process commissioning engineer arrives |
| Install service gland packing in all minor machinery and drivers. | Completed by mechanical installers before process commissioning engineer arrives |
| Install service gland packing and lubricate all types of valves as required | Completed by mechanical installers before process commissioning engineer arrives |
| Check alignment and lubrication of all minor rotating machinery and drivers: Pumps to be checked | Completed by mechanical installers before process commissioning engineer arrives |
| Lock-off or isolate all equipment before line flushing and testing | Completed by mechanical installers before process commissioning engineer arrives |
| Correct any construction errors or omissions | Inspected by process commissioning engineer and snag list produced |
| **Phase B Construction and pre-commissioning** | |
| Check electrical installations for power, lighting, and instrumentation for operability and safety | Inspected by process commissioning engineer and snag list produced |
| Check for correct rotation of minor rotating machinery drivers and carry out uncoupled run | Inspected by process commissioning engineer and snag list produced |
| Hydraulic and/or pneumatic pressure test equipment to specification requirements to check connections and joints for pressure tightness | Carried out by mechanical installers monitored by process commissioning engineer |
| Clean all lines of loose material by flushing | Carried out by mechanical installers monitored by process commissioning engineer |
| Hydraulic and/or pneumatic pressure test lines to specification requirements | Carried out by mechanical installers monitored by process commissioning engineer |
| After completion of line and equipment pressure testing, remove all swing blinds (slip-plates) from lines other than those required for operation purposes | Carried out by mechanical installers observed by process commissioning engineer |
| Correction of construction errors and omissions | Inspected by process commissioning engineer and snag list produced |
| Retest after corrective work or alteration | Carried out by mechanical installers monitored by process commissioning engineer |
| **Phase C Construction and pre-commissioning** | |
| Check alignment and lubrication of all major drivers assembled on site | Carried out by mechanical installers monitored by process commissioning engineer |
| Carry out drop tests on pumps with water to ensure satisfactory operation | Carried out by process commissioning engineer |
| Check action of instruments, continuity of connections and instrument circuits | Carried out by process commissioning engineer, assisted by electrical installer |
| Check control valves and penstocks are correct for direction of flow and action on power failure | Carried out by process commissioning engineer |
| Test instruments and loop-check control circuits | Carried out by process commissioning engineer, assisted by electrical engineer |
| Test electrical controls and plant operation systems | Carried out by process commissioning engineer, assisted by electrical engineer |
| **Phase D Construction and pre-commissioning** | |
| Check safety equipment and communications | Carried out by process commissioning engineer |
| Calibrate instruments | Carried out by process commissioning engineer, assisted by electrical engineer |
| Test for leak-tightness of plant-systems | Carried out by process commissioning engineer, assisted by mechanical installer |
| Check completeness of battery limit connections | Carried out by process commissioning engineer |
| Check battery limits disposal systems are complete and ready for function | Carried out by process commissioning engineer |
| Adjust pipe supports for expansion and loading strains | Carried out by process commissioning engineer, assisted by mechanical fitter |
| Correct construction errors and repairs | Inspected by process commissioning engineer and snag list produced |

**Table 6.** (*Continued*)

| Task | Notes |
|---|---|
| **Phase E Commissioning** | |
| Check supports of all lines | Check carried out by process commissioning engineer; mechanical fitter remedies |
| Optimize operating adjustments | Carried out by process commissioning engineer, assisted by electrical engineer |
| Agree procedures for plant performance tests | Procedures proposed by process commissioning engineer proposes if specification does not provide them |
| Maintenance, routine cleaning and normal adjustments to plant | Carried out by process commissioning engineer, assisted by mechanical fitter |
| Complete lagging and painting | Carried out by mechanical installer |
| Complete minor construction details | Carried out by installers |
| Record any modifications carried out during commissioning and annotate drawings/diagrams accordingly | Carried out by draftsmen from main contractor |
| Clean up site | Inspected by process commissioning engineer and snag list produced |

- Spares schedules
- Equipment manufacturers brochures and contact details
- Certification of equipment and plant
- Plant drawings including P+IDs, GAs, ELDs, etc.

A good O & M manual is concise, clear, comprehensive, and correct in all respects. Poor O & M manuals are, however, commonplace.

## 20. Training of Plant Personnel

The personnel to operate the plant are ideally trained during the final stages of commissioning by the commissioning team. The training should be carried out in accordance with the O & M manual.

It is important that the operators gain a favorable impression of the plant during their training, so training should be delayed until the plant works reliably, and the O & M manual is correct.

Training should generally proceed from a discussion of the general principles of plants of the type being considered, through a discussion of the specific needs addressed by the new plant, and how it addresses these requirements. These general discussions can take place in a training room, where audiovisual equipment might be useful to the presentation, but the majority of the training should, however, take place on the plant itself.

Small groups of operators should witness the plant operating routinely under the control of the construction company's commissioning engineers. The operators should operate the plant themselves in accordance with the O & M manual under the supervision of the commissioning engineers.

The operation and maintenance procedures of more sophisticated individual items of equipment may be demonstrated by the commissioning engineers, or by specialists from the equipment vendors in the case of unusual or complex items of equipment.

Once the operators are familiar with routine operation, the shutdown, maintenance, and start-up procedures can be demonstrated and practiced. Next, sampling, field testing, and other required off-line control actions should be taught to operators.

By this point, operators should be confident in operating the plant. Emergency and fault situations can then be set up by the commissioning engineers, and the operators can be tasked to use the O & M manual to diagnose and fix them.

Once operators are fully confident in operating the plant, the commissioning engineers should satisfy themselves that all operators are competent in plant operation before signing certificates of competence to operate the plant for operators.

| | |
|---|---|
| BIM | building information modeling |
| BOD | biological oxygen demand |
| CAPE | computer aided process engineering |
| CEPCI | chemical engineering plant cost index |
| CFD | computational flow dynamics |
| COMAH | control of major accident hazards |
| DCS | distributed control system |
| EPC | engineering, procurement, construction |
| EPCI | engineering, procurement, construction, installation |
| EPCM | engineering, procurement, construction, management |
| FDS | functional design specification |
| FEED | front end engineering design |
| FIDIC | International Federation of Consulting Engineers |
| GA | General Arrangement |
| HAZID | hazard identification |
| HAZOP | Hazard and Operability study |
| HMI | human machine interface |
| HSE | Health Safety and Environmental |
| IET | Institute of Engineering and Technology |
| NTNU | Norwegian University of Science and Technology |
| O & M | operating and maintenance |
| P+ID | piping and instrumentation diagram |
| PC | personal computer |
| PFD | process flow diagram |
| PLC | programmable logic controller |
| QA | quality assurance |
| SCADA | system control and data acquisition |
| URS | user requirement specification |
| VOC | volatile organic compounds |

## References


1 Moran, S. (2015) *An Applied Guide to Process and Plant Design*, Butterworth-Heinemann, London.
2 Branan, C. (2012) *Rules of Thumb for Chemical Engineers*, Elsevier, Amsterdam.
3 Kletz, T. (2001) *Hazop and Hazan*, Institution of Chemical Engineers, London.
4 Center for Chemical Process Safety (2009) *Inherently Safer Chemical Processes*, 2nd edn, J. Wiley & Sons, New York.
5 International Standards Organization (2014) *ISO 10628-1 Diagrams for the chemical and petrochemical industry – Part 1: Specification of diagrams* http://www.iso.org/iso/catalogue_detail.htm?csnumber=51840 [accessed 15 December 2015].
6 American National Standards Institute (1961) A.N.S.I. Y32.11 61st ed., *Graphical Symbols for Process Flow Diagrams in the Petroleum and Chemical Industries* https://global.ihs.com/doc_detail.cfm?document_name=ANSI%20Y32.11 [accessed 15 December 2015].
7 Mecklenburgh, J.C. (1985) *Process Plant Layout*, Institution of Chemical Engineers, London.
8 Green, D. and Perry, R. (2007) *Perry's Chemical Engineers' Handbook*, 8th edn, McGraw Hill, New York.
9 Guthrie K.M. (1969) Capital Cost Estimating. *Chem. Eng.*, **76** (6), 114–142.
10 Williams, R. Jr. (1947) Sixth-tenths factor aids in approximating costs, *Chem. Eng.*, **54** (6), 102.
11 Great Britain, Health and Safety Executive, *What Are Risk Matrices*? http://www.hse.gov.uk/risk/faq.htm (accessed 30 March 2016).
12 International Standards Organization (2002) ISO 14617-6 Graphical symbols for diagrams – Part 6 Measurement and control functions http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=22654 [accessed 15 December 2015].
13 International Society of Automation (2009) *ANSI/ISA-5.1-2009 Instrumentation Symbols and Identification* https://www.isa.org/templates/two-column.aspx?pageid=124355 (Accessed 15 December 2015).
14 United Kingdom Health and Safety Executive (2015) Control of major accident hazards Regulations 1999 (COMAH) http://www.hse.gov.uk/comah/background/comah99.htm (Accessed 15 December 2015).
15 King, M. (2010) *Process Control A Practical Approach*, Wiley-VCH Verlag, Weinheim.
16 United Kingdon Institution of Chemical Engineers, *The Sustainability Metrics: Sustainable Development Progress Metrics Recommended For Use in the Process Industries* https://www.icheme.org/communities/subject_groups/sustainability/resources//~/media/Documents/Subject%20Groups/Sustainability/Newsletters/Sustainability%20Metrics.pdf [accessed 30 September 2015].
17 Peters, M. and Timmerhouse, K. (2002) *Plant Design and Economics for Chemical Engineers*, McGraw-Hill, New York.
18 Sinnot, R.K. and Towler, G. (2005) *Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design*, 2nd edn, Butterworth-Heinemann, London.
19 United States of America, Association for the Advancement of Cost Engineering (A.A.C.E. International) (2005) *Recommended Practice no. 18r-97: cost estimate classification system – as applied in engineering, procurement and construction for the process industries*.
20 Chemical Engineering Magazine (2016) *Chemical Engineering Plant Cost Index* http://www.chemengonline.com/pci-home (Accessed 15 December 2015).
21 United Kingdom, Association of Accounting Technicians (2004) *AAT Intermediate Course Companion, Units 6 & 7: Costing and Reports and Returns*, 4th edn, B.P.P. Professional Education, London.
22 United Kingdon Institution of Chemical Engineers (1999) *The Use of Computers by Chemical Engineers: Guidelines for practising engineers, engineering management, software developers and teachers of chemical engineering in the use of computer software in the design of process plant* https://www.icheme.org/~/media/Documents/Subject%20Groups/CAPE/TheUseof

ComputersbyChemicalEngineersGuidelines1999.pdf (Accessed 21 December 2015).
23 El-Hagawi, M.M. (2006) *Process Integration*, Academic Press, New York.
24 Reay, D., Ramshaw, C., and Harvey, A. (2013) *Process Intensification: Engineering for Efficiency, Sustainability and Flexibility*, 2nd edn, Butterworth-Heinemann, London.
25 European Commission (2000) *Communication from the Commission on the precautionary principle (COM(2000) 1 final of 2 February 2000)* http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3Al32042 (Accessed 21 December 2015).
26 United Kingdom, Institution of Chemical Engineers, *Forms of Contract* http://www.icheme.org/resources/forms_of_contract/the%20contracts.aspx (Accessed 15 December 2015).
27 United Kingdom, Institution of Engineering and Technology (I.E.T.) (2014) *Model Form of Contract for the design, supply and installation of electrical, electronic and mechanical plant, MF/1 (Rev 6)*.
28 International Federation of Consulting Engineers (F.I.D.I.C.) (1999) *The F.I.D.I.C. Suite of Contracts* http://fidic.org/sites/default/files/FIDIC_Suite_of_Contracts_0.pdf (Accessed 21 December 2015).
29 International Standards Organization (2015) *I.S.O. 9000 – Quality Management* http://www.iso.org/iso/iso_9000 (Accessed 21 December 2015).
30 International Standards Organization (2015) *I.S.O. 14000 – Environmental Management* http://www.iso.org/iso/home/standards/management-standards/iso14000.htm (Accessed 21 December 2015).
31 British Standards INSTITUTE (2007) *BS OHSAS 18001 Occupational Health and Safety Management* http://www.bsigroup.com/en-GB/ohsas-18001-occupational-health-and-safety/ (Accessed 15 December 2015).
32 Kilcross, M. (2011) *Chemical and Process Plant Commissioning Handbook*, Butterworth-Heinemann, London.