Second Edition

# An Applied Guide to Process and Plant Design

Seán Moran

IChemE ADVANCING CHEMICAL ENGINEERING WORLDWIDE

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## Second Edition

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Elsevier
Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands
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50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

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**British Library Cataloguing-in-Publication Data**
A catalogue record for this book is available from the British Library

**Library of Congress Cataloging-in-Publication Data**
A catalog record for this book is available from the Library of Congress

ISBN: 978-0-12-814860-0

For Information on all Elsevier publications
visit our website at https://www.elsevier.com/books-and-journals

*Publisher:* Joe Hayton
*Acquisition Editor:* Kostas KI Marinakis
*Editorial Project Manager:* Sara Pianavilla
*Production Project Manager:* Poulouse Joseph
*Cover Designer:* Matthew Limbert

Typeset by MPS Limited, Chennai, India

# Preface

I am a highly experienced practical professional process engineer who has designed, commissioned, and undertaken troubleshooting of many process plants, and mentored and trained many other professional engineers in how to do these things. I have also been a university professor who has taught process plant design to undergraduates and postgraduates for a number of years. This has required me to reflect upon what I know about the subject, how I know it, and how I can teach it to someone else. In this book I will assume the role of the experienced engineer, who takes lucky graduate chemical engineers by the hand in their first job or two and shows them what engineering is really about. Many are not so lucky as to have expert guidance.

(I say "lucky" because so many engineering graduates never get to work as engineers, and those who do may work in places where more senior engineers are either absent or unwilling to help.)

In doing so I will take the fairly informal tone I do when undertaking that task in person, and may on occasion express my frustration with the way the subject is taught in UK (and to the best of my knowledge worldwide) higher education. After all, it is not possible to describe how something might be improved without acknowledging that the present situation is less than perfect. I may also express the odd opinion and, as this is a distillation of experience rather than a scientific paper, I may not necessarily offer references to peer-reviewed journal articles in support of these opinions. However (despite the informal style of writing), the more controversial or provocative an opinion expressed, the more effort I have put into making sure that it is held by the majority of professional process plant designers. Toward this end, this book has now been reviewed, added to, and improved by hundreds of professional engineers across sectors and worldwide. Many of the ideas which seem controversial in academic circles have been the subject of articles I have written for various engineering publications, and on social media, where they have been met with consistently positive professional comment. They have very often however been subject to strong negative feedback from academics, including calls to ban this book and allegations that it constituted professional misconduct on my part to hold and express these views, which might be considered "injurious to academics." Although these came to nothing, I admit I now fear academia may be a lost cause. Maybe professional engineers should focus on correcting misunderstandings and teaching the things academia cannot or will not, rather than trying to prevent them at source.

The foundation of this book is practice, not theory. Throughout the text I will, however, offer quotations from others, links to books and even, on occasion, primary

literature. These should not be misunderstood as the basis of my opinions. In the case of quotations, I am simply quoting people who agree with me. Suggestions for Further Reading are referenced to avoid my having to reproduce the content of these often-weighty books or reinvent the wheel.

# Acknowledgments

I would like to thank all of those who have helped me, especially my wife, Annemarie. Her patient assistance and sure hand with language have been essential in the preparation of this book.

My fellow engineers have given generously of their time in helping me to make sure that what I have written represents consensus opinion, most notably this time (in addition to those I acknowledged in the first edition): James Trevelyan, Graeme Trotter, Charles Sanderson, Rahul Chavan, Rick Rhead, Morgan Rodwell, Tim Highfield, Martin Armstrong, Steve Lancaster, Deryck Coetzer, Shoaib Wangde, Nicolas Capon, Steven Woolley, Warwick Bagnall, Titi Oliyide, Cesar Puma, Stephen Kirby, Paul Richards, Robert Seitz, Jon Brooking, Pat Kinsella, and Justin Jetmar.

I am also grateful to those who have kindly allowed me to reproduce images and material, including Sophie Brouillet at AMOT, Doosan Enpure, John Evans at the former Olympic Delivery Authority, Kerry Harris at AUMA, Tom Huddle, Ernest Kochmann at Newson Gale, Razib Khan, Malcolm Ledger at Lechler, Ian Andrews at SLR Consulting, Edward Luckiewicz, Fiona Macrae at Crowcon, Glenn Miller at Grundfos, Ross Philips at the EEMUA, Keith Plumb, Jennifer Reeves at Elfab, Henry Sandler, Tosh Singh at Lutz-Jesco (GB) Ltd., Mike Wainwright at Ascendant, and Kirsty Warren at WRAP.

PART I

# Practical Principles

# Introduction

The discipline of chemical engineering was originally developed based on the insight, by Davis, that all process industries used similar unit operations, which could be understood using sector-independent analytical tools.

Process plant design is the pinnacle of chemical engineering design. This book is about process plant design, across the broad discipline of chemical engineering. It is especially important to avoid confusion between chemical engineering and petrochemical engineering, a small and arguably diminishing subset of the discipline. Although I often use examples from the water and environmental sectors—because that is my own area of specialism—chemical engineering does of course encompass the energy, food and drink, organic and inorganic chemical manufacture, and many other sectors. This book is therefore intended to reflect consensus practice across the entire discipline. I have ensured this is the case by consulting hundreds of process designers, most notably in the United Kingdom, North America, and the Middle and Far East, working in all industries to verify that the approaches suggested in this book do represent current consensus practice.

I wrote this book originally because I thought that Chemical Engineering Education had lost its way and become too theoretical and abstract to adequately serve its purpose, namely to provide the "academic formation of a Chartered Chemical Engineer" as the UK's IChemE puts it in its course accreditation guidelines. However, as well as confirming current consensus practice, my discussions with fellow engineers have also confirmed that professional engineering does not seem to have changed very much over the last couple of decades, in contrast to what is taught in universities, which has drifted further and further from professional practice during the same period.

The book is based on material I have delivered as part of the design courses I have taught at the Universities of Manchester, Nottingham and Chester, which were in turn based on my continuing professional engineering practice and professional training of my fellow engineers. When I wrote the first edition of this book, I had hoped that the content would enable other academics to develop a more realistic approach to teaching process plant design, but my experience since publication of the first edition suggests that this book, whilst more relevant than ever to the teaching of realistic process design, is most useful to undergraduate and postgraduate students and early career process plant designers.

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00001-X
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The book is in five parts. Firstly, I explain what process plant design is and how it is done in broad terms. Next, I give advice on professional practice in the most important aspects of process plant design, in general, and then at low and at high levels; lastly, I cover more advanced aspects of design.

It should be noted that this is a book about *process plant* design, rather than what is known nowadays in many research-led universities as "process design." There is no such thing as process design—processes happen in plants, and plants are the things which engineers design.

It has become clear in writing this book that we as a profession unhelpfully use the same words to mean different things. The meaning of words and phrases such as Conceptual Design; HAZOP; Functional Design Specification; Design Philosophy; Design Basis; Process Intensification; Process Design; Optimization; Reproducibility; Repeatability; and Precision are particularly contested and vary between industry sectors and countries. To minimize confusion, I have explained the sense in which I use these terms in the text at the point of first using them and I have also included a glossary at the end. I am not claiming that my usage is the only correct one, but I have used terms consistently in the book, and my usage reflects, to the best of my knowledge, the most common meaning.

Seán Moran
Wirksworth, United Kingdom
2019

# CHAPTER 1

# Process plant design

## Introduction

While this may not be as obvious to today's students of the subject as it should be, chemical engineering is a kind of engineering, rather than a branch of chemistry. Similarly, professional engineering design practice has next to nothing to do with the thing called process design in many university chemical engineering departments. I will cover the reasons for this elsewhere, but first let's start by dispelling some confusion, by clearing up what engineering is (and is not), and what design is all about.

## What is engineering?

> *I still feel glad to emphasize the duty, the defining characteristic of the pure scientist—probably to be found working in universities—who commit themselves absolutely to specialized goals, to seek the purest manifestation of any possible phenomenon that they are investigating, to create laboratories that are far more controlled than we would ever find in industry, and to ignore any constraints imposed by, as it were, realism.*
>
> *Further down the scale, people who understand and want to exploit results of basic science have to do a great deal more work to adapt and select the results, and combine the results from different sources, to produce something that is applicable, useful, and profitable on an acceptable time scale.*
>
> ***C.A.R. Hoare***

Engineers are those people "further down the scale" as Hoare (the classicist and philosopher) puts it, although I disagree that we "exploit the results of basic science." Our profession stands on other foundations, though we may have been taught something different in university.

In academia there is almost universal confusion between mathematics, applied mathematics, science, applied science, engineering science, and engineering. Allow me to unconfuse anyone so confused before we get started.

Mathematics is a branch of philosophy. It is a human construction, with no empirical foundation. It is made of ideas, and has nothing to do with reality. It is only "true" within its own conventions. There is no such thing in nature as a true circle, and even arithmetic (despite its great utility) is not factually based.

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00002-1
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Applied mathematics uses mathematical tools to address some real problem. This is the way engineers use mathematics, but many engineers use English too. Engineering is no more applied mathematics than it is applied English.

Science is the activity of trying to understand natural phenomena. The activity is rather less doctrinaire and rigid than philosophers of science would have us believe, and may well not follow what they call the scientific method, but it is about explaining and perhaps predicting natural phenomena.

Applied science is the application of scientific principles to natural phenomena to solve some real-world problem. Engineers might do this (though mostly they do not) but that doesn't make it engineering.

Engineering science is the application of scientific principles to the study of engineering artifacts. The classic example of this is thermodynamics, invented to explain the steam engine, which was developed without supporting science.

*Science owes more to the steam engine than the steam engine owes to Science.*

***L.J. Henderson***

This is the kind of science which engineers tend to apply. It is the product of the application of science to the things engineers work with, artificial constructions rather than nature.

Engineering is a completely different kind of thing from all preceding categories. It is the profession of imagining and bringing into being a completely new artifact which achieves a specified aim safely, cost-effectively, and robustly. It may make use of mathematics and science, but so does medicine if we substitute the congruent "medical science" for "engineering science." If engineering was simply the application of these subjects, we could have a more-or-less common first and second year for both medical and engineering courses, never mind the various engineering disciplines.

A degree which is characterized by researcher-led approaches is an ideal preparation for postgraduate research, but far less so for industry. Uff (see Further Reading) has reported that there is "a disconnect between Higher Education (HE) providers and industry in terms of capturing employers' requirements, willingness to satisfy those requirements and competence to satisfy them. This was especially so in research-intensive universities whose academics are armed with a particular set of skills.... The view is expressed that too many universities focus on research outputs as a success measure, rather than on their primary role to produce the graduates that industry and the economy need." As a result, today's students consistently report surprise at how little of their jobs after university are the "proper engineering" they learned at university.

Now that we are clear about what engineering is, let us consider what design is.

## What is design?

Rather than being some exotic province of polo-necked professionals, the ability to design is a natural human ability. Designers imagine an improvement on reality as it is,

we think of a number of ways we might achieve the improvement, we select one of them, and we transmit our intention to those who are to realize our plan. The documents with which we transmit our intentions are, however, just a means to the ultimate end of design—the improvement on reality itself.

I will discuss in this book a rather specialized version of this ability, but we should not lose sight of the fact that design is in essence the same process, whether we are designing a process plant, a vacuum cleaner, or a wedding cake.

Designers take a real-world problem which someone is willing to expend resources to resolve. They imagine solutions to that problem, choose one of those solutions based on some set of criteria, and provide a description of the solution to the craftsmen who will realize it. If they miss this last stage and if the design is not realized, they will never know whether it would have worked as they had hoped.

All designers need to consider the resource implications of their choices, the likelihood that their solution will be fit for the purpose for which it is intended, and whether it will be safe even if it not used exactly as intended.

If engineers bring a little more rigor to their decision-making than cake designers, it is because an engineer's design choices can have life-and-death implications, and almost always involve very large financial commitments.

So how does engineering design differ from other kinds of design?

## Engineering design

> *Engineering problems are under-defined, there are many solutions, good, bad and indifferent. The art is to arrive at a good solution. This is a creative activity, involving imagination, intuition and deliberate choice.*
>
> ***Ove Arup***

Like all designers, design engineers have to dream up possible ways to solve problems and choose between them. Engineers differ from, say, fashion designers in that they have a wider variety of tools to help them choose between options.

Like all designers, the engineer's possible solutions will include approaches to similar or analogous problems which they have seen to work. One of the reasons why beginners are inferior to experts is their lack of qualitative knowledge of the many ways in which their kind of problems can be solved and, more important still, those ways which have been tried and found wanting.

Engineers need to make sure they are answering the right question. For example, a UK missile program called "Blue Streak" was a classic engineering failure because the problem was not correctly stated. It was designed to be a long-range missile for nuclear warheads, but the missile had to be fueled immediately before launch and it took 30 minutes to do this. Hence the missile was useless for the intended purpose, as it was not capable of sufficiently rapid deployment.

In *To Engineer is Human*, Henry Petroski discusses the importance of avoiding failure in engineering design. Many of his examples of failure, however, were caused not by misspecification, but by designers who forgot that the models used in design are only approximations, applicable in a fairly narrow range of circumstances.

Billy Vaughn Koen goes still further toward the truth, when he points out that "all is heuristic." Even arithmetic is a heuristic. There are no useful absolute truths in mathematics, science, or engineering. There are only approximations, probabilities, and workable approaches. Engineers may just be a little clearer about these issues than mathematicians and scientists, because our solutions absolutely have to work.

## Project life cycle

The niche or niches into which process plant design fits exist in the wider background of an engineering project life cycle. Engineers *conceive*, *design*, *implement*, and *operate* (CDIO) engineering solutions, as the CDIO Initiative in engineering education points out.

The details of project life cycles vary between industries, but there is a common core. Take, for example, the life cycle for a pharmaceutical project:

1. *Identify the problem* (a stage frequently overlooked if there is an assumption that the problem has already been defined). In addition, problems can be mis-identified through following a root cause analysis or through relying on the assumptions of operators who may not fully understand the operation.
2. *Define the problem* in business, engineering, and science terms (starting from inputs to the desired level of output and product quality). Note that for a problem to be recognized by managers, it mostly comes down to defining on how business is affected.
3. *Generate options* that provide potential solutions to the problem.
4. *Review the options* against predetermined selection criteria and eliminate those options that clearly do not meet the selection criteria and/or requisite safety, health, and environmental standards.
5. *Generate the conceptual process design* for the selected options.
6. *Commence Front-End Engineering Design (FEED) studies*. In parallel:
   a. Commence development work at laboratory scale to provide more data to refine the business, engineering, and science basis of the options. However, this may not be practical where there is a lack of historical data - e.g. where business ownership has changed during the life of a process.
   b. Commence a FEED study to evaluate the possible locations, project timescale, and order of magnitude of cost.
   c. Develop the business case at the strategic level.
   d. Determine regulatory requirements for product/process.

7. Based on the outcomes of step 6, *reduce the number of options* to those carried forward to the next level of detail.
8. *Commence detailed design*. In parallel:
   a. Continue the development work at pilot plant scale for setting process parameters for optimal output and quality, utility requirements (steam, electricity, water, compressed air, etc.) for a unit output.
   b. Based initially on the data from the laboratory and pilot scale, develop the detailed design of the remaining options to allow a sanction capital cost estimate to be generated and a refined project timescale.
   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 the pilot scale.
    b. *Carry out the "design for construction"* of the lead option. A "design freeze" will almost certainly need to occur before the development work is complete.
11. *Construct the required infrastructure, utilities, piping, instrumentation, buildings, etc., and install the required equipment*.
12. *Qualify/commission the equipment*.
13. *Commission the process* and verify that the plant performs as designed and produces product of the required quality; validate the process.
14. *Commence routine production* keeping a close watch on quality consistency and output.
15. *Improve process efficiency* based on qualitative and quantitative data and experience gained during routine production.
16. *Increase the plant capacity* making use of process improvements, overcoming constraints, and optimization based on the data and experience gained; revalidate.
17. *Decommission the plant* at the end of the project life cycle.

The pharmaceutical sector tends to run more stages in parallel than other sectors but most of these stages exist in all sectors. The italicized text above represents the consensus stages of the process.

Where does design fit into this? Consultants might call stages 1–3 above plant design. Those with a background in design and build contracting, like me, usually think of design as being predominantly what those in operating companies call "grassroots design," broadly stages 3–10 above. Those who work for operating companies might call stages 15 and 16 plant design.

I suppose an argument can be made for all the above, but it should be noted that before step 14, very limited design information is available. The "design tools" popular in academia are used professionally only for stage 15/16 plant design, rather than stage 3–10 "grassroots" plant design for this reason.

I am going to use the term "process plant design" in the sense of stage 3–10 design throughout this book, even though stages 1–3 and stages 15 and 16 are certainly related fields of professional activity which I have been involved in. This is because this kind of design is closest to the meaning of the terms outside chemical engineering and there are several reasons for this:

- First, a piece of UK legislation called the Construction Design and Management (CDM) regulations requires a person or company to declare themselves the designer of a plant, responsible for the safety implications of the design. This designer is almost always the entity responsible for stage 3–10 design.
- Second, the process guarantee is almost always offered by the company responsible for stage 3–10 "grassroots" design.
- Third, this definition of design is that used by more or less everyone involved in design activity other than chemical engineers.
- Fourth, it's my book, and there are already lots of books on stage 15/16 "process design." This is, as far as I know, the only current book on "grassroots" process plant design, though I have included in this edition a chapter on "brownfield" design associated with stages 15 and 16.

## Process plant design

When I was doing research for this book, I looked at what had been published in other textbooks which claimed to describe a process plant design methodology. I found promising sounding books with titles like *The art of…, A strategy for…, Systematic methods for…, Design of simple and robust process plants*, etc. I know that students and early-stage designers lack an understanding of these things, as well as a "gestalt" of systems, but I felt that the overwhelming majority of these books failed to meet the promise of their titles.

Process plant design is an art, whose practitioners use science and mathematics, models and simulations, drawings and spreadsheets, but only to support their professional judgment. This judgment cannot be supplanted by these things, since people are smarter than computers (and probably always will be). Our imagination, mental imagery, intuition, analogies and metaphors, ability to negotiate and communicate with others, knowledge of custom and practice and of past disasters, personalities, and experience are what designers bring to the table.

If more people understood the total nature of design they would see the futility of attempts to replace skilled professional designers with technicians who punch numbers into computers. Any problem a computer can solve isn't really a problem at all—the nontrivial problems of real-world design lie elsewhere.

Engineering problems will almost certainly always be far quicker to solve by asking an engineer, rather than by programming a computer, even if we had the data (which

we can never have on a plant which hasn't yet been built, or on very old plants where processes have not been well defined and/or documented), a computer smarter than a person, and a program which codes real engineering knowledge, instead of a simplified mathematical model with next to no input from professional designers.

I wonder how the medical profession would feel if scientists and mathematicians suggested, without consulting medics, that they could produce an expert system which would exceed the competence of doctors?

This seems like the classic academic purist's mistake: The psychologist claims that sociology is just applied psychology; the biologist says that psychology is just applied biology, the chemist that biology is just chemistry with legs, the physicist that chemistry is just applied physics, the mathematician that physics is applied mathematics, and the philosopher that mathematics is applied philosophy. Emergent properties are irrelevant to the theorist, but in practical matters they may be everything.

Donella Meadows explains, in *Thinking in Systems*, an intuitive system-level view which is identical in many ways to the professional engineer's view. We share this view with the kindergarteners who also excel at a design exercise called the "Marshmallow Challenge" which I use in my teaching (see Further Reading). The roots of this system-level view are natural human insights, which we may be educating out of our students.

Meadows explains that she makes great use of diagrams in her book because the systems she discusses, like drawings, happen all at once, and are connected in many directions simultaneously, while words can only come one at a time in linear logical order.

Process plant design is system-level design, and drawings are its best expression—other than the plant itself—for the same reasons as given by Meadows.

## Process plant design versus process design

> *Experimental scientists today, despite Einstein and Darwin, seem loath to abandon the search for an eternal changeless unhistorical reality of which pure mathematics could be the model.*
>
> ***Gordon Childe***

An inward-looking school of "process design" as a form of applied mathematics has arisen in some elite research institutions, whose practitioners collaborate only with their fellow researchers. They build upon each other's work, but their outputs are not used by, or indeed of use to, practising engineers.

Extending this philosophy to teaching programs, many universities have replaced essential professional knowledge with modules in which students learn to use researcher software so that, later in the course, they can carry out "process design" as these researchers do it.

Adherents of this school of thought sometimes argue that it is the job of industry to produce engineers, while academia's job is to provide an education in applied

mathematics. They might even argue that, not only should we follow institutions such as Tokyo University in not teaching our students to read engineering drawings, but they should not spend too much time learning about science.

The prevalence in academia of this approach based on modeling, simulation, and mathematical techniques such as network analysis seems to some extent to be an artifact of the way research is funded. Research which takes place in a PC rather than a laboratory (or worse yet a pilot plant) is relatively cheap to conduct, and thus to fund.

It is, of course, a valid function of engineering research departments to develop new design methodologies. Some aspects of these approaches may have niche applications in professional practice, but the overwhelming majority will not be taken up by the profession, as they do not help professional engineers to achieve their aims.

It is inevitable that researchers will consider their work important, even vital, but if it is not of use to the profession, it is research material of academic interest only. In my view, its most useful place (if any) within the UK model of chemical engineering education is only during the masters' year, when the Institution of Chemical Engineers (IChemE) requires students to receive greater exposure to research.

## Variation and selection

### *Variation/creativity*

> *When I examined myself and my methods of thought, I came to the conclusion that the gift of fantasy has meant more to me than my talent for absorbing positive knowledge.*
>
> ***Einstein***

The engineering design process consists of the generation of candidate solutions, and of then selecting those most likely to be safe, cost-effective, and robust.

Coming up with the candidates is a creative process, involving the use of imagination, analogy from natural or artificial systems, knowledge of the state of the art, and so on. Selection of candidates is, however, often more of a grind.

Engineers will almost always make use of mathematical tools to help them with selection, though the academic study of engineering can overemphasize these tools, which are supposed to inform professional judgment rather than supplant it.

In *Engineering and the Mind's Eye*, Ferguson points out a certain intellectual snobbery common in academia which values the mathematical over the verbal, and both of these over the visual, to the detriment of what we might call visual intelligence. Chemical engineering students may leave university with little or no drawing ability, or any development of their "visual intelligence."

It is left by many academics to their employers to teach new engineers this essential part of their skill set. This is bad enough, but perhaps the greatest problem with engineering education is slightly broader: the lack of opportunity to exercise creativity.

In a group design exercise previously referred to, known as the "Marshmallow Challenge," kindergarten children have been shown to outperform many engineering graduates in a test of practical imagination, visual reasoning, feel for materials, and group work.

I used to teach my students a risk management tool called Hazard and Operability (HAZOP) Study (described later in this book) early in their course of study. All of them could master the formal methodology, but very few indeed could realistically imagine what might happen if a component failed (I have included at Appendix 2 a table to help with this).

Incidentally, there also exists an academic exercise called "HAZOP" in which instrumentation is added to a P + ID. However, this bears no resemblance to any professional practice. It is unfortunate that this exercise has been given the same name as a completely different professional technique, confusing students.

Similarly, we used (as many institutions still do) to teach students how to use modeling and simulation programs such as Hysys in place of teaching process design. The vast majority of our students never learned to carry a mental model of a complex system in their heads, nor did they understand the limitations of the programs. They were Hysys operators, not engineers. This is not to say that modeling and simulation programs are worthless, but that they are being misused in academia, to the detriment of our students' understanding.

There is some evidence to suggest that this is a subset of a more general problem, in which the arguably too-ready availability of IT means that less is held in memory by younger people, and their visualization and mental modeling abilities are suffering as a result.

There are many formal systems intended to enhance creativity, but there is little evidence to suggest that they do more than ensure that a larger number of approaches are considered than might be if a less formal approach was followed. I find in my teaching that a greater degree of life experience is a better predictor of the number of candidate solutions generated than the degree of adherence to a formal creativity enhancement methodology.

### *Selection/analysis*

Modeling and simulation programs only address this part of the design process, and may allow thoughtless processing of options rather than making a genuine considered choice between well-understood options. Some say we are making technologists rather than engineers with this approach.

Tools which help the understanding of a system are good. Tools which allow bypassing of understanding to get to a decision (even if our understanding is "mere" intuition rather than science) are not. Our best students will still understand, but the generality will not and there are risky implications associated with this.

Simulation programs are not usually written by professional chemical engineers. They are usually written by numerate graduates with no plant design or operating experience, and they run necessarily simplified mathematical models on machines with far less processing power than people. Designs may be produced by this approach that no human understands. Anyone who has seen the movie *The Terminator* knows what happens when machines build machines!

Professional engineers validate simulation programs against real plants before giving their outputs any credence. This is why the use of such programs by professional engineers is usually limited to modification of existing plant rather than the whole-plant grassroots design addressed by this book.

## Academic versus professional practice

In universities, students mainly practice alone or in small single-discipline groups with simplified and idealized examples. In order to turn the vague messiness of real engineering problems into a collection of unambiguous tasks, a great deal of data is given, the problem is very tightly framed, and in a "successful" example (judged by student satisfaction), it is very clear to students that they are faced with carrying out a number of the tasks which they were previously trained in.

Though these are very often supposedly group exercises, they are structured so that students can readily split them into a number of standalone tasks. When we examine students who have carried out such exercises, it becomes clear that only the most able have any understanding of the overall picture—the majority are just grinding through the textbook method, or operating the program. Neither do they have any appreciation of the complexity of the substructures of a process plant. The method has produced neither system-level vision nor an engineer's grasp of detailed considerations.

This may be useful as a way to learn design calculation techniques, or to illustrate basic principles, but this is not how the majority of engineering design is done. Pugh (see Further Reading) calls these academic approaches "Partial Design," which he contrasts with the professional's *Total Design*.

Students mostly learn their basic science and math from professional researchers, with a very deep knowledge of a necessarily small area, and in the main a love of radical novelty. Engineering practice is far more holistic, and those who practice tend to dislike excessive novelty, which they see as inherently risky.

They also tend to dislike too much prediction of real-world outcomes based on scientific or mathematical models. They would rather see a full-scale working example of what is proposed: a model is not the thing itself. Professional engineers design things that absolutely have to work, and usually cost a great deal of money. Efficacy is a great deal more important than novelty.

This day-to-day activity of most practicing engineers is what Kuhn might call "normal design," where most designs are at best an incremental improvement on what has gone before, with a correspondingly small potential downside.

Practicing engineers operate in a highly constrained environment, and they understand that many of the problems inherent in a design scenario are simply too complex or vaguely defined to be analyzed rigorously within the resources available.

> *The design dimension sees engineering as the art of design. It values systems thinking much more than the analytical thinking that characterizes traditional science. Its practice is founded on holistic, contextual, and integrated visions of the world, rather than on partial visions. Typical values of this dimension include exploring alternatives and compromising. In this dimension, which resorts frequently to non-scientific forms of thinking, the key decisions are often based on incomplete knowledge and intuition, as well as on personal and collective experiences.*
>
> ***Figueredo***

Pahl and Beitz's "Systematic Approach" (see Further Reading) splits the challenges of a design problem into these two components: uncertainty and complexity. According to them, if it is neither too uncertain nor too complex to be solved using standard design tools or methodologies, it is not a genuine problem at all, but it is merely a task.

Standard methods are of no use when there are insufficient data to apply them. There may well be some "tasks," such as checking the sizes of unit operations using heuristics, but these are mathematically trivial, and the product may well be ambiguous. There is no opportunity in professional life to start thinking that engineering is a branch of applied mathematics, or that a computer can solve engineering problems—computers only carry out tasks. Common sense is what is needed, and a feeling for ambiguity, qualitative knowledge, and multidimensional evaluation of options: in short, professional judgment.

The key to a successful design is to understand the problems just well enough to be able to predict that the desired outcome will be reliably attainable. Science and mathematics are certainly tools in the engineer's portfolio, but they are very often not the most important ones, and they are not its basis.

Capturing nonscientific information about how past designs of the type being attempted have performed, and the factors associated with success, is often at least as important. The information is highly situation-specific and is essentially a codification of experience.

Such information may be presented as a design manual, or as standards, codes of practice, or rules of thumb. Such documents allow the very complex situations common in real-world design to be appropriately simplified, making theoretically impossible parts of the design practically possible. The main purpose of such documents is to control the design process, constraining innovation within the envelope of what is known to be likely to work based on experience.

In researching this book, I found books by nonchemical engineers who clearly understand all that I have said so far, but for some reason, the link between professional practice and academic understanding seems to have been broken entirely in my discipline.

## Process plants versus castles in the air

An architect friend tells me that there are two kinds of architects, those who know how big a brick is and those who do not. Castles in the air are such stuff as dreams are made of, but real designs need to be built using things we can buy.

Process engineers do not often make things out of bricks, but we nevertheless make most of what we build from simple standardized subunits, such as lengths of pipe, and ex-stock valves, pumps, and so on. These items have types and subtypes which differ from each other in important ways. Choosing between them is no trivial matter. The essential but qualitative knowledge required to differentiate between these things is often believed, by those who insist that only pure theory matters, to be beneath the dignity of universities to teach.

If you do not know the dimensions and characteristics of the standard subunits from which you build something, your designs will be impractical to build. They will be likely to be less cost-effective, less robust, and less safe than the output of a more practically minded designer.

Commercially available components almost always represent the lower limit of the professional engineer's resolution. We do not care about the atomic structure of the metal in our pump, but we do care about those of its properties which affect the overall design.

## What we design and what we do not

We don't tend to design things which we can buy, because having things specially made costs a lot more than buying stock items, and those who design things guarantee their efficacy. Engineers like to optimize both costs and risks.

Process engineers tend not to carry out design of mechanical, electrical, software, civil, or building works. They do, however, have to know about the constraints imposed on designers in these disciplines, and have a feel for the knock-on cost and other implications of their design choices.

Engineers mostly put standard components together in fairly standard ways. This doesn't sound very clever, until you consider that 32 chess pieces arranged on 64 squares following a set of simple rules can be positioned in $10^{50}$ legal ways. Engineers have to manage a similar level of complexity to that handled by chess players when designing a process plant. Standard parts and standard methodologies do not reduce

the plant designer's profession to monkey work. They just make it humanly possible to reliably produce a working outcome.

In the academic setting, many students are taught engineering science in exercises intended to teach science in context. This is fine, but should not be mistaken for actually teaching engineering. Such academic exercises, which make engineering design look like applied science, have been stripped of their true complexity. Often there is only one "right answer" in such exercises. This is neither engineering nor design.

## Standards and specifications

> *As practicing engineers we do not design, we specify. Specifications have the collective experiences over many years. They include successes and failures, and ultimately they stop us from killing people.*
>
> ***Anonymous Oil and Gas Process Engineer***

Standards and specifications exist to keep design parameters in the range where the final plant is most likely to be safe and to work. They also serve to keep design documentation comprehensible to fellow engineers. A brilliant design which no one else understands is worthless in engineering.

There are a number of international standards organizations—ISO in Europe, DIN in Germany, ANSI, ASTM, and API in the United States, and so on ("British Standards" in the United Kingdom are now officially a subset of ISO).

Since I work primarily in the United Kingdom, I am going to refer to British Standards (where available) in this book, most notably those governing engineering drawings. The use of British Standards (or any other used consistently and clearly) for drawings reduces the likelihood of miscommunication between engineers via their most important channel of information exchange.

The availability of interchangeable standard parts makes much of engineering design simple in one way, but introduces an extra stage which can often be omitted in academic practice. After an approximate theoretical design, practitioners redesign in detail using standardized subcomponents. At this point, the very precise-looking academic design can turn out to be very precisely wrong.

We do not, for example, use 68.9 mm internal diameter pipe, we use 75 mm NB (nominal bore), because that is what is readily commercially available. NB and its US near-equivalent NPS (nominal pipe size) are themselves specifications, rather than sizes.

## Design manuals

Companies frequently have in-house design manuals which are a formal way to share the company's experience of the processes it most often designs. These manuals are not in the public domain, because they contain a significant portion of the company's know-how. They are jealously guarded commercial secrets.

Some national and international standards are also essentially design manuals—for example, PD5500 used to be a British Standard and is now more of a design note or manual which embodies many years of experience of safe design of a safety-critical piece of equipment (namely the unfired pressure vessel), despite being superseded in 2002 by a European standard (BS EN 13445).

## Rules of thumb

Rules of thumb are a type of heuristic, and are usually very simple calculations which capture knowledge of what tends to work. As Koen points out, there are only heuristics in engineering.

Rules of thumb do not necessarily replace more rigorous (but still heuristic) analysis when it comes to detailed design, but their condensation of knowledge gained from experience provides a quick route to the "probably workable" region of the design space (Fig. 1.1), especially at the conceptual design stage.

Rules of thumb are only ever good in a limited range of circumstances. These limitations have to be known and adhered to if they are to be valid (though experts might knowingly break this rule on occasion). Rules of thumb encapsulate experience and are therefore better than first principles design.

It should be noted that simulation and modeling offer at best a kind of first principles design, and cannot be used to generate valid rules of thumb.

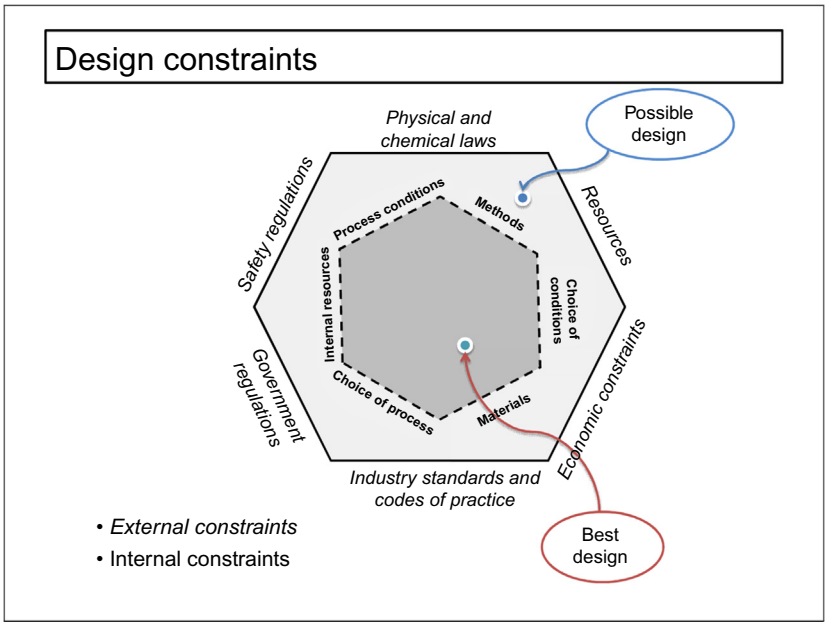


**Figure 1.1** Design constraints. *After R.K. Sinnott.*

It should also be understood that first principles design, generally speaking, doesn't work, and that literature examples of successful first principles design are often no such thing when investigated.

## Approximations

All is approximation in engineering. If you think you are precisely right, you are precisely wrong. Engineers who grew up in the era of the slide rule know that anything after the third significant figure is at best science, rather than engineering.

We need to know how precise and certain we have to be in our answers in order to know how rigorous to be in our calculation. Very often, in troubleshooting exercises, knowing the usual interrelationships between a few measurements is all that is needed to spot the most likely source of problems.

Coarse approximations will get us looking in the right general area for our answers, allowing design to proceed by greater and greater degrees of rigor as it homes in on the area of plausible design.

## Engineering judgment space

I have borrowed this section heading from Harvey Dearden (see Further Reading), whose second edition of *Professional Engineering Practice* includes an essay by this name. The essay makes explicit why professional judgment is the right tool for much engineering decision-making.

It's all to do with the degree of novelty of the area in which you are working, the sensitivity of the outcome to judgment errors, and the predictability of the area. Fig. 1.2 illustrates this.

In Fig. 1.2, the $x$ axis represents novelty (increasing from left to right) and the $y$ axis sensitivity (increasing from bottom to top). This shows why, in a highly novel situation, professional researchers—who may perceive low consequences to being wrong—prefer to study and confer, while professional engineers will prefer to seek independent review, though we would rather not enter this space at all. We prefer the familiar and predictable.

Familiarity plus predictability make for a situation in which individual professional judgment is likely to provide a "right-enough" answer. If the stakes are low, we can self-validate. If the stakes are high, professional engineers look to sanity check with other professional engineers.

## Professional judgment

Douglas gives a figure in *Conceptual Design of Chemical Processes* of $10^5-10^8$ possible variations for a new process plant design, and he leaves out many of the important

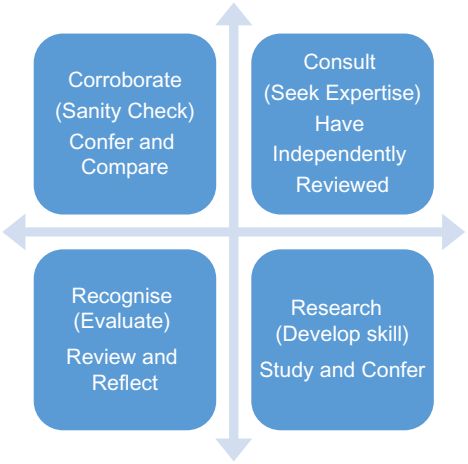


**Figure 1.2** Guidance on design approaches based on novelty versus sensitivity. *After Dearden.*

variables. This is a far lower number than the possible positions in chess, but it is similar to the number of patterns memorized by an experienced chess player.

An engineer's professional judgment allows them to semi-intuitively discern approaches to problems which might work in a similar way to the experienced chess player. They will summarily discard many blind alleys which a beginner would waste time exploring and include options which beginners would be unlikely to think of. They will know which simple calculations will allow them to choose quickly between classes of solution.

Consequently, experts can quickly achieve outcomes which less experienced practitioners might never arrive at. This judgment takes many years of practice to develop, but its development may be started in an academic setting, though usually it is not.

## State of the art and good engineering practice

*Six blind men who had never seen an elephant were asked to see what they could make of one which had wandered into their village.*

*The first man touched its leg, and concluded it was like a pillar.*

*The second man touched its tail and thought it like a rope.*

*The third who touched its trunk thought it was like the branch of a tree.*

*The fourth felt its ear, and thought it was like a fan.*

*The fifth felt its side, and thought it like a huge wall.*

*The sixth who felt its tusk thought it like a pipe.*

*They began to argue about who was right about the elephant. Each insisted that he was right.*

*A wise man passing by asked them, "What is the matter?" They explained that they each thought the elephant was quite different in form.*

*The wise man explained that all of them were correct, which made them happy and allowed them to stop arguing about who was right.*

The man in this story was clearly also wise enough not to point out to the villagers that, as they were blind, their understanding was rather partial, and none had grasped what a whole elephant was like to a sighted person, let alone an elephant keeper. No one thanks you for being that wise.

When I serve as an expert witness, the court requires me to differentiate between fact (perceptible directly to human senses or detectable with a suitable calibrated instrument), current consensus opinion (that held by the majority of suitable qualified professionals), and other opinion. These are held by the court to represent progressively weaker evidence. UK civil courts have a lower standard of proof than our professional one (they are content with a mere "more likely than not"), but their definition of sound professional opinion is a good one.

Koen essentially denies the existence of facts in engineering from a rather philosophical point of view, but he defines best engineering practice rather similarly, as current consensus professional opinion (essentially that part of a Venn diagram which would represent the overlap between the heuristics of all professionals).

I agree with these definitions, which indicate that good engineering practice is always changing, and no single engineer is an entirely reliable source of good engineering practice.

My experience as an expert witness has, however, taught me that we have, as professionals, an idea of the gap between our personal practice and common practice. We know whether each of our heuristics is on the fringes or at the heart of consensus/best practice. Even those maverick professionals who hold fringe ideas which they think better than good practice know that these opinions are not commonly held.

This means that only current practitioners who regularly engage professionally with other practitioners are in touch with the moving target of good practice. It also means that those closest to the heart of a discipline tend to have the greatest concordance between personal heuristics and consensus heuristics. This does not prevent people far from the heart of the discipline from holding fringe opinions strongly; it just keeps them from understanding that they are fringe opinions.

## The use and abuse of computers

Back in 1999 the IChemE's Computer Aided Process Engineering (CAPE) working group produced Good Practice Guidelines for the Use of Computers by Chemical Engineers. These have never been superseded, but they seem to have been largely forgotten in the interim.

The guidelines emphasize the legal and moral responsibility of the professional engineer to ensure the quality and plausibility of the inputs to and outputs from the system, to understand fully the applicability, limitations, and embedded assumptions in any software used. They also emphasize the importance of being properly trained to use the software, and only using fully documented software validated for the particular application.

They emphasize the primary importance of understanding the problem one is trying to solve, working within proper engineering limits, of taking into consideration not just static but even transient dynamic conditions and, most of all, of applying sensitivity analysis to the results produced, especially for those areas identified as the most important to a successful outcome. The severity of the consequences of being wrong should also be taken into consideration.

They warn users to beware of the assumptions implicit in software, and to know where default values exist, and to be able to back-trace any data used to a validated source. This allows the documented accuracy of the data in the range used to be known, as well as whether it is valid in that range.

They recommend contacting more senior engineers and/or the suppliers of the software in the event of any uncertainty at all about the correctness, accuracy, or fitness for purpose of any software or outputs.

In several places, they specifically recommend suspicion about the outputs of computer programs and an assumption of guilt until proven innocent.

They say again and again, in different ways, that software cannot be a substitute for engineering judgment, and its use without understanding is a dangerous abandonment of professional responsibility.

However, I have seen many times, in both academic circles and in recent graduates, a failure to understand this simple truth. Computers may be a little faster than they were in 1999, but they are no closer to being people. All the potential problems of software are still there, but the awareness of their limitations has decreased.

In my view, this is a disaster waiting to happen. Petroski describes a process of growth of irrational exuberance until catastrophe ensues, a process which reminds me by analogy of other failures in the wider world. In investment circles such failures are often referred to as "bubbles" or boom and bust cycles, but the analogy is also applicable in design where this phenomenon matches the cycle of "design bubbles" quite closely. There are certain frequently heard comments which can be symptomatic of a bubble situation.

"You can't lose"—the idea of high, uninterrupted, and irreversible growth in the value of anything sets aside all that we have learned of the history of economic value. Investments which have a high rate of growth in value are in general more risky than those with a low rate. Human nature means that high-growth assets can very rapidly become assets whose high rate of growth is based solely on a bandwagon effect. In the 17th century, tulip bulbs were subject to this effect, an episode now referred to as "tulipmania."

"The old rules don't apply"—The dotcom crash came as no surprise to those who knew about other tech-stock crashes of the past, such as railway mania, and the stock market crash of 1929, which in turn owed much to bubbles in the prices of then-novel electrical, radio, automotive, and aviation technology companies. An idea develops that these new technologies will mean that unlimited profits are available, and that consequently old models of pricing do not apply.

But you can always lose in any game worth playing, and 21st century people are just people, whose natural inclinations are just as they always were. Overconfidence is followed by disaster, followed in turn by forgetting the cause of disaster, and the substitution of wishful thinking for rational analysis which restarts the cycle. Unless we act in a way which does not come naturally to humans and remember the past, we repeat it.

The present model of engineering education has no mechanism for remembering the lessons of the past, and its overreliance on often ill-understood modeling techniques is setting engineers up for another reminder of the truths of engineering.

Design based on computer models is so complex that their users cannot fully understand the provenance of their outputs is not better than old methods. I have even heard reports of margins of safety on modeled plants being cut to the bone, but management still coming back to operational staff to ask for debottlenecking and optimization exercises.

Computers cannot do anything other than handle complex but essentially rote tasks—such as pinch analysis—better than people. Computers are not creative, and engineering is a creative activity. Therefore computers cannot engineer.

Even the cleverest computer simulation in engineering is just a model based on applied mathematics and science which does not fully describe what is being modeled, and commercial software normally has a 1% chance of containing significant errors. Placing more faith in such models than the professional judgment of a group of experienced engineers is foolish.

## Further reading

Dearden, H. T. (2017). *Professional engineering practice* (2nd ed.). CreateSpace Independent Publishing Platform.

Ferguson, E. S. (1994). *Engineering and the mind's eye*. Cambridge, MA: MIT Press.

Institution of Chemical Engineers CAPE Working Group. (1999). *The use of computers by chemical engineers: Guidelines for practicing engineers, engineering management, software developers and teachers of chemical engineering in the use of computer software in the design of process plant*. London: IChemE.

Koen, B. V. (2003). *Discussion of the method*. New York, NY: Oxford University Press.
Meadows, D. H. (2009). *Thinking in systems*. New York, NY: Routledge.
Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. H. (2006). *Engineering design: A systematic approach*. New York, NY: Springer.
Petroski, H. (1992). *To engineer is human: The role of failure in successful design*. Vintage, New York, NY: Vintage.
Pugh, S. (1991). *Total design: Integrated methods for successful product engineering*. Addison-Wesley.
The Worldwide CDIO Initiative. Available at <www.cdio.org>. Accessed 23.10.18.
Trevelyan, J. (2014). *The making of an expert engineer*. Boca Raton, FL: CRC Press.
Uff, J. (2017). *UK Engineering 2016: An Independent Review*. Institution of Mechanical Engineers/ Institution of Engineering & Technology/Institution of Civil Engineers (pdf). Available at <https://www.engc.org.uk/news/news/review-of-uk-engineering-profession-published/>. Accessed 28.03.18.
Vincenti, W. G. (1990). *What engineers know and how they know it: Analytical studies from aeronautical history*. Baltimore, MD: Johns Hopkins University Press.
Wujek, T. (2010). *The Marshmallow Challenge*. TED talk. Available at <https://www.ted.com/talks/tom_wujec_build_a_tower>. Accessed 23.10.18.

# CHAPTER 2

# Stages of process plant design

## General

Process plant design (and indeed almost all design) proceeds by stages which seem not so much to be conventional as having evolved to fit a niche. The commercial nature of the design process means that the minimum necessary resources are expended to get a project to the next approval point. This results in design being broken into stages leading to three approval points, namely feasibility, purchase, and construction.

This is why Pahl and Beitz's systematized version of the engineering design process resembles that which applies to all engineering disciplines (including chemical engineering's process plant design) as practiced by professionals. It may very well also apply to fashion design. Design is design. Is design.

Note that in recommending Pahl and Beitz's approach I am not seeking to enter the academic debate on how the design process *ought* to be done. Having read many books on engineering design across many disciplines, I found Pahl and Beitz's description to be one of the closest to how design *is* done. That is the subject of this book.

The basically invariant demands of the process are the reason why everyone who designs something professionally does it basically the same way, even though chemical engineers are often nowadays explicitly taught a radically different approach in university (if they are taught any approach at all).

## Academic approaches

### "Conceptual design of chemical processes"

Academic approaches are based on a book Douglas wrote of this name which essentially attempts to design chemical processes (whatever they are), rather than process plants.

Douglas understood that the expert designer proceeds by intuition and analogy, aided by "back of the envelope" calculations, but saw the need for a method which would help academics and beginners to cope with all the extra calculations they have to do while they are waiting to become experts (who know which calculations to do).

The arguments underlying the academic approach which has since been built on Douglas's approach are helpfully set out in explicit detail. There is an assumption that the purpose of conceptual design is to decide on process chemistry and parameters such as reaction yield. Choices between technologies (the usual aim of conceptual

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00003-3
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design exercises) are not considered. Pumps are assumed to be a negligible proportion of the capital (capex) and running (opex) cost, and heat exchangers are assumed to be a major proportion of capex and opex.

It is implicit in the chain of assumptions used to create the simplified design methodology that a particular sort of process is being designed. Like all design heuristics, the methodology has a limited range of applicability. While it mentions other industries, it is based throughout upon examples taken from the petrochemical industry, and it is clear that the assumptions it makes are most suited to that industry.

Having omitted many items which are of great importance in other industries, Douglas finds time for pinch analysis, which was quite new when the book was written. Perhaps this really was a worthwhile exercise for the novice process designer in the petrochemical industries of the 1980s, but there are many process plant designs in 2018 which do not have a single heat exchanger.

In the majority of industries, process chemistry is a job for chemists, and from the plant designer's point of view is in any case usually limited to choosing between a number of existing commercially available process technologies.

Douglas offers a plausible approach to the limited problem he sets out to solve, few of whose assumptions I can argue with in the context of his chosen example. He attempts to offer the beginner a way to choose between potential process chemistries and to specify the performance of certain unit operations in a rather old-fashioned area of chemical engineering.

The approach hangs together coherently, in a way more recent developments based on it do not. A good amount of effort goes into constructing as rigorous a costing as is possible at the early design stage (ignoring the issue of the items which are left out).

However, the problem which this methodology seeks to address is not one I have ever been asked to find a solution for. When I am asked to offer a conceptual design, I am being asked to address different questions, on plants with a different balance of cost of plant components. Petrochemical plants of the sort used as the example in this book do not really get built in the developed world any more.

In essence this book seems, in my view, to reflect the slight wrong turns and oversimplifications which, exaggerated by successive oversimplifications and misunderstandings, led to the utterly unrealistic approaches common in academia nowadays.

The attraction of the approach to academics is presumably that it is intended to allow people who have never designed a process plant (like the majority of academics) to use the skills they do have to approximate an early-stage design process.

The approach is a tool to allow a very inexperienced designer who does not have access to expert designers to simplify the design of a certain sort of petrochemical plant to the point where they can mathematically analyze the desirability of a small number of parameters such as degrees of reactor yield and energy recovery.

This approach is, essentially, another design heuristic, and like all heuristics it has a limited range of applicability. If the very specific assumptions it makes to achieve this aim are not met, its use is invalid.

Even if they are met, process integration at the conceptual design stage is both uneconomic and unwise, for reasons I discuss elsewhere in the book.

## Modeling as "conceptual design"

Much work thought of as conceptual design, especially in the case of modifications to existing plant, takes place in large consultancies and operating companies. Because plant operating companies and consultants lack real whole-plant design experience, this may feature some elements of the academic approaches derived from Douglas's approach discussed in the last section, combining the application of network and pinch analysis to the output of modeling and simulation programs.

The scope of such studies is usually for a small number of unit operations rather than a whole plant, and it is by collaborating almost exclusively with those carrying out such studies (and each other) that academics get the impression that their techniques are used in industry.

However, this work differs from the design techniques of professional process plant designers (as I define them in Chapter 1: Process plant design) in a number of ways.

The "conceptually designed" plant will not be built by those carrying out the conceptual design exercise. The contractors who will build it may use this "design" as the basis of their design process, but since it is they who will be offering the process guarantee, they will redesign from the ground up. They will, however, probably not point this out to the client, who will consequently retain the impression that they designed the plant.

Genuine information from pilot studies on the actual working plant allows the model used to be fed with a specific and realistic design envelope, and for its outputs to be validated on the real plant. This is very different from using the modeling program in an unvalidated state.

Thus such conceptual design studies, while potentially very valuable as a debottlenecking or optimization exercise, are not a true process plant design exercise. The modeling, simulation, and network analysis beloved of research academics are of their greatest utility in this area, due to the availability of the large quantities of specific data which such approaches require to yield meaningful results.

However, I would still suggest to those carrying out such exercises that they should be willing to listen to suggestions from contracting companies if they would like to arrive at a safe, robust, and cost-effective solution. There is no substitute for experience.

All should understand that professional judgment is still superior to the output of computer programs, however much effort went into the pilot trials and modeling exercises, but human nature leads people to wish to benefit from costs which have been irreversibly incurred. If you have spent a great deal of resources on these studies, it may be hard to accept that you could have simply got a contractor to design the plant without spending the resources. The sunk cost fallacy needs to be avoided.

## Professional approaches

### Conceptual design

Professional conceptual design of process plants is sometimes carried out in an ultimate client company, more frequently in a contracting organization, and most commonly in an engineering consultancy.

In this first stage of design, we need to understand and ideally quantify the constraints under which we will be operating, the sufficiency and quality of design data available, and produce a number of rough designs based on the most plausibly successful approaches.

I am told that, in the oil and gas industry, the conceptual stage starts from a package of information known as Basic Engineering Design Data (BEDD), which is often confused with (Process) Basis of Design. BEDD includes, typically, information to start the concept design such as:

- general plant description;
- codes and standards;
- location;
- geotechnical data;
- meteorological data;
- seismic design conditions;
- oceanographic design conditions;
- environmental specifications;
- raw material and products specifications;
- required utilities and their specifications;
- flares;
- Health, Safety and Environment (HSE) requirements and guarantees; and
- production throughput.

Other industries have alternative formats, but initial information packages ideally cover many of the same areas.

Practicing engineers tend to be conservative, and will only consider a novel process if it offers great advantages over well-proven approaches, or (in a case which is very rare in professional practice) if there are no proven approaches.

Reviews of the scientific literature are very rarely part of the professional design process. Practicing engineers do not have the free access to scientific papers which academics enjoy, and are highly unlikely in any case to be able to convince their colleagues to accept a proposal based on a design which has not been tried at full scale several times, preferably in a very similar application to the one under consideration.

The conceptual stage will identify a number of design cases, describing the outer limits of the plant's foreseeable operating conditions. Even at this initial stage, designs will consider the full expected operating range, or design envelope.

The documents identified in Chapter 3, Process plant design deliverables, are produced for the two or three options most likely to meet the client's requirements (usually economy and robustness). This will almost always be done using rules of thumb, since detailed design of a range of options (the majority of which will be discarded) is uneconomic.

This outline design can be used to generate electrical and civil engineering designs and prices. These are important, since designs may be optimal in terms of pure "process design" issues like yield or energy recovery, but too expensive when the demands of other disciplines are considered.

At the end of the process, it should be possible to decide rationally which of the design options is the best candidate to take forward to the next stage. Very rarely, it will be decided that pilot plant work is required, and economically justifiable, but this is very much the exception; design normally proceeds to the next stage without any trial work. [Unless it is a new product introduction where scaling is generally taken in steps; from lab to pilot plant (or kilo lab) and then to plant scale.]

There are academic arguments for including formal process integration studies at this stage, though this is incredibly rare in practice. The key factor in conceptual studies is usually to get an understanding of the economic and technical feasibility of a number of options as quickly and cheaply as possible. As many as 98% of conceptual designs do not get built, so you don't want to spend a fortune investigating them.

Client companies have advantages over contractors in carrying out conceptual designs, as they may have a lot of operating data unavailable to contractors, however, they do usually lack real design experience.

Contractors are in the opposite situation, while the majority of staff employed by many consultancies tend to have neither hands-on design experience nor operational knowledge.

In an ideal world, therefore, client companies would collaborate with contractors to carry out conceptual design. In the real world, this cooperation/information sharing is less than optimal.

## Front-End Engineering Design/basic design

If the design gets past the conceptual stage, a more detailed design will be produced, most commonly in a contracting organization.

Competent designers will not use the static, steady-state model used in educational establishments, but will devise a number of representative scenarios which encompass the range of combined process conditions which define the outer limits of the design envelope. All process conditions in real plants are dynamic; they do not operate at "steady state." They may approximate the steady state during normal operation if the control system is good enough, but they must be designed to cope with all reasonably foreseeable scenarios.

The process engineer normally begins by setting up (most commonly in Excel) a process mass and energy balance model linking together all unit operations, and an associated process flow diagram for each of the identified scenarios. It is usually possible to set up the spreadsheets so that the various scenarios are produced by small modifications to the base case.

In certain industries (especially the oil and gas sector) a modeling system like Pro II might be used for this stage, but across all sectors this is the exception rather than the rule, because business licenses for such programs are very expensive, and the available unit operations tend to be tailored to a specific industry sector.

A more accurate version of the deliverables from the previous stage will be produced, based on this more detailed design/model and, wherever possible, bespoke design items will be substituted with their closest commercially available alternatives, and the design modified to suit.

Process designers normally avoid designing unit operations from scratch, preferring to subcontract out such design to specialists who have the know-how to supply equipment embodying the specialist's repeated experience with that unit operation.

Drawings at this stage should show the actual items proposed, as supplied by chosen specialist suppliers and subcontractors. Even such seemingly trivial items as the pipework and flanges selected should be shown on the drawings, as they are supplied by a particular manufacturer, and pricing should be based on firm quotes from named suppliers.

The drawings should form the basis of discussions with, at a minimum, civil and electrical engineering designers, and a firm pricing for civil, electrical, and software costs should be obtained.

All drawings and calculations produced are checked and signed off at this stage by a more experienced—ideally chartered/licensed professional—chemical engineer.

Once that is done, a design review or reviews can be carried out, considering layout, value engineering, safety, and robustness issues. Where necessary, modifications to the process design to safely give overall best value should be made.

## Detailed design or "Design for Construction"

This virtually always takes place in a contracting organization. The detailed design will be sent to the construction team, who may wish to review the design once more with a view to modifying it to reflect their experience in construction and commissioning.

Many additional detailed subdrawings are now generated to allow detailed control of the construction of the plant. The process engineer would normally not have much to do with production of such mechanical installation drawings, other than participation in any design reviews or Hazard and Operability (HAZOP) studies which are carried out.

The junior process engineer will, however, be heavily involved in the production of documents such as the datasheets, valve, drive, and other equipment schedules, installation and commissioning schedules, as well as the project program.

This painstaking work is required to allow the procurement of the items which are described in them by nonengineers. It is not so much design work as contract documentation.

## Site redesign

This does not usually feature much in textbooks on the subject, but it is not uncommon for designs to pass through all the previous stages of scrutiny and still be missing many items required for commissioning or subsequent operation.

It is far cheaper to move a line on a drawing than it is to reroute a process line on site. If communication from site to designers is managed very poorly in a company, expensive site modifications may be required on many projects before the problem comes to the attention of management. Hence it is best to walk the plant with drawings to confirm the routes before amending on drawing to ensure the proposed modification is feasible.

Commissioning and site engineers are rarely involved in the design process (though they should be involved in the HAZOP) but often find these omissions when they review the design they have been given, or, worse still, find the error on the plant after it was built. (Common issues are installation and maintenance accessibility issues identified quite late in the process.) This is an expensive stage at which to modify a design, but in the absence of perfect communication from site to design office, it will continue to be needed.

On behalf of commissioning engineers everywhere, therefore, I would like to encourage designers to make sure that the following items are included in designs at the earliest stage:

- Tank drains which will empty a tank under gravity in less than 1 hour, and somewhere for the drained content to go to safely;

- Tank vents or vent/vac valves (with protection where required) to allow air to enter and exit a tank safely;
- Suitable sample points in the line after each unit operation (there may be far more to this than a tee with a manual valve on it);
- Service systems adequately sized for commissioning, maintenance, and turnaround conditions;
- Connection points for the temporary equipment required to bring the plant to steady-state operation from cold need to be provided, especially where process integration has been undertaken;
- Water and air pollution control measures required under commissioning conditions;
- Access and lifting equipment required under commissioning, maintenance, and turnaround conditions.

Designers should, in my opinion, also avoid permanent pump suction strainers or filters, especially fine mesh filters, which are likely to be removed by commissioning engineers or operators. There is a lot more on this in Chapter 17, Success through failure (or "you don't want to do it like that!").

## Posthandover redesign

The commissioning engineer may have tweaked or even redesigned the plant to make it easier for it to pass the performance trials which are used to judge the success of the design, but the nature of the design process means that, while the unit operations have been tuned to work together, they actually have different maximum capacities.

When the spare capacity in the system is analyzed, it is usually the case that the output of the entire process is limited by the capacity of the unit operation with the smallest capacity. This is a restriction of capacity or "bottleneck." Uprating this rate-limiting step (or a number of them) can lead to an economical increase in plant capacity.

Similarly, it might be that services which were slightly overdesigned to ensure that the plant would work under all foreseeable circumstances, and optimized for lowest capital cost rather than lowest running cost, can be integrated with each other in such a way as to minimize cost per unit of product. This is important, because prices for a plant's product tend to fall over its operating life, as competing plants which are built in low-cost economies or based on newer, better processes bring prices down.

It should be noted that those carrying out this kind of operation have at their disposal a lot more data than whole-process designers. Clever mathematical tools were developed back in the 1970s to facilitate the energy integration process, and their conceptual approach has since been applied to mass flows, including those of water and hydrogen.

However, these were devised to be optimization tools, rather than process design tools. As I discuss elsewhere in this book, there are a number of inevitable drawbacks to their misuse as design tools, which are more serious the earlier they are used in the design process.

This book does not have much to say about posthandover design activity, as this activity does not meet a number of my criteria to qualify as process plant design. Most notably, it does not involve designing a whole plant; there is a great deal of site-specific detailed information available to validate computer models; and small improvements in performance are within the resolution of the design process.

This activity is, to my mind, more akin to aftermarket tuning of a plant which has been designed by others, rather than designing one from scratch, the subject of this book.

## Fast-tracking

Mixing the natural stages of design in order to accelerate a program is a reasonably common approach in professional practice (though it has a downside). It is telling that contractors who are asked to make a program move faster (or "crash the critical path") are usually given acceleration costs to compensate them for the inherent inefficiency of the fast-tracked process.

As well as costing more for the reasons given below, fast-tracking is commonly held to increase speed at the cost of quality, whether that be design optimization quality and/or quality of design documentation.

The standard approach practically minimizes the amount of abortive work undertaken, since each stage proceeds on the basis of an established design envelope and approach. Each stage refines the output of the preceding stage, requires more effort, and comes to a more rigorous set of conclusions than the preceding stage.

When stages are mixed, more rigorous steps are carried out earlier in the program when the design has a larger number of variables. We may well therefore need to have a larger team of more experienced people working on the project. Even with the improved feel for engineering given by using more experienced engineers, it is much more likely in fast-tracking that a design developed to quite a late stage will need to be binned, and the process restarted from the beginning of the blind alley which the design went down. Of course, if you are in a sector where you are making an extremely profitable product, this will be less of a concern than if you are in a less lucrative field.

Generally, costs for product by sector may be ranked as follows:

Biopharmaceuticals
Pharmaceuticals/nanotech products and similar
Fine chemicals
Oil and gas
Bulk chemicals
Water and environmental

Oil and gas have an anomalous position in this hierarchy (and are highly profitable) because they produce huge volumes of a product whose price is effectively set largely by an international cartel.

### *Unstaged design*

Sometimes it is more important to get a design completed quickly than to spend time optimizing cost, safety, and robustness. These things still matter and have to be addressed to at least a minimum standard, but there can be commercial drivers which mean that getting the product of the process on the market as soon as possible is the most important factor.

The premier example of this is the design of systems to manufacture a product which is subject to patent, especially pharmaceuticals. Once patent protection is removed, generic substitutes manufactured in low-cost/wage economies will usually rapidly out-compete the patented version.

Almost all the profit which will be made on the product will be generated between the day it hits the shelves and the day the patent expires. Thus getting the product to market quickly is more important than plant design optimization, to the dismay of my colleagues who work in pharma.

### *Conceptual/Front-End Engineering Design fast-tracking*

In a contracting company or design house, conceptual design can be very quick indeed. Senior process engineers know from experience which is likely to be the best approach to an engineering problem. A few man-hours may be all that they require to rough something up.

However, this means that a client who wishes to skip the stage where they or a consultant do the initial designs is ceding control of the design to a contractor. This is not without a downside—senior process engineers in contracting organizations will almost certainly come up with a design which will be safe, cost-effective, and robust, but a design based entirely on generic experience is unlikely to be the most innovative practical approach.

### *Front-End Engineering Design/detailed design fast-tracking*

If a project is definitely going to go ahead, and the contractor has been appointed, Front-End Engineering Design (FEED) and detailed design can be combined, and the operating company/ultimate client can take part in the design process. This was quite a common approach using the Institution of Chemical Engineers (IChemE) "Green Book" contract conditions back at the start of my career.

This approach can produce a very good-quality plant, which is unusually fit for purpose, but the FEED study is used as the basis of competitive tendering. The removal of a discrete FEED study, along with that of the usually adversarial

approach between client and contractor in process plant procurement, does seem to inflate costs somewhat.

### Design/procurement fast-tracking

Time is generally lost from the originally planned design program at each stage of design such that the later stages—which produce the greatest number of documents, employ the most resources, and are most crucial to get right—often proceed, unhelpfully, under the greatest time pressure.

There are barriers to communication between the various stages of design which need to be well managed if conceptual design is to lead naturally to detailed design and from there to design for construction. If the communication process is managed poorly, unneeded redesign may be carried out by "detailed" or "for construction" design teams who do not understand the assumptions and philosophy underlying the previous design stage. Alternatively, designs may have to be extensively modified on site during construction and commissioning stages, usually at the expense of the contractor.

Design/procurement fast-tracking is quite popular as a response to time lost in earlier stages for projects where the end date cannot move. As soon as an item's design has been fixed, the procurement process is started, especially with long lead time items like large compressors.

The nature of design being what it is, this can result in variations to specifications for equipment design after procurement has started, and this usually carries a cost penalty, as does the high peak manpower loading, duplication of designs, and backing-out of design blind alleys inherent in this approach.

### The fast-track to bad design

The "chemical process design" approach popular in academia attempts to mix all design stages prior to construction, and often substitutes modeling for construction (a mistake I comment on elsewhere in the book). In academia, it is frequently argued that it is how design *ought* to be done, as sustainability concerns mean that we need to approach thermodynamic limits to energy recovery.

The first problem I have with this is that sustainability is a highly politicized term. A Greenpeace member, a trade union activist, and a chartered chemical engineer might use the term to mean three completely different things. The IChemE have helpfully written guidelines on what it means to chemical engineers, in the form of sustainability metrics. We engineers like a metric, so that we can analyze a problem and its possible solutions at least semiquantitatively.

The IChemE interpretation does not support aspiring to theoretical perfection in a small number of aspects of process design. Chemical engineers are concerned about the environment, but we know that the curves of process yield, energy recovery,

safety, and environmental protection against cost are exponential. Both perfect processes and complete safety are infinitely costly.

My second problem is that it is not just that you cannot optimize a process before you design it in detail: you cannot really optimize a process before you have built it. At the conceptual design stage, the design subcomponents are not items which you can actually buy economically. There are a number of reasons for this which are as follows.

Firstly, sizes of commercially available process equipment are not a continuous variable. There are minimum and maximum available sizes, and the available size increases in discrete steps. This is true of the very simplest items such as lengths of pipe. You can have special items made to order, but they are far more expensive than stock items, take far longer to deliver, and are more likely to have unforeseen problems.

Secondly, no plant is ever built exactly as specified. Sometimes this is due to errors in construction or poor QA in materials or construction but, more significantly, many plants need site-level redesign due to design errors, unforeseen consequences, or a late change in client specification.

Thirdly, this approach takes no consideration of the interactions with other disciplines (most notably civil and electrical engineering) of process design choices. These can be very significant, far more so than the cost implications of theoretically tweaking a virtual plant for small increases in energy efficiency or yield.

Fourthly, it is commonplace in this approach to take no real consideration at all of the impact of process choices on either capital or running costs of the plant. If you aren't costing, you aren't engineering, but those who practice "chemical process design" apparently consider cost only by comparing the cost of feedstock with that of product. If product can be sold for more than feedstock can be bought, the process is deemed to be economic. Thus the marginal cost of yet another heat exchanger is set to zero, such that it is always viable to go one step closer to theoretical perfection.

I have been told that the application of aspects of this approach to real plant design has led to processes whose safety factors are so tight that it is thought unwise by experienced engineers to attempt debottlenecking, though management still expects it.

This is arguably what the approach really does: any savings which might be found will come out of safety factors and plant operability, which is reminiscent to me of the erosion of safety factors which presage disaster in many of Henry Petroski's examples. It all seems terribly clever until your bridge falls down, or your plant is replaced by a crater.

All of this said, there are circumstances where simulation can be used to partially replace design: if you have a great deal of operating data for exactly the plant you are "designing," you can tune and validate the model, such that you are no longer designing from first principles and generic data, but have an empirically verified simulation of the actual plant.

This is the case if you are working for an operating company or a contractor/operator with access to such data, and the spare time necessary to tweak the simulation. However, you may not necessarily understand why the simulation behaves as it does, even in the case where you seem to have made it behave exactly like the real plant. And, if you do not understand your model, it is worse than useless.

### *Product engineering*

European chemical engineering bodies such as FEANI are encouraging the promotion of "product engineering" into chemical engineering curricula. It should, however, be noted that "product engineering" is not the same thing as "product design," a term used in academia for something which is often not any kind of engineering.

Product engineering is the name given to shortening the classic approach described in this chapter and running it alongside a product design program. The deliverables of product engineering are identical to those listed earlier in this chapter. Price, practicality, and safety issues need to be as much at the forefront of the process as they are with the classic approach.

Process plant designers design coordinated assemblies of machines (gubbins) to make chemicals (stuff). Our plants make stuff, rather than gubbins, and our plants are made of gubbins rather than stuff. Mechanical engineers design gubbins, and chemists work with stuff.

Academic "product design" is often just rebranded chemistry content, with little consideration of plant or production cost, safety, or robustness. I have even seen it used to describe an exercise in which students were asked to research and design a university teaching module.

The design methodology of professional product design is just like that of the professional plant designer. Pugh's "Total Design" is about product design, but is far closer to a description of how process plant design is actually undertaken than almost all books by "chemical engineers."

## Further reading

Azapagic, A. (2002). *Sustainable development progress metrics recommended for use in the process industries*. London: Institution of Chemical Engineers.

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. H. (2006). *Engineering design: A systematic approach*. New York, NY: Springer.

Petroski, H. (2012). *To forgive design: Understanding failure*. Cambridge, MA: Harvard University Press.

Pugh, S. (1991). *Total design: Integrated methods for successful product engineering*. Addison-Wesley.

# CHAPTER 3

# Process plant design deliverables

## Overview

"Deliverables" may not be the most elegant word, but it is freighted with meaning. It comes from project management, and it reminds us that the immediate purpose of the design process is to deliver to a client a set of documents which they can use to build a plant, or more usually approve formally, so that the designer's company can build it.

Less frequently, the plant itself is described as a deliverable, but we will restrict ourselves in this section to the drawings and other documents which are commonly used to transmit design and construction intent from the designer to vendors, clients, and the construction team.

The following sections list these documents in the rough order in which they are first produced, although revision of such documents may continue throughout the project.

These are only the most important and commonplace deliverables; I am deliberately omitting many sector-specific deliverables.

Sometimes there will be a misalignment or inconsistency between the deliverables, in which case it is important to know which documents take precedence. From my experience, the key document is the project specification, followed by the piping and instrumentation diagram (P&ID), and then the standard or general specification. It is, however, usually best to point out to the purchaser any misalignment as soon as it is noticed (subject to any commercial considerations).

## Design basis and philosophies

The output from the conceptual design stage may sometimes be restricted to guidance on the approach which should be followed in subsequent design stages: a *design basis* or *design philosophy*.

These terms are sometimes taken to be the same thing, but I will differentiate between them as follows.

I have heard some engineers describe the design basis to their mentees as a form of project "bible" that contains all the fundamental information that should be referenced and used as the project progresses. In professional practice, a design basis will usually be a succinct (no more than a couple of sides of A4) written document which might define the broad limits of the Front End Engineering Design (FEED) study. Even the

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00004-5
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most succinct versions of this document include such things as project location, intended design life, operating and environmental conditions, feedstock and product qualities, and the acceptable range of technologies. In some industries a slightly longer version is used, including design assumptions, applicable codes, standards, and regulations (where appropriate or specific standards apply as well as commonly used ones), but even these longer versions should only run to a few pages. They are not design philosophies.

Design philosophies, by contrast, may run to 40 pages, including overpressure protection philosophies, vent, flare, and blowdown philosophies, isolation philosophies, etc. Clients often specify a design philosophy in their documentation, and individual designers and companies may have their own in-house approaches. Examples of these include BP's ETP (engineering technical practices), and Shell's DEP (design engineering practices).

It is good practice for a formal design philosophy to be written as one of the first documents on a design project. (Similarly, a safety and loss prevention philosophy is ideally produced early on in the design process.) The design philosophy should record the standards and philosophies used in its own construction, together with underlying assumptions and justifications for choices made. This is both to allow a basis for checking in the detailed design stage and for legal purposes.

If there is no written design philosophy, there is a risk that other engineers joining the project at detailed design stage might attempt to apply their own different preferred philosophy, and the plant may become subject to pointless expensive and extensive redesign. On a poorly integrated project (multiple design teams working on different upgrades to different design philosophies and/or lack of consideration for the original design philosophy of existing plant), different areas may be built to different philosophies producing confusion and potential safety risks.

## Specification

There are a number of types of specifications which are introduced at various stages of the design process, which can be split broadly into specific and boilerplate categories. Let us first dispense with the boilerplate category.

Boilerplate is a term used in legal contexts, but it originates in engineering. A rating-plate containing standard text was required to be attached to a boiler by the UK's Boiler Explosions Act (1882), and the term subsequently came to mean standard text which is cut and pasted into documents.

Much of this sort of text might be described as "write only" documentation [or WOD—we engineers do love a three-letter acronym (TLA)], because someone has to write it but virtually no one has to read it. The consultant draws the attention of the designer to it, and they in turn draw it to the attention of their suppliers.

The tender documentation sent out to contractors by consultants frequently contains great volumes of boilerplate specification, lists of applicable (or inapplicable, if your consultant is lazy and/or risk averse) legislation and standards, and references to all the other things which the conceptual designers didn't personally consider, but think someone else should. I am not convinced that this frequently lazy approach actually provides the degree of legal protection those responsible for it imagine.

For example, an exhaustive list of codes/standards could be assumed to be "inclusive" even if the original intent was actually to provide a generic list of typical standards. In such cases, parties could argue that they didn't comply with a particular standard because it wasn't on the list.

> *I have to tell one of our contractors EVERY SINGLE ******* TIME they give us a design basis document to remove their generic codes/standards appendix because it runs to 10 pages and adds nothing to the document.*
>
> ***Anon Engineer***

Far more useful than the boilerplate, in contrast, is the far thinner volume of specifications which informs the definition of the design envelope.

The expected quantities and qualities of feeds into the process should be included, as well as a description of product quality and quantity. These descriptions will ideally be in the form of ranges of parameters such as concentrations, flows, temperatures, and pressures. There may be statistical information to allow the designer to understand the distribution of likelihood of various conditions. Additional specifications such as start of run, end of run, and possibly special operational conditions (such as regeneration) might also be included.

There may be reference to specifically applicable standards, legislation, etc. This differs from boilerplate as those responsible for the previous stage of design have identified that these documents are likely to really matter to this specific design. An additional term which is sometimes seen is "RAGAGEP" (Recognized and Generally Accepted Good Engineering Practice). This term comes from the US OSHA and is a sort of a catch-all statement that the contractor/vendor is required to do their work properly and apply experience-based judgment where codes/standards are not specifically available. Note that RAGAGEP refers to *good* practice, rather than *best* practice: best practice is the exception, not the rule.

The separation of these useful specifications from the boilerplate is often the first job of the design contractor's plant design engineers. The boilerplate has to be checked for anomalous content alongside undertaking the real design process, but that is not usually on the critical path. It usually suffices in the first instance to send out (largely unread) relevant sections to those offering prices for the equipment to be purchased.

At the same time, equipment should not be overspecified. Equipment vendors are experts in their field and, as I state elsewhere in this book, their expertise should be utilized to the fullest. Many equipment vendors simply follow specifications in making a proposal. Any aspects of the specification that can be left to vendor discretion should be, to allow the vendor the freedom to exercise their expertise and maximize the chances that they will offer better (i.e., safer, more robust, more economical) designs.

## Process flow diagram

The process flow diagram (PFD) is a visual representation of the mass and energy balance. The PFD treats unit operations more simply than the P&ID (see "Piping and instrumentation diagram" section). Unit operations are shown using ISO or British Standard (BS) P&ID symbols or sometimes as simple blocks; pumps are shown, as are the main instrument loops (the controller and the final element) (Fig. 3.1). It is also useful to show main isolation and ESD valves on the PFD. This makes it easy to read at-a-glance where the isolatable sections are. This is more helpful for operations, but can be useful during design safety studies.

Although there are generally recognized "minimum" requirements for a PFD, specific company standards may dictate that additional items be added as well.

The lines on the PFD are labeled in such a way as to summarize the mass and energy balance, with flows, temperatures, and compositions of streams. It is also good

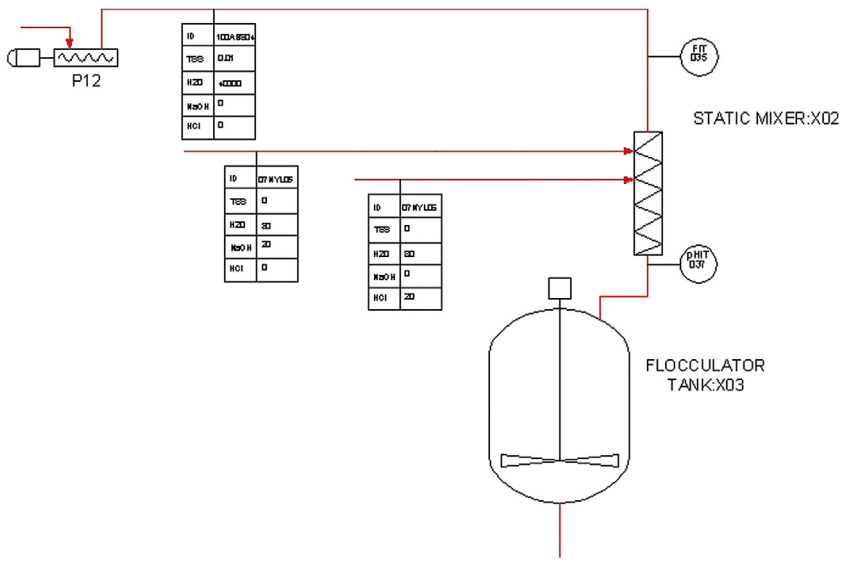



**Figure 3.1** Process flow diagram for the pH correction section of a water treatment plant.

practice to show heat exchanger duties as this can help with the identification of potential energy savings during review meetings.

Please do not call the PFD a flow sheet, as this term can be used to mean quite a few different things (for my suggested use of the term in a process plant design context see Chapter 15: How to lay out a process plant). Neither should you think that a simulation program printout is a substitute for a professional PFD conforming to a recognized standard. PFDs typically form the basis for control room mimic screens: unnecessary/extraneous data should therefore be left out, as it could otherwise get in the way of operators easily grasping what is going on at any given time.

The block flow diagram (BFD) used in academia as a simplified substitute for a PFD is not something I have seen used in practice, other than when drawn on a beermat in a pub discussion, though it might be useful when presenting ideas to nontechnical types without knowledge of PFD symbols.

In the United Kingdom/Europe BS 5070, the general British Standard for engineering diagrams, together with BS EN ISO 10628, apply to the PFD. The symbols used on the PFD should ideally be taken from BS EN ISO 10628, BS1646, and BS1553. There are corresponding US standards.

## Piping and instrumentation diagram

The P&ID is a drawing which shows all instrumentation, unit operations, valves, process piping (connections, size, and materials), flow direction, and line size changes both symbolically and topographically (Fig. 3.2). Thus it is not a scale drawing, and lines on a P&ID turning corners mean nothing, though the joining or splitting of three or more streams is meaningful.

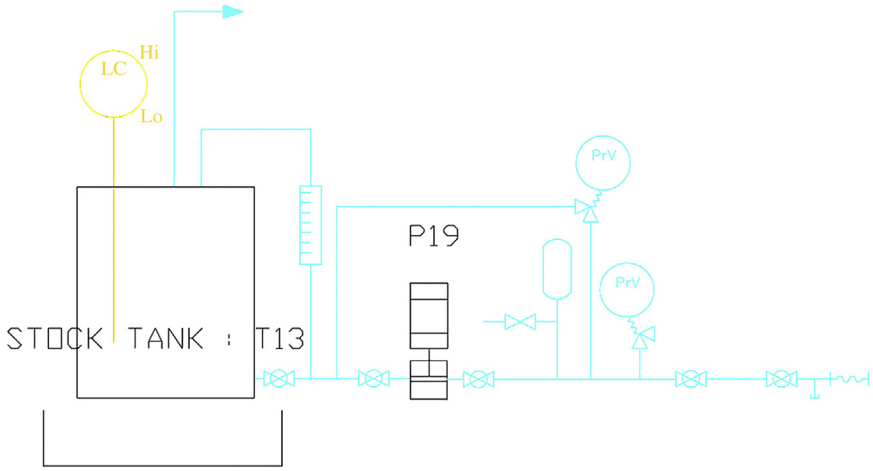



**Figure 3.2** Extract from a piping and instrumentation diagram.

The P&ID is the process engineer's signature document, and its purpose is to show the physical and logical flows and interconnections of the proposed system. Recording them visually on the P&ID allows them to be discussed with software engineers, as well as other process engineers. There are a great many variants in additional features between industries, companies, and countries, but producing the drawing to a recognized standard makes it an unambiguous record of design intent, as well as a design development tool. This is, however, rather idealist. I have only ever worked for one client who produced unmodified BS P&IDs.

The standards for the symbols which should ideally be used by British engineers are BS EN ISO 10628, BS1646, and BS1553 and, like all engineering diagrams, a P&ID should be compliant with BS 5070. Having said how things "should be," how things "actually are" is that many companies and industries have their own internal standards for P&IDs. Professional engineers get used to the range of symbols and conventions commonly used on P&IDs (though I try to shield my students from this at first to avoid confusion).

There are also a number of P&ID conventions which do not appear in standards; the idea being that all P&IDs have a typical "feel" so that they can be quickly and accurately interpreted by engineers not necessarily familiar with the company/process:

- Flow comes in on the top left of the drawing and goes out at the bottom right.
- Process lines are straight and either horizontal or vertical.
- Flow direction is marked on lines with an arrow.
- Flow proceeds ideally from left to right, and pumps, etc. are also shown with flow running left to right.
- Sizes of symbols bear some relation to their physical sizes: valves (at maybe 1 mm tall as printed) are smaller than pumps (at maybe 10 mm tall as printed), which are in turn smaller than vessels (approximately 50 mm tall as printed), and the drawn sizes of symbols reflect this.
- Similarly, major process, utility, vent/drain, and instrument impulse line sizes are often drawn at different weights to reflect their relative physical size.
- Unit operations are tagged and labeled.
- Symbols are shown correctly orientated: vertical vessels are shown as vertical, etc.
- Entries and exits to tanks connect to the correct part of the symbol—top entries at the top of the symbol, etc.
- Where it is necessary to include certain design/operating considerations which cannot be communicated in symbolic form, "NOTES" are often added to the drawing to provide further data;

Less complex P&IDs produced during earlier design stages will normally come on a small number of ISO A1 or A0 drawings, but the P&IDs for a complex plant may be printed in the form of a number of bound volumes where every page carries a small P&ID section. This requires many continuation flags on the inlet and outlets of drawings so that a line can quickly be traced to subsequent drawings.

Every process line on the drawing should be tagged in such a way that its size, material of construction, and contents can be identified thus:

| Number showing Nominal Bore (N.B.) in mm | Letter code for material of construction | Unique line number | Letter code for contents |
|---|---|---|---|
| 150 | ABS | 004 | CA |

In the example above, a line tagged 150ABS004CA would be a 150 mm NB line made of ABS (plastic), numbered 4, containing compressed air.

Personally, in common with many other designers, I number the main process line components first, increasing from plant inlet to outlet. Therefore line 100ABS001CA would, for example, normally be upstream of line 150ABS004CA above. Design development can, however, mean that this gets a bit muddled on the as-built version of the drawing, especially lines added later in the project.

Every valve and unit operation on the P&ID will also be tagged with a unique code; a common key is given in Table 3.1. The letter code will be followed by a unique number for that coded item.

Similarly, every instrument will be given a code as set out in BS1646 as follows:

First letter—measured parameter:

L = level;

P = pressure; and

T = temperature.

Additional letters—what is done with the measurement (you can have more than one of these):

I = indicator;

T = transmitter; and

C = controller.

**Table 3.1** P&ID tag table

| | |
|---|---|
| ***Valves*** | |
| MV | Manual valve |
| AV | Actuated valve |
| FCV | Flow control valve |
| CV | Control valve |
| ESV | Emergency shutdown valve |
| ***Unit operations*** | |
| U | Unit |
| T | Tank |
| P | Pump |
| B | Blower |
| C | Compressor |

The British Standards cover these conventions in more detail. However, in summary, the letter code will be followed by a unique number for that coded item, for example, PIT1 would normally be the first pressure indicator/transmitter on the main process line.

It is also common to see the design information for each major equipment item displayed along the top of the drawing (e.g., for a pump: rated head, flow, and motor power).

The P&ID also frequently shows useful termination points between vendor and main contractor, and between main contractor and equipment supplier, and pipe specification break points.

While it is not best practice, vendor P&IDs for skid- or packaged-mounted items may not be upgraded to "project standard." Instead, a simple drawing with inlets and outlets to a big box that says "refer to vendor drawing xxx" may be considered sufficient.

The P&ID is a master document for Hazard and Operability (HAZOP) studies. P&IDs are typically "frozen" prior to the HAZOP study and will be updated based on HAZOP outcomes. After this point, all changes are made via a management of change process to avoid invalidating the study results or unknowingly introducing risks/conflicts.

Sometimes, due to unforeseen construction conflicts or enforced last minute design changes, the plant cannot be built exactly to the "issued for construction" (IFC) drawings. It is therefore important, following completion of the construction/installation stage, that the P&IDs (and other documents where necessary) are updated to reflect the "as-built" nature of the system.

## Functional design specification

A functional design specification (FDS) is sometimes called a control philosophy, although both of these terms are used in other contexts to mean other things. The document I am referring to describes (ultimately, in practice, for the benefit of the software author) what the process engineer wants the control system to do.

It starts with an overview of the purpose of the plant and proceeds to document, one control loop at a time, how the system should respond to all states, including start-up, shutdown, and various failure states.

This is done in clear and straightforward language, designed to be entirely unambiguous and comprehensible by nonspecialists.

It is read in conjunction with the P&ID and refers to P&ID components by tag number and is used alongside the P&ID in HAZOP studies.

## Plot plan/general arrangement/layout drawing

The general arrangement (GA) drawing shows the plant and pipework as it is intended to be installed (or as it was installed in the case of an "as-built" GA).

In professional practice a specialist piping or mechanical engineer may produce the finished drawing, but chemical engineers lay out equipment in space, and produce this drawing as part of their design process (Fig. 3.3).

In the United Kingdom, drawings should conform to BS8888 and show (as a minimum), to scale, a plan and elevation of all mechanical equipment, pipework, and valves which form part of the design, laid out in space as intended by the designer. Where possible, the tag numbers used in the P&ID should be marked on to their corresponding items on the GA as well, to allow cross-referencing.

The inclusion of key electrical and civil engineering details is normal in professional versions, and there are also usually detailed versions for each discipline which refer back to a common master GA.

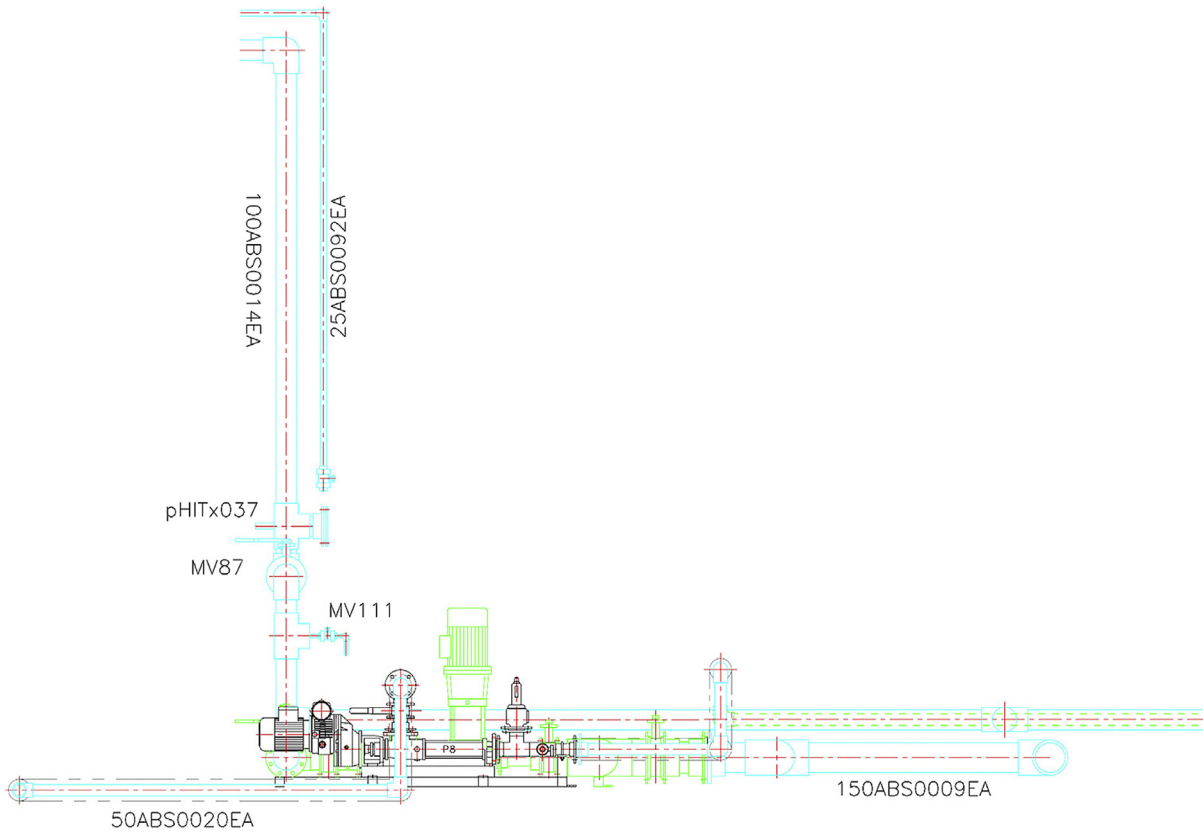



**Figure 3.3** Section of plot plan/general arrangement/layout drawing.

Ideally, the drawing will be produced to a commonly used scale (1:100 being the commonest scale for these drawings) and would be marked with weights of main plant items. Fractional or odd-numbered scale factors should be avoided. Sectional views demonstrating important design features are a desirable optional extra.

## Program

A project "program" or "schedule" most usually refers to a Gantt chart which sets out the planned timescale and resourcing of a project. While a specialist may produce this in a larger company, chemical engineers should be able to produce a competent program as part of the plant design process.

In the absence of a resourced program (Fig. 3.4), any estimate of capital cost must be treated with great suspicion. AACE offer a recommended practice for schedule classification (27R-03) which divides them by their level of detail into levels 1 through 5, in a way which corresponds with their cost estimation levels discussed in Chapter 13, How to cost a design.

The overall project is broken down into discrete tasks, and the time and resources necessary to achieve each of these tasks is estimated. "Milestones" usually appear at the end of phases or tasks, and are often associated with the production of deliverables, triggering payment or another phase of the project. "Dependencies" have to be identified—certain tasks must precede or follow others. Additional time ("float" or "bunce") should be added to the minimum reasonable times for each task, to reflect the uncertainty of the estimate.

A program can then be generated which shows a reasonable estimate of the time to complete all tasks, which can be analyzed to see which activities set overall project time. The critical path through a program involves the chain of activities whose completion is critical to overall program length.

Microsoft market a programming tool called "Project" which can be used to produce this document to a professional-looking standard, though in practice, other specialist tools such as "Primavera" are at least as commonly used by specialist project programmers.

## Cost estimate

### Academic approach

Cost estimation is usually taught in academia using the Main Plant Items/Factorial method, a method I have never once seen used in professional practice, though the prices it produces are normally acceptable as very broad ballpark estimates.

It is well explained in Sinnott and Towler (aka Coulson and Richardson 6), a book all chemical engineers should be familiar with, so I will not reproduce it in detail. In outline, however, student-style pricing goes something like this:

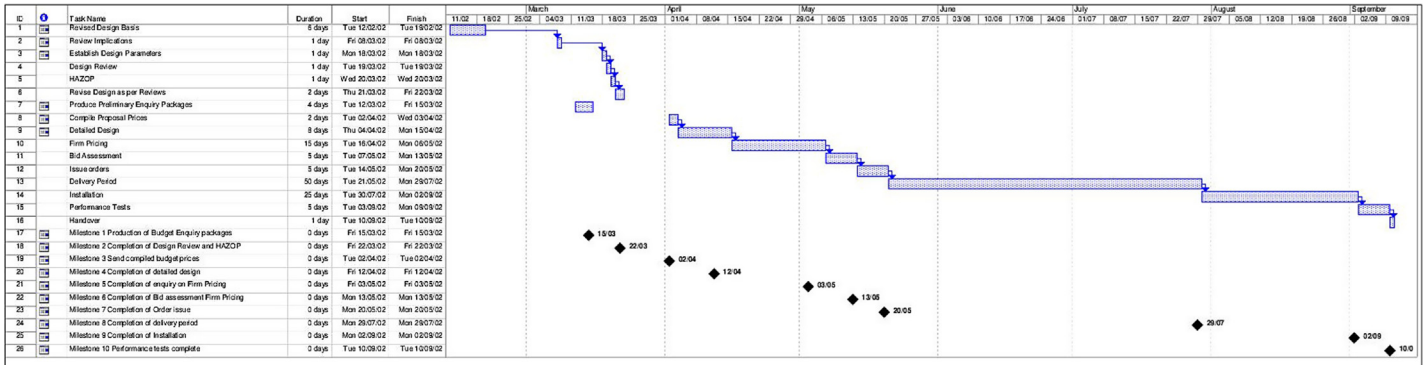



**Figure 3.4** Example Gantt chart.

- Price up your main unit operations, probably using curves of unit price against duty.
- Use factors which accompany curves to account for quality of materials, pressure, etc.
- Multiply prices by the CPI (Chemical Price Index) or similar indices to reflect sector-specific inflation since curves were drawn.
- Convert prices obtained to desired currency at today's prices.
- Add together all the prices.
- Multiply this total by Lang factors to estimate cost of all the other items and services necessary to get a complete plant (around 4).
- Marvel at how big the numbers are (even though they are probably a radical underestimate).

The technique does, however, raise a number of important issues, and gives a feel for the relationships between the prices of the inputs to a project.

Students come away with the useful impression that the cost of a complete plant is a great deal more than the cost of delivering its main unit operations to site, and that electrical and civil costs in particular are very significant. It also introduces students to the idea that plants are built to make a profit—one of the Lang factors even has that name.

It is, however, usually insufficiently powerful to genuinely resolve differences between options—the margin of error is probably more like $\pm 50\%$ than the $\pm 10\%$ many of my students think it is.

This is, however, incredibly rigorous in contrast to the version of the "economic potential" technique I have seen used by academics, who just want to get to the pinch analysis as soon as possible, and don't wish trivia like safety, cost, and robustness to get in the way. Their technique is as follows:

- Google the bulk price of the proposed feedstock ($F$) and expected product ($P$).
- If $P > F$, any process which turns $F$ into $P$ is economic.

The former technique might be a bit woolly, but the latter is operating at an accuracy of $\pm$ several hundred percent. It is not merely worthless; its use encourages overly complex and uneconomic design choices. It does, however, have the advantage of taking only a few seconds.

## Professional budget pricing

Nonbinding "budget" estimates are produced or sought to allow budgets to be set for a project at the conceptual stage. Even these least rigorous real-world pricing exercises tend to start from quoted prices for main plant items. If you work in a contracting company, reasonably recent quotes for reasonably similar equipment will usually be available.

Costs of control panels, software, electrical and mechanical installation, and civil and building works will also be priced based upon past quotations or rules of thumb.

Internal cost will be estimated based on experience and/or rules of thumb. A good chunk of contingency will be added to reflect the high degree of uncertainty at this early stage of the job.

Someone who does this for a living will be able to produce a ±30% budget price in this way in a few hours.

## Professional firm pricing

If a company is going to contract to build a plant for a fixed sum of money, it needs to be certain that it can make a profit at the quoted price.

Some companies will leverage existing relationships with vendors to purchase equipment themselves for the contractor to simply install—this is known as "free-issuing."

Otherwise, commercially binding offers of equipment prices are obtained from multiple sources for specific items whose specifications come from reasonably detailed design.

Civil, electrical, and mechanical equipment suppliers and installation contractors are also invited to tender for their part of the contract.

Internal quotations are also usually obtained from discipline heads within the company for the internal costs of project management, commissioning, and detailed design.

There may well be negotiations with all of these information providers. Ideally there will be multiple options for equipment supply and construction. Cost estimates can be affected by whether or not fabrication shops are busy. Labor costs too can be very dynamic depending on supply and demand at the site location, so a price based on a single quotation is far less robust than one which has a broader base.

Once there are prices for all parts and labor, residual risks are priced in. The profit, insurances, process guarantees, defect liability periods, and so on are then added. This exercise can take a good-sized team of people weeks or months to complete, and the product is a ±1%–5% cost estimate.

There was an article in *The Chemical Engineer* magazine a few years back about a company using an Excel spreadsheet they had developed to produce Class 3 budget price estimates at an early stage by a process they call "conceptual design emulation." I have no idea how well this works, but I do know it isn't free, although the conventional approach is far from cheap.

## Equipment list/schedule

A schedule or table of all the equipment which makes up the plant is usually first produced at the FEED stage. Tag numbers from drawings are used as unique identifiers,

and a description of each item accompanies them. There may be cross-referencing to P&IDs, datasheets, or other schedules.

Similar schedules are produced for all instrumentation, electrical drives, valves, and lines (Fig. 3.5 and Table 3.2).

Some modern software promises to remove the necessarily onerous task of producing these schedules from the junior engineer's task-list. The nit-picking rigor required is certainly arguably more suited to the infinitely patient stupidity of computers than the inventive mind of a professional engineer, but schedules are still mostly generated by unlucky people (though perhaps luckier than the 50% of engineering graduates who never become engineers due to oversupply).

## Datasheets

Datasheets gather together all the pertinent information for an item of equipment, mainly so that nontechnical staff can purchase it. Process operating conditions, maximum design conditions, service type (corrosive/flammable/toxic, etc.), materials of construction, duty points, and so on are brought together into this document to explain to a vendor what is required (Fig. 3.6).

Datasheets need to be cross-checked with a number of drawings, calculations, and schedules, and care has to be taken to ensure that they are in accordance with the latest revisions. This is a more skilled task than the generation of schedules and will therefore be likely to remain in the purview of young engineers for years to come. Some data can only be provided by the vendor based on their offered equipment, so it is not uncommon for datasheets at the early stages of design to be annotated with "vendor to confirm" (VTC) or "to be confirmed" (TBC) statements.

## Safety documentation

As well as the following key documents, there may also be Escape & Evacuation Risk Assessments, HAZIDs, Quantitative Risk Assessments, and many others, all of which may be summarized in a Design Safety Case.

## Hazard and Operability study

As I and all professional engineers use the term, a HAZOP study is a "what-if" safety study.

Confusingly for new graduates, academia has developed a procedure improperly called HAZOP in which students add instruments to PFDs to make them into a kind of P&ID. This is not HAZOP, and neither are HAZOPs the design reviews they are often made into in academia (and sometimes the real world). My fellow engineers have complained to me of the "leave it to the HAZOP" mentality which such

## INSTRUMENT SCHEDULE

| | | | | | Rev 0 | Rev 1 | Rev 2 | Rev 3 | Rev 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Project | Permanent Effluent/Groundwater Treatment Plant | Project Ref | | Prepared by | SMM | | | | | | | |
| Project Site | | Document Ref | | Checked by | STM | | | | | | CONFIRM | |
| Client | | | | Date | 30/04/2004 | | | | | | | |
| Client Ref | | | | Approved by | | | | | | | | |
| | | | | Date | | | | | | | | |

| Inst No | Description | Supplier | Type | P&ID no | Line No | Size (mm) | Material of Constr | Design Fluid conditions | | Operating range | | Alarm conditions | | Notes | CSL /Equip supplier |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Press (bar) | Temp ( C ) | Min | Max | H | L | | |
| LC001 | MH 102 (PS1) Level Controller | Milltronics | Ultrasonic | 90501 002 | | n/a | proprietary | atmos | ambient | 0 | 5000 mm | Y | Y | Milltronics Multiranger with 2 sensors in sump, panel mounted indicator. Some alarms from PLC | CSL |
| PI002 | Pressure Indicator | TBA | Bourdon | 90501 002 | 0056 | tbc | SS enclosure | 5 | ambient | 0 | 2 bar | N | N | Standard 50/75/100 mm pressure gauge | CSL |
| PTx003 | Pressure Transmitter | GEMS | Transducer | 90501 002 | 0056 | n/a | 316 ss | 6 | ambient | 0 | 2 bar | Y | Y | Pressure transmitter and panel mounted indicator | CSL |
| FTx004 | Flow Transmitter | ABB | Electromagnetic | 90501 002 | 0056 | 300 | proprietary | 16 | ambient | 0 | 120 m3/hr | Y | Y | AB Magmaster inline meter with panel mounted display | CSL |
| LC005 | MH 92A (PS2) Level Controller | Milltronics | Ultrasonic | 90501 002 | | n/a | proprietary | atmos | ambient | 0 | 5000 mm | Y | Y | Milltronics Multiranger with 2 sensors in sump, panel mounted indicator. Some alarms from PLC | CSL |
| PI006 | Pressure Indicator | TBA | Bourdon | 90501 002 | 0062 | tbc | SS enclosure | 5 | ambient | 0 | 2 bar | N | N | Standard 50/75/100 mm pressure gauge | CSL |
| PTx007 | Pressure Transmitter | GEMS | Transducer | 90501 002 | 0062 | n/a | 316 ss | 6 | ambient | 0 | 2 bar | Y | Y | Pressure transmitter and panel mounted indicator | CSL |
| FTx008 | Flow Transmitter | ABB | Electromagnetic | 90501 002 | 0062 | 300 | proprietary | 16 | ambient | 0 | 240 m3/hr | Y | Y | AB Magmaster inline meter with panel mounted display | CSL |
| LC009 | MH 55A (PS3) Level Controller | Milltronics | Ultrasonic | 90501 002 | | n/a | proprietary | atmos | ambient | 0 | 5000 mm | Y | Y | Milltronics Multiranger with 2 sensors in sump, panel mounted indicator. Some alarms from PLC | CSL |
| PI010 | Pressure Indicator | TBA | Bourdon | 90501 002 | 0066 | tbc | SS enclosure | 5 | ambient | 0 | 2 bar | N | N | Standard 50/75/100 mm pressure gauge | CSL |
| PTx011 | Pressure Transmitter | GEMS | Transducer | 90501 002 | 0066 | n/a | 316 ss | 6 | ambient | 0 | 2 bar | Y | Y | Pressure transmitter and panel mounted indicator | CSL |
| FTx012 | Flow Transmitter | ABB | Electromagnetic | 90501 002 | 0066 | 300 | proprietary | 16 | ambient | 0 | 540 m3/hr | Y | Y | AB Magmaster inline meter with panel mounted display | CSL |

**Figure 3.5** Extract from an equipment schedule.

**Table 3.2** A schedule of schedules with example column headings

| Schedule type | Column 1 | Column 2 | Column 3 | Column 4 | Column 5 | Column 6 | Column 7 |
|---|---|---|---|---|---|---|---|
| Instrument schedule | Instrument no. | Description | Supplier | Instrument type | P + ID tag no. | Line no. | Size |
| Valve schedule | Valve no. | Description | Supplier | Valve type | P + ID tag no. | Line no. | Size |
| Drive | kW rating | Description | Supplier | Starter type | – | – | – |
| Line | Line no. | Description | Supplier | Line type | P + ID tag no. | Connection type | Size |
| Equipment | Equipment no. | Description | Supplier | Equipment type | P + ID tag no. | Line no. | Rating |

**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 ancillaries 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 information not requested which the supplier believes will add to his offer to be provided on separate sheets

| Performance parameter | Description | Pipework | Valves | Option1 | Option 2 | Option 3 | Option 4 |
|---|---|---|---|---|---|---|---|
| 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) | | | | | | | |
| Starting (Star delta/DoL) | | | | | | | |
| Starting current (amp) | | | | | | | |
| **Price for complete 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 3.6** Example of an equipment datasheet.

approaches produce in graduates faced with design challenges. You should strive to do it right in the design stage. In an academic setting, the calculations and specifications of equipment may stand in for the datasheets which would be available to a real HAZOP, but the procedure should otherwise be identical to a real HAZOP, to avoid confusing students and getting them into the habit of ducking design challenges.

A properly conducted HAZOP requires, at a minimum, a P&ID, FDS, process design calculations, and information on the specification of unit operations, pumps, etc., as well as probably eight professional engineers from a number of disciplines. Depending on the project stage, vendor reps and operations/maintenance staff may be present as well. It is also good practice to ensure that at least one person (sometimes the chairman) is "independent" from the project to avoid "blinkered" thinking.

However, to ensure that the study is productive, it is also important to limit the number of nonessential people in the room, otherwise everyone just ends up talking at once and nothing gets done and/or things get missed out.

The report produced by the participants will usually nowadays include a full description of the line-by-line (or node-by-node) permutation of keywords and properties used in carrying out such a study, but it was more usual in the past to produce a summary document listing only those items which were identified by HAZOP as being problematic, what the problems were, and how it was intended to avoid them.

In today's litigious environment, a full and permanent record of all that was discussed and considered in a HAZOP is increasingly considered prudent. This may most conveniently be achieved by video recording of the entire procedure. Recording the entire procedure one way or another is now considered best practice.

As I previously stated, HAZOP is not a design review. Engineers tend to try to solve problems as they are presented to us, and HAZOPs can quickly get side-tracked by well-intentioned debate on how to solve a problem rather than concentrating on the purpose of the study. Actions should therefore be assigned and carried out later.

Since students frequently have a great deal of difficulty imagining what they might do about any problematic upset conditions they have identified, I have included at Appendix 2 an upset conditions table from *Process Plant Design and Operation—Guidance to Safe Practice*, by Scott & Crawley which offers useful guidance.

## Zoning study/hazardous area classification

Zoning the plant with respect to the potential for explosive atmospheres and ignition sources is not a strictly quantitative exercise (Fig. 3.7).

It is common for a small number of engineers to get together with design drawings to produce a zoning drawing or drawings showing the explosive atmosphere zoning they think appropriate for the various parts of the plant. There are more details on this in Chapter 15, How to lay out a process plant.

## Design calculations

These are usually not really a deliverable at all, since only other process engineers can understand them, and designers are normally loath to release them to the client. Design proceeds by a number of stages, from initial coarse approximations to the level

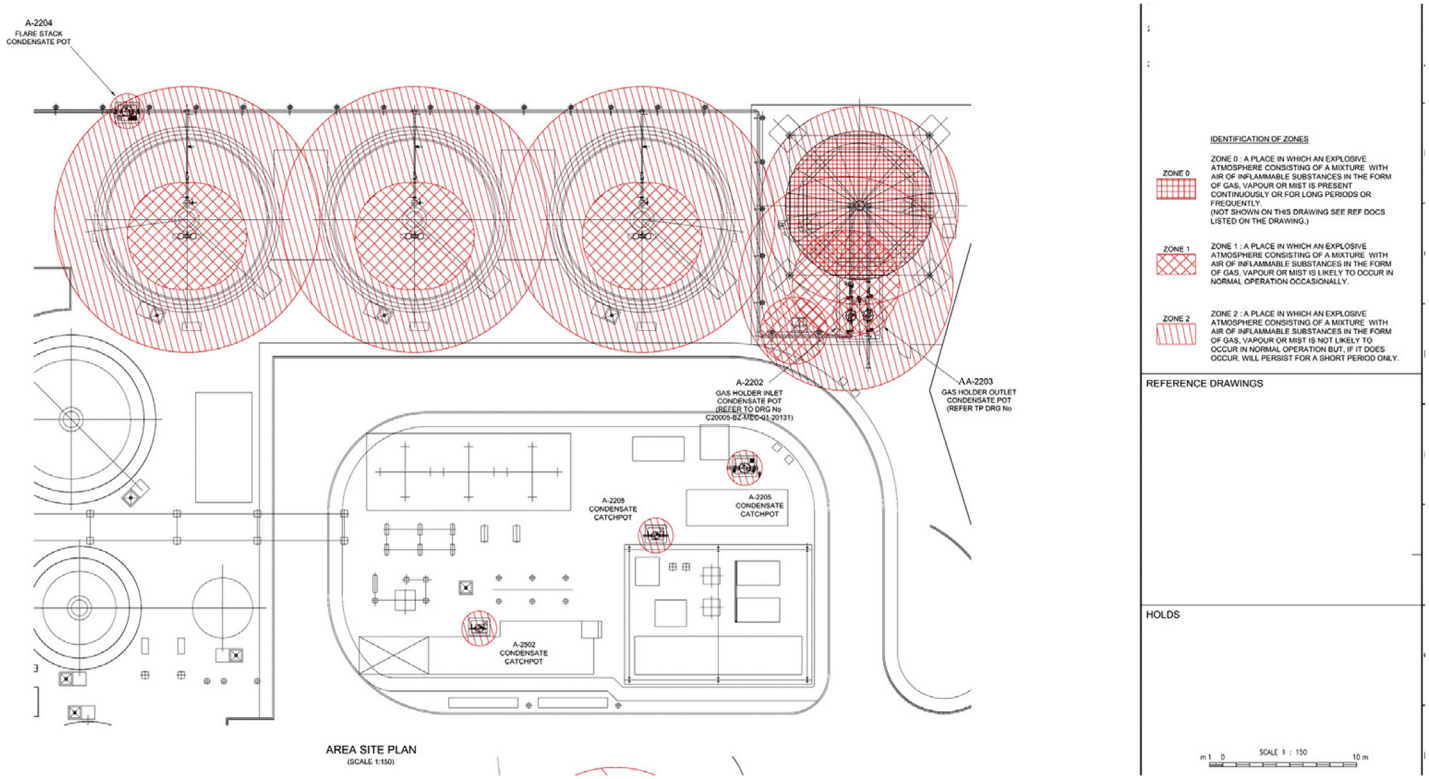



**Figure 3.7** Zoning study/hazardous area classification. *Copyright image reproduced courtesy of Doosan Enpure Ltd.*

of fineness specified in the design brief issued. Academic exercises are normally carried out around the level of detail used for budget costing (though they often use tools which would not be used at this stage in practice).

If the design is not utterly novel, heuristic design is realistic for the majority of items. First-principles design should not be favored for items which are commercially available, because this is unrealistic, and is the opposite of professional practice (and, in a teaching environment, it is difficult to detect cheating). If it is desired to evaluate students' ability at first-principles design, a genuinely completely novel item should be chosen.

Process designs normally aim to determine certain key dimensions, areas, and volumes based on a number of parameters. For nonnovel processes there may be rough rules of thumb, established design guides, standards, or codes of practice.

In professional practice these will be combined to inform a design sizing. Only in the near-complete absence of relevant guidance of this sort will first-principles design be used, and large design margins will be added to reflect the high degree of uncertainty.

More generally, an understanding of the degree of applicability of the design methods used and uncertainty around design data should be reflected in a stated added design margin.

The design calculations should include consideration of construction, corrosion, reasonable service life, materials selection, cost, and practicality, and should cover all foreseeable operating conditions, including start-up, shutdown, and maintenance, as well as environmental considerations such as power outage, and plausible natural and man-made disasters. The range of variability in feedstock flows and compositions under normal conditions should be considered as well as these more extreme variations from steady state.

The opaque outputs from modeling and simulation programs are no substitute for transparent process design calculations, as it is easily likely that neither the author nor the checker can readily understand what is going on in the simulation.

In assessing process design calculations, it should be borne in mind that the point of such calculations is not to demonstrate proficiency in mathematics or chemistry. The point of process design calculations is to produce a minimum specification for an item, so that the next size up (or sometimes down) commercially available unit can be purchased with a reasonable degree of confidence in its robustness.

It is also common (and sometimes desirable) to include a certain degree of overdesign to allow for future expansion (in the case of pump flowrate, for example) or equipment deterioration over time (loss of heat transfer area within exchangers due to fouling or broken tubes). Where this is done, care should be taken to ensure such overdesign is credible and not excessive. Overdesign upon overdesign is particularly to be avoided. A plant can be too big as well as too small.

Process design is not a matter of finding exactly the right-size item, but of finding one large and flexible enough such that we can be sure that the commissioning engineer can make it work.

Complementary with the process design calculations are the calculations used to size pumps, pipework, channels, and so on, which we might collectively refer to as hydraulic calculations.

Precise determination of dynamic heads by fluid mechanics is extremely difficult in practice and, furthermore, completely unnecessary. There are a number of heuristics which may be used to carry out rapid determinations of approximate head losses to distinguish between competing conceptual designs and produce initial layouts. The use of appropriate tabulated values and nomograms for this purpose should be entirely acceptable for early-stage design.

More detailed hydraulic calculations should be required for the final selected design. These should at a minimum degree of rigor and be based on one of the friction factor methods, with *k*-values for fixtures and fittings. All dimensions used in the calculations should refer back to the dimensioned GA drawing or "iso." The calculations should be based on actual selected commercially available pipework, valves, pumps, instrumentation, and so on. (For those teaching this subject, the internet means that our students will no longer need to bother manufacturers to obtain these data, so we have no reason not to expect this degree of realism.)

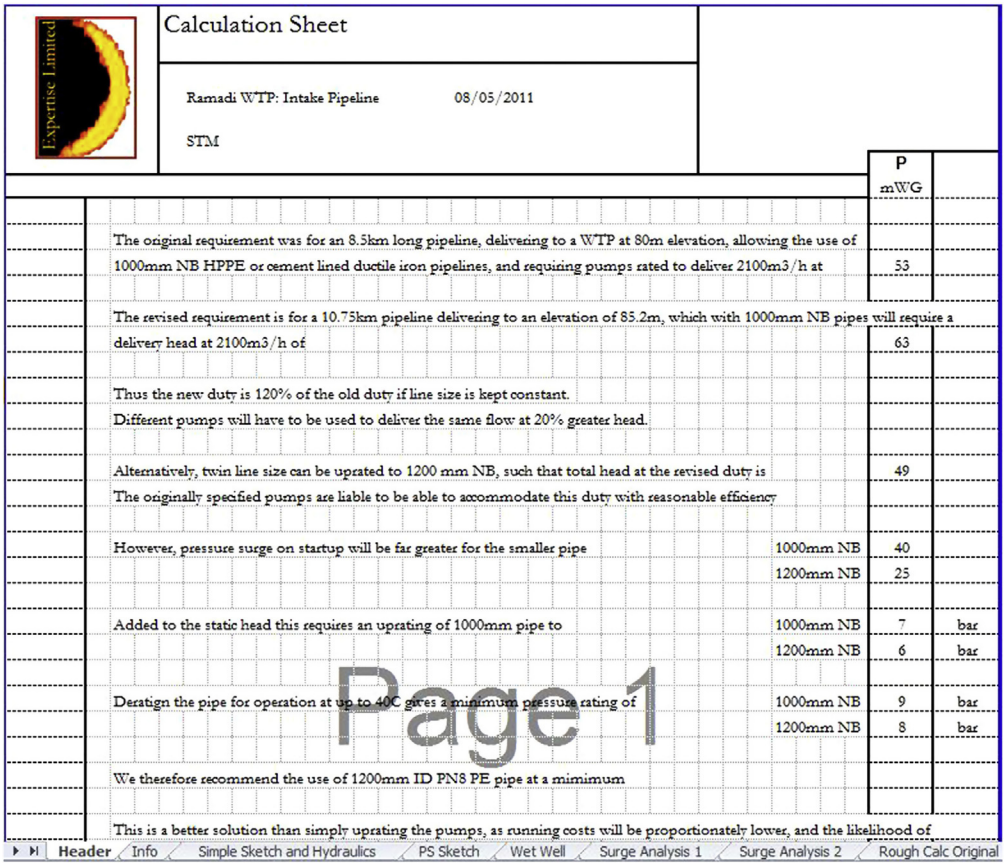
A fairly common approach (and my personal preference) is to use one tab of a spreadsheet program for each unit operation, and to link the inputs and outputs to the tabs in such a way that the whole spreadsheet is a standalone model encompassing mass and energy balance, unit operation sizing, and hydraulic calculations. I use a standard template which looks like an engineer's calculation pad. Each tab has a vertical column of these virtual pages in which the argument and calculations for that unit operation are set down in a logical and readable form (Fig. 3.8).

However it is achieved, transparency and clarity of design intent should be an important factor in evaluating process and hydraulic design calculations. Calculations should be double-spaced, ideally on an engineers' calculation pad or electronic facsimile, and every step should refer to any drawings, design standards, or other references upon which it relies.

## Isometric piping drawings

At the detailed design stage, piping isometrics are produced for larger pipework, either by hand on "iso pads" or by computer-aided design (CAD) (Fig. 3.9).

Isometric piping drawings are not scale drawings; they are dimensioned drawings. They are not realistic, pipes are shown as single lines, and symbols are used to represent pipe fittings, valves, pipe gradients, welds, etc. Lines, valves, etc. are tagged with the same codes used on the P&ID and GA. Process conditions like temperature, pressure, and so on may also be put on the iso.


Calculation Sheet

Ramadi WTP: Intake Pipeline 08/05/2011

STM

| | | P mWG | |
|---|---|---|---|
| The original requirement was for an 8.5km long pipeline, delivering to a WTP at 80m elevation, allowing the use of | | | |
| 1000mm NB HPPE or cement lined ductile iron pipelines, and requiring pumps rated to deliver 2100m3/h at | | 53 | |
| The revised requirement is for a 10.75km pipeline delivering to an elevation of 85.2m, which with 1000mm NB pipes will require a | | | |
| delivery head at 2100m3/h of | | 63 | |
| Thus the new duty is 120% of the old duty if line size is kept constant. | | | |
| Different pumps will have to be used to deliver the same flow at 20% greater head. | | | |
| Alternatively, twin line size can be uprated to 1200 mm NB, such that total head at the revised duty is | | 49 | |
| The originally specified pumps are liable to be able to accommodate this duty with reasonable efficiency | | | |
| However, pressure surge on startup will be far greater for the smaller pipe | 1000mm NB | 40 | |
| | 1200mm NB | 25 | |
| Added to the static head this requires an uprating of 1000mm pipe to | 1000mm NB | 7 | bar |
| | 1200mm NB | 6 | bar |
| Deratign the pipe for operation at up to 40C gives a minimum pressure rating of | 1000mm NB | 9 | bar |
| | 1200mm NB | 8 | bar |
| We therefore recommend the use of 1200mm ID PN8 PE pipe at a mimimum | | | |
| This is a better solution than simply uprating the pumps, as running costs will be proportionately lower, and the likelihood of | | | |



**Figure 3.8** Example intake pipeline design calculations.

It may well be that "clashes," where more than one pipe or piece of equipment occupy the same space, are only identified at the stage of production of isos, so design cannot be considered complete before isos are produced.

The purpose of the iso is to facilitate shop fabrication and/or site construction. They are also used for costing exercises and stress analysis, as they conveniently carry all the necessary information on a single drawing.

Producing isos by hand is quite time-consuming. There are some CAD systems now which can automatically produce isometric drawings from the GA drawings. It is claimed that these reduce drafting errors and inconsistencies, spot clashes earlier, facilitate links to other software such as costing programs, and save time. Hand drafting is, however, still the norm in many industries. The choice of approach is partly affected by the size of a project: for a large project with many isos there is justification for such a CAD system to save cost and time to produce (and in future revise) these iso drawings.

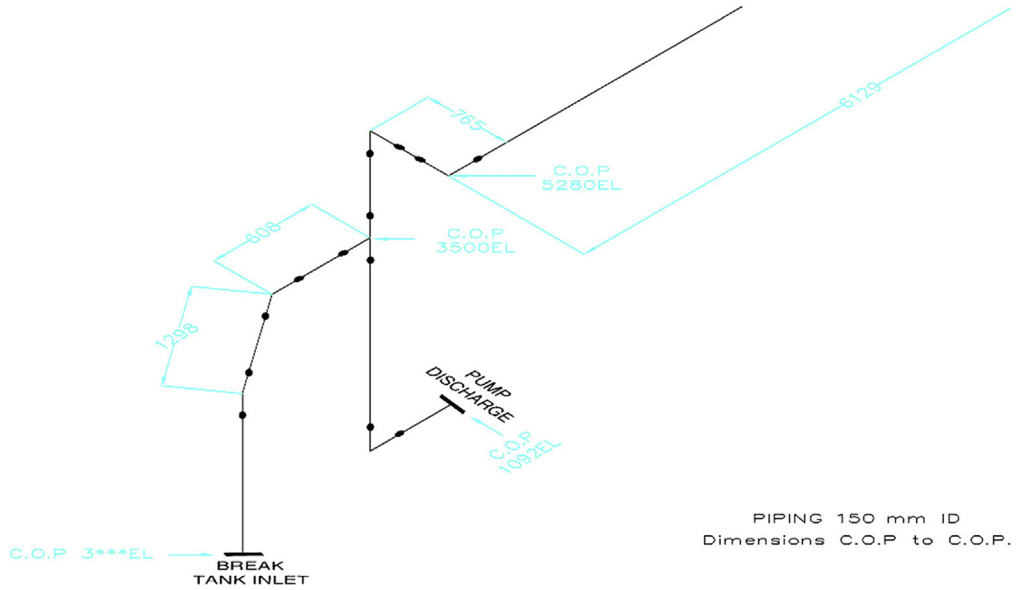



**Figure 3.9** Isometric pipeline drawing.

## Simulator output

This is not really a deliverable at all, as at best only other process engineers can understand it. The purpose of modeling and simulation on those occasions where it might be used by process designers is to provide supporting information.

I have also seen simulator outputs used to attempt to resolve conflicts between engineers as to which heuristics are most applicable, but in such circumstances it becomes very clear that the output of such programs has a great deal to do with who is choosing the inputs.

If both engineers are competent, the use of a model in my experience merely makes it clear that they are arguing about which design basis or heuristic is most applicable to the situation in question. This should have been obvious without the modeling exercise.

## Three-dimensional model

Three-dimensional (3D) software models are becoming increasingly important on larger projects as a deliverable. They allow (for good or ill) nontechnical staff who cannot read engineering drawings to have input into the design. Equipment such as 3D scanners can be used to scan existing process buildings and convert them into a 3D model, saving drafting time and increasing accuracy, but they always require a lot of resources to set up.

While this approach is causing problems with front loading of projects for design houses, 3D models can help to identify operability issues, layout clashes, and deviations from company (or customer) design standards early—before equipment gets placed in the field. It is always easier and cheaper to correct on paper than once something gets built.

## Document control/management of change

Document control is not a process design deliverable as such, but without it the deliverables are worthless. It is crucial to record all the documentation and associated revisions, whether produced by the engineering team, received from suppliers and clients, or issued internally and/or externally. While setup can be time consuming, the benefit of harmonization between all parties engaged in the project is critical to success.

## Further reading

British Standards Institute. (1977). *Specification for graphical symbols for general engineering. Piping systems and plant*. BS 1553-1, BSI Standards.

British Standards Institute. (1988). *Engineering diagram drawing practice. Recommendations for general principles*. BS5070-1, BSI Standards.

British Standards Institute. (1999). *Symbolic representation for process measurement control functions*. BS1646, BSI Standards.

British Standards Institute. (2017). *Technical product documentation and specification*. BS8888, BSI Standards.

International Standards Organization. (2001). *Flow diagrams for process plants—General rules*. BS EN ISO 10628, BSI Standards.

Kletz, T. (1999). *Hazop and Hazan*. London: Institution of Chemical Engineers.

Sinnott, R., & Towler, G. (2009). (5th ed.). *Chemical engineering: chemical engineering design*, (Vol. 6). Oxford: Butterworth-Heinemann/Elsevier.

# CHAPTER 4

# Twenty-first century process plant design tools

## General

There is a far greater use of computers in process plant design than when I started in practice. Hand drafting of most drawings is no longer really practiced, and handwritten calculations are also uncommon. Neither do we need to write our own computer programs as I had to if I wanted a computer to do something for me back in 1990.

There is also some use of modeling and simulation programs to support design activity, especially in certain sectors. This has not, however, replaced design activity, and it cannot, for reasons I will explain in this chapter.

Professional plant design engineers worldwide and across sectors only use a small subset of the available programs, largely for reasons of economy and consistency to allow information sharing.

We more or less all use MS Excel, MS Project, and Autodesk AutoCAD. Modeling and simulation programs tend to be sector-specific specialist products. Oil and gas industry specific modeling and simulation programs tend to be popular in universities, but there are equivalent specialist programs (such as the Hydromantis products used in my sector) which never seem to feature in university courses.

Staff in university chemical engineering departments make a lot of use of simulation and modeling programs in their research, and they have consequently started making use of these programs in teaching what they call "design." Some of these programs (e.g., Matlab) are never used by professional engineers, and are being shoehorned into a duty they are unsuited for. Some (notably Hysys) are frequently misused by researchers unfamiliar with professional practice to fill a gap in their own knowledge.

These programs are highly discounted in price or even supplied free to academia whilst often incredibly expensive to commercial users. Thus many of the computer programs used to teach what is known as "process design" in academia do not feature in professional practice.

In this chapter I will discuss a few of the programs actually used by plant designers, as well as some of those misused by researchers for "design" teaching.

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00005-7
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Before I do that, I would like to draw your attention again to how we ought to be using computers, according to the Institution of Chemical Engineer's (IChemE's) Computer-Aided Process Engineering (CAPE) subject group.

## Use of computers by chemical engineers

All the new tools used by chemical engineers are computer-based, and the IChemE guidelines on use of computers by chemical engineers should be followed. The most important thing to understand about these design tools is that they are intended to support, rather than replace, professional judgment. The guidelines summarize themselves with the following key points:

*Management has the overall responsibility for developing appropriate standard procedures and practices and for ensuring that they are followed.*

*It is a professional engineer's legal and professional responsibility to exercise good engineering judgment in making design decisions and, therefore, to satisfy him/herself regarding the adequacy of the information upon which design decisions are based. This means you!*

*Much of this information is today generated by computer-based systems and so the quality of these systems and the skill and judgment with which they are applied to a design problem are a critical part of these responsibilities.*

*The purpose of these Guidelines is to suggest some simple precautions which should be taken to help protect the integrity of proposed engineering solutions and thus to adequately discharge professional responsibilities, for example:*

*What matters is the quality of the engineering decision: focus on "fitness for purpose" of both the computer-based system and the data which is fed into it.*

*Assume that everything is "guilty until proven innocent": you must check and ensure that the computer-based model is appropriate to your needs and that the data (including any data from databanks, etc.) is correctly specified and adequately covers the expected ranges (for example, of temperatures, pressures and compositions).*

*You must check and ensure that the program has worked successfully and that the results are adequate for your purpose: you must satisfy yourself that you fully understand any weaknesses and that you apply them sensibly and with good engineering judgment*

*Sensitivity analysis is a key weapon in identifying where the critical problems lie and in assessing their likely impact on your design decisions.*

*Program development is not a trivial job and to do it well requires special skills and experience.*

*Engineering decisions will be based upon the results generated by these programs. The program must therefore work correctly and proper records must always be kept.*

*Do not hesitate to seek help and guidance from your more experienced colleagues, from your support services or even from the suppliers of the systems concerned (and seek it early, not when things have already gone wrong).*

Unfortunately, these principles are not universally understood. Such programs are consequently being used to carry out tasks they were not intended to be used for. Such misuse is sometimes actively taught in universities as proper practice, and engineering employers consequently have to reeducate their graduate intake.

## Implications of modern design tools

The workhorse computer programs allow for great increases in productivity and the possibility of more decentralized and flexible engineering services. When I graduated, calculations were done by hand on paper pads by engineers. Full-size drawings were exchanged between offices in hard copy by courier. Copying of drawings was done by means of a machine which produced the blue lines on a beige background known as a "blueprint" (and a terrible smell of ammonia). Fax might be used to transmit A4 copy. There might be one PC shared between a dozen engineers, and time had to be booked on it. If you wanted a program, you needed to write it yourself, so it tended to be a bit "buggy."

Now, an engineer working alone at a PC can research alternatives, carry out their own calculations with reliable and extensively debugged programs, generate their own drawings, and collaborate with others worldwide using more or less instantaneous communications. They can send and receive editable versions of their drawings to and from the other side of the world in seconds.

This universal use of computer-aided design (CAD) and web-based communications has also had the effect of closing the drawing offices which were a feature of engineering companies back when I started. There are now drawing offices in India and elsewhere which will produce drawings for you at a fraction of UK drafting rates, but even these rarely feature drawing boards.

The general implication of all modern design tools is that they can harness a great deal of stupid, patient computing power. This can be used to produce models of process plants in MS Excel, dedicated modeling and simulation programs (or even use programs like Matlab to throw ourselves back to the time when we had to write our own programs).

So, we can use computers to produce reliable, transparent models, or models which are rather opaque to all but the most experienced engineers (and therefore quite possibly unreliable). Just as banks will only lend money to people who don't need it, the only people who should use many modern design tools are those who don't need them.

Both lecturers and students often think that, because modeling and simulation programs work on the basis of first principles, their output is somehow more rigorous or better understood than heuristic design. I am, however, fairly sure that even those who write such programs do not completely understand them, as no one can completely understand a computer program beyond a fairly low level of complexity. I am also fairly sure that those who write these programs would not understand the plant "design" produced by such programs, even if they did understand the program itself, for similar reasons of complexity.

Furthermore, a belief that the output of such programs is more trustworthy or transparent than professional approaches shows a lack of understanding that all approaches to engineering design are approximate and heuristic. The professional approach is based on producing a model simple enough for complete human comprehension, founded as directly as possible in empirical evidence and professional judgment, and tested at full scale by generations of professional process designers.

The modeling-as-design approach taught in universities on the other hand is based on a necessarily cut-down version of pure theory, running on a desktop computer in a model which no one fully understands, written by people without any experience in designing process plants, untested at any scale, and never intended to be used as a substitute for real design calculations.

I have always been mistrustful of models that use a lot of very complicated math, as I suspect that it is obscuring a lack of real-world design or operational experience on the part of the program developers. An example from the practice of a reviewer:

> *Once I had to design a reaction-distillation column. There exist quite a lot of publications on the topic, but after studying all this literature I found that nothing was applicable in my case as all models deal with very simplified ideal cases one would not meet in the real world. I even got as far as contacting one of the authors of some of the papers and he admitted that all the models are useless in my case. He admitted that I will have to build a pilot plant to get valid data for my design. I'm afraid that the academic paradigm 'publish or perish' forces people in chemical engineering departments to publish a lot of unnecessary papers producing what might be called 'white noise'. It's my impression that chemical engineering is more of a vocational discipline rather than an academic one. Of course, you need the basics, but you can't become a proper chemical engineer straight from the university.*

## Categories of design

### Unit operation sizing and selection

Universities still teach students approaches to unit operation sizing based on hand calculations using charts dating back to the slide-rule era. Many who do this think it helps students to understand the unit operation—whether this is true or not, it isn't

much to do with modern professional practice, since process plant designers mostly use spreadsheet programs to do their calculations.

Equipment suppliers are the ones who do detailed calculations to specify unit operations (or more likely punch numbers into a proprietary spreadsheet or program), so that what goes on in universities is at best a relic of an earlier era.

Since spreadsheet programs can't read charts, many of these techniques aren't of much practical use any more. We need equations rather than charts to allow us to work with spreadsheets.

Modeling and simulation programs are also used to "design" unit operations, in as much as they are used to model a number of unit operations with a view to writing specifications for the equipment.

This kind of "design" is far more common in operating companies than in the contracting companies or design houses who design complete plants and offer process guarantees for them. Even in operating companies, simulation programs are supposed to support design activity rather than substitute for it.

Operating companies have access to large quantities of real plant-specific data, so they can tune and validate the simulation programs to make them match their plant. Whole-plant designers do not have this luxury, as their plants have not yet been built, and they lose access to operating data for the plants they do build once commissioning is completed.

## Hydraulic design

In the hydraulic calculations used to size pumps and pipework, empirical approximations like the Colebrook–White have superseded the Moody diagram, for the reasons discussed in the last section: MS Excel can't read diagrams.

The modeling and simulation programs used for plant "design" can usually do some hydraulic calculations, but often come with a set of defaults which causes problems for the unwary or uncritical user.

There are quite a number of fluid dynamics modeling programs which can be used for complex fluid dynamics problems, but these are a bit overpowered and slow for the most common hydraulic calculations.

## Mass balance

I would expect that anyone reading this book would know what this is but, just in case, process plant designers work out how much stuff is going to flow from one place to another in their plants by applying a simple principle: if matter is neither created nor destroyed, all the masses of stuff must add up across any closed boundary drawn on the PFD.

This "mass balancing" is usually done by practitioners using MS Excel. It is particularly common and helpful to have one unit operation per tab and have the mass balance expressed in making links between tabs. My suggested methodology is explained in Chapter 9, How to do a mass and energy balance.

## Energy balance

Energy is no more created or destroyed than mass is (other than in nuclear reactors), so we can work out the energy needs and yields of our plant by balancing energy inputs and outputs in a similar manner to a mass balance. This energy balance is usually built into the same MS Excel spreadsheet as the mass balance.

# Tools—hardware

## Mobile devices

Price £1−1000

Virtually everybody has one of these with them all the time nowadays. Mobile devices all have a basic calculator application, which is perhaps why no one can do mental arithmetic any more.

You might need to memorize pi and a few other numbers like root 2 and root 3 to a few decimal places (or you can google them), but I find that the calculator in my mobile phone can do most of my back-of-an-envelope calculations.

Many can also run MS Excel-compatible spreadsheet programs for when you want to do something a little trickier, and have a permanent record of your calculations which you can tweak up in MS Excel later.

When I asked my students to evaluate graphical calculators, one asked me why they would pay £200 for one when everybody already has a mobile device which can do pretty much the same tasks, as well as many other things as well.

## Handheld calculators

Price £10−20

These are the slide rules of the modern era, but mine doesn't make it out of my desk drawer very often nowadays.

Sums I can't do in my head are more likely to be done with my mobile phone than with my far more powerful scientific calculator. Anything remotely tricky is done in a spreadsheet, which allows for easy checking, and automatically records the output of the calculation.

I have a friend who is an enthusiast for the graphical calculators now commonly available, but usually banned from school and university examinations in a way which limits their use in academia.

## Graphical calculators

Price £100–200

My enthusiastic friend tells me that modern graphical calculators can not only produce full-color graphs, they can also do calculus.

I guess they might be very handy once you have mastered their operation, but they are ultimately a kind of handheld calculator and for me, therefore, are similarly unlikely to see much daylight.

The use of a spreadsheet program on a PC automatically produces a checkable, annotated, and fairly permanent record of the calculations you have carried out, and the assumptions made in doing so. Quality assurance (QA) and traceability of documentation are very important in professional practice.

It turns out that these calculators are easily linked to a PC and import and export commonly used file formats. I looked into a couple of models which were recommended to me: the TI Nspire and the Casio FXCG20.

The TI calculator solves differential equations, whilst the Casio unit does not, but TI have pulled these calculators from the UK market due to lack of interest, so it is hard to get hold of one.

Both look like they might be pretty good teaching tools, as they come with an emulator which runs on a PC which you can use to demonstrate their use. I'm not sure what advantages they would give to a practitioner though.

## Tools—software

PCs do most of the heavy lifting nowadays in process design. Engineers have to care about the price of products so, in the course of researching this book, I attempted to obtain prices for all the programs I looked at.

This was trickier than I thought it would be and, consequently, many of the prices quoted in the following sections are approximate. There seems to be a culture of secrecy about pricing in the sector, and the generation of confusion with complex price lists.

I believe, however, that the prices quoted are approximately correct for similar functionality.

## Spreadsheets

### *MS Excel*

Annual license from approximately £100.

This is the workhorse which does most chemical engineering calculations. I'm not recommending MS Excel; I'm just noting that it's what everyone else uses. There are

competing products, such as Apache OpenOffice's opensourced "Calc," which do essentially the same things, but are free.

I used to prefer Lotus123 back when it was a viable alternative but, as is so often the case, the most commonly used product drives out the competition, if only so that engineers have a common file format to collaborate with. Lotus123 only went off sale in 2013, but it became a hassle to use it from a collaborative point of view around the year 2000.

The MS Excel product is clearly very powerful and versatile straight out of the box, but it has a more powerful tool still contained within it: Visual Basic (see the next section).

Many of the software tools used and taught in academia have no functionality for professional engineers greater than that offered by MS Excel and are not as transparent or shareable as MS Excel.

It may be a pain to grind through someone else's spreadsheet checking that all the calculations are set up right, but at least you can, and you are certain that the program itself will do what is asked of it.

Naming MS Excel tabs appropriately facilitates the checking of calculations, and is practiced by most engineers, but many are still unaware of a feature which helps even more: naming cells. This makes self-checking (and more important still checking by others) a great deal easier.

To the left of the formula bar above the worksheet is the name box. You can use this to give individual cells or cell ranges a name (Fig. 4.1).

If you do this the formulae in your spreadsheet will have a format which allows you to check that they are correct without having to roam all over a multipage spreadsheet to see if the correct box has been referenced.

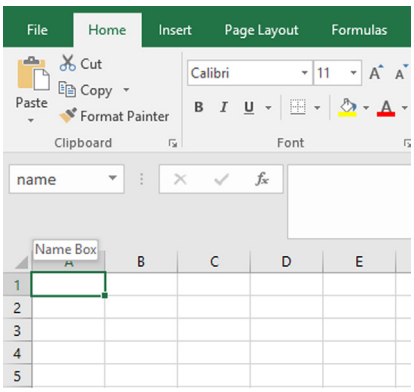


**Figure 4.1** Screenshot of a blank MS Excel spreadsheet.

To give a simple example, labeling cells C8−C10 with a description of their contents:

$$\text{Volume} = \text{height} \times \text{PI}(\bullet) \times (\text{diameter}/2)^2$$

is significantly more transparent than:

$$\text{C10} = \text{C8} \times \text{PI}(\bullet) \times (\text{C9}/2)^2$$

For similar reasons, I avoid simplifying the equations I put into MS Excel. I create the terms in the equations within discrete brackets from obvious sources. This looks ugly and unwieldy, but we should always think of someone else having to check your calculations, as well as perhaps having to come back to them in 15 years' time yourself.

Despite these simplifying measures, there will still be implicit assumptions or a required way of using spreadsheets which others might not know about, and we might forget over time. We should annotate the spreadsheet using comment boxes with this information, at its point of use. Separate documentation or instructions for use are much more likely to be lost over time than embedded versions.

### *Microsoft Visual Basic*

Price: free with MS Excel.

Back when I started with computers, if you wanted them to do anything, you had to write the program yourself. Most of us began with a language called Basic, a cut-down version of the venerable Fortran.

Microsoft's version was called GW Basic (GW being commonly thought to stand for "Gee-Whizz!"—they are Americans after all). GW Basic's modern descendant is Microsoft's Visual Basic (VB).

It allows us to automate spreadsheet functions and write programs to do things which standard MS Excel cannot. However, this means that we are doing programming, in other words doing "a nontrivial job... requiring special skills and experience," as it says in the IChemE guidelines.

Those without these skills and experience need to consider the two main aspects of checking computer modeling programs: *verification*, in which we check that all the elements are correctly coded; and *validation*, in which we check that the model matches reality.

Past a certain (quite low) degree of complexity, computer programs do things we didn't expect them to. The best fully verified and validated commercial programs are thought to contain around 4% undiscovered errors. Our own programs should be assumed to be far faultier. Writing your own program is rarely going to be the quickest way to solve a practical engineering problem, when the necessary validation time is considered.

That said, Douglas Erwin has written a useful book on how to use VB to assist with carrying out real design tasks (albeit only in industries based on organic chemicals)—see Further Reading at the end of the chapter for details.

If you have time for proper verification, writing programs in VB becomes a viable approach. This is usually only the case if the program is to be used many times. For example, I used some VB in writing the Excel spreadsheets I use for hydraulic calculations (of which there are dozens on every plant design I carry out), so it was worth paying to have the spreadsheets third-party beta-test verified.

I have used these programs with confidence hundreds of times since they were verified, even though the initial effort of producing them and having them checked was far more than I would have expended on manual calculations for a single project.

One-off programs are unlikely to be economic to properly test and verify. Erwin acknowledges this by telling the reader that the VB programs which come with his book are not tested and are consequently likely to generate error messages which he challenges users to fix for themselves.

## Other numerical analysis software

### *MathWorks MATLAB*

Single-user license—depends on options, but certainly £10,000 + .

Matlab is commonly used and taught in academia, though hardly anyone uses it in professional chemical engineering practice. It underpins Simulink, a program which allows you to write your own dynamic modeling software (just like the IChemE tells us not to).

The IChemE's guidance on the use of computers tells us why practitioners should not write their own models—unverified programs are error prone, and unvalidated programs are misleading.

It will undoubtedly be quicker to use a commercial program than to write, verify, and validate our own from scratch, but, of course, modeling is not design in any case.

As programs, Matlab and Simulink both may be fine when used as intended, but they just do sums. They do not do engineering.

### *PTC Mathcad*

Single-user license around £1000.

Mentioned only for completeness, Mathcad mainly just does algebra. I have never seen it used in professional practice, probably because engineers can do their own algebra. It integrates with Creo, a drafting program from the same vendor, but process plant designers don't use Creo either.

## Simulation programs

Many people think I am too down on simulation programs, but I am only opposed to their misuse. A simulation program developer with plant operational experience comments as follows:

*I think there are 4 main simulation vendors globally — Aspen (Hysys), Honeywell (Unisim), Invensys (Pro/II and SimSci), Yokogawa (Petrosim) . . . Since it treads the path of competitor's info I cannot comment beyond that. I know this as I am in the business of simulation.*

*I like how you provide enough caveats regarding simulation being useful, but not a substitute for real experience, common sense, and sound engineering judgement. Trust me, a lot of young and even senior people of our profession trust the simulation programs more than the developer (like me) of the program themselves do. Every single time we have performed simulation training we have tried our best to reinforce this fundamental principle — simulation is a tool, an aid, not a substitute for real experience, and sound understanding of the underlying process.*

*I would like to comment about what is data and what is simulation, as most people never seem to understand this. I have reviewed at least a dozen papers that use the words "simulation data" which is absurd. Data comes from a plant instrument, DCS, or lab measurement. Everything else is numerical or model information.*

*One thing that most people never understand is comparing simulator A to simulator B as a consistency check is outright stupid. Many engineers seem to do this in order to not do the heavy lifting of due-diligence. They justify their designs by saying that the numbers are consistent across two simulators. The only comparison one should make with numbers coming out of a simulator is with the plant data itself.*

*Also, it is important for the people using the simulator to know the assumptions and predictability of the models. There is a false sense of trust in being able to tune the models to whatever is coming out of the plant. This is inherently devoid of logic. We fight this battle every day.*

*The margin for a simulator compared to plant data, maybe 10% without doing tuning, should be considered reliable and sound. A good example for this is if you queried Google Maps to go from place A to B, and Google Maps responded back by saying it will take you 10 minutes + x minutes for traffic. Please fill the "x" with whatever keeps you or your boss happy. That false sense of tuning to dial in plant numbers must go.*

*If a simulation provider cannot explain the differences between the plant data and the simulation at least reasonably qualitatively, then the simulation should not be trusted with any margin less than 100%. If a simulation vendor offers the ability to tune the simulation to meet plant information — it should be treated as the inability of the simulation to adequately model a specific process.*

*As with many things in the modern day, people like to believe the simulation vendor more than the process information available to them. Please encourage students and faculty to question this.*

*In college, students should also be informed that you do not need to buy a fancy simulation software for all your requirements, you can create your own using VBA/Excel for most requirements. The power of tools such as Excel/VBA are never illustrated enough. Purchase and use of simulation software should be treated with utmost caution.*

My suggested dividing line between the use and misuse of simulation and modeling programs is whether the IChemE CAPE guidelines are followed, and particularly whether model verification and validation has been undertaken.

If you have a great deal of applicable data on the exact plant you are designing, and are designing many similar plants, you can go to the effort required to fit a modeling program to your plant and write accurate models of your unit operations. Plant design then becomes a question of linking these blocks into an integrated model, and optimization of the model can be a valid proxy for optimizing the plant.

If, however, you are doing a one-off design, you do not usually have a great deal of information about the plant which will be built. Rather than using a validated model, you will be using the straight-out-of-the-box generic data and models, and optimization of this unvalidated model makes no sense. The errors in the model are very likely to be greater than the resolution of the optimization procedure.

Plant operators are the ones holding the information necessary to validate 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.

This is presumably why the most commonly used modeling software is written to support the oil and gas companies who are best placed to put in the data, time, and effort needed to validate modeling software.

There are quite a number of modeling programs, so I shall restrict myself to the most popular ones in the discussion to follow.

### *Aspentech Hysys, etc.*

Single-user license £10−20K

Hysys is clearly written for process optimization in the oil and gas/petrochemicals industry, though it is nowadays commonly misused as if it were a design tool for all sectors in academia. Many recent graduates I meet cannot attempt to "design" a plant without it.

If you Google "Hysys," you will find Aspentech's site (where it is described in terms which match my understanding of its purpose, and that of the developer quoted above), and a great many other search results from academia, where it is described as a design program of use across all process sectors.

### *Invensys SimSci Pro/II*

Single-user license £15K.

This is a steady-state process simulator which is, I am told, perhaps more popular with contracting and operating companies in the oil and gas industry than Hysys.

The manufacturer's website states that "PRO/II offers a wide variety of thermodynamic models to virtually every industry," but its available unit operations are mostly limited to those of the oil and gas industry. As they themselves state:

> *Spanning oil & gas separation to reactive distillation, PRO/II offers the chemical, petroleum, natural gas, solids processing and polymer industries the most comprehensive process simulation solution available today.*

Pro/II is, like Hysys, used as an optimization and debottlenecking tool in that industry, and it is similarly misused in academia to attempt to replace proper process design.

### *Chemstations CHEMCAD*

Single-user license £9K.

This was the simulation program I learned to use in university back in 1990. I never used it in practice and have never seen it used in professional practice or academia, although the supplier's website suggests that it is still in production.

It appears to do the same things as Hysys, etc., and I have no reason to believe it does them any better or worse, other than its seeming lack of use in practice.

### *COMSOL Multiphysics, etc.*

Single-user license around £15,000.

COMSOL Multiphysics is slightly different to the preceding products. It does not attempt to model whole plants but does more detailed modeling of smaller systems. It is described by its manufacturer thus:

> *You can model and simulate any physics-based system using COMSOL®. COMSOL Multiphysics® includes the COMSOL Desktop® graphical user interface (GUI) and a set of predefined user interfaces with associated modeling tools, referred to as physics interfaces, for modeling common applications. A suite of add-on products expands this multiphysics simulation platform for modeling specific application areas as well as interfacing to third-party software and their capabilities.*

It is claimed to be able to interface seamlessly with MS Excel, Matlab, AutoCAD, and Pro/II via other add-ons.

The problem? There is a great deal more going on in a process plant than physics, however "multi" that might be. It is not the software vendor's fault that someone might think that optimizing the physics of a highly simplified model of a subsection of a plant is optimizing the plant, but this is how it is misused in academia.

### *Other*

There are also proprietary programs written as one-off specialist products which allow specific issues to be analyzed. They are designed to be more accurate than generic products and I am told that, even when stripped of all components not related to the limited duty they are designed to, they may take weeks of processing time on a modern desktop PC to reach a solution.

## Project management/programming tools

Plant designers need to be able to analyze and communicate the coordinated tasks which will be required to design, procure, construct, and commission the plant if they are to do accurate pricing calculations.

They will usually use the same tools for this as project managers will later use to keep the project on track and on budget, so the programs are usually a little overpowered for the use which plant designers will put them to.

### *Microsoft Project*

Single-user desktop license £620–1050.

The MS program is fairly commonly used by plant designers. Although other, more powerful specialist programs are probably more common tools for specialist project programs, everyone's familiarity with MS products makes "Project" easy to pick up.

### *Microsoft Excel*

Annual license from approximately £100.

You can produce rough project programs in MS Excel, and sometimes it is expedient to do so as not everyone has MS Project, given that it is not included in the standard MS Office suite. Programs produced in MS Excel are not, however, really up to a professional standard of presentation, so it is preferable to use MS Project as a minimum standard.

You can export your MS Excel program into MS Project if you have formatted it correctly, as well as exporting MS Project data to MS Excel.

### *AMS Realtime*

Single-user license around £1000.

I only mention this because it is the direct descendant of the program I learned to write project programs with, Artemis Schedule Publisher. Unlike Schedule Publisher, I have never seen Realtime used by a plant designer.

### *Oracle Primavera*

Single-user license around £3000+ .

This is a far more sophisticated program than MS Project, which seems to have superseded Schedule Publisher in the sort of companies I work for. As the promotional literature states:

> *Primavera P6 Professional Project Management, the recognized standard for high-performance project management software, is designed to handle large-scale, highly sophisticated and multifaceted projects. It can be used to organize projects up to 100,000 activities, and it provides unlimited resources and an unlimited number of target plans.*

Not really for use by the plant designer, it is more for project managers, usually via a specialist project programmer, but if working in a company with such a specialty program, designers may use the program by proxy.

## Computer-aided design: drawing/drafting

### *Autodesk AutoCAD/Inventor, etc.*

Single-seat license for basic package around £5000.

As with MS Excel, it doesn't matter whether AutoCAD is the best program—it's the one everyone uses, and all serious competitors make sure that their programs can export to Autodesk's dxf (Drawing Exchange File) format.

AutoCAD used to be tricky to learn because, for a long time, the makers resisted the now-standard (from MS products) meanings of mouse-clicks, return key and so on, but now the program allows you to use these as well as supporting the old-school "draffies" who still use it as if it were running under MS-DOS.

AutoCAD comes in a number of specialist flavors, with preinstalled content and other customizations suitable for various engineering disciplines, as well as a version specially for drafting P&IDs to US standards.

### *Bentley Systems Microstation*

Single-seat license for basic package around £3K.

Whether Microstation or AutoCAD is the better product isn't the question—AutoCAD dominates the market. In my opinion, Microstation does itself no favors by being consciously so different from AutoCAD, such that there is a steep learning curve to master the most basic functions of what will probably always be the second-banana product.

Other than that, Microstation is a perfectly good program, whose main advantages are keeping AutoCAD on its toes, and listening to its users. Virtually no one uses it for process plant design. Microstation has built-in simulation and modeling capabilities while AutoCAD does not.

### *PTC Creo*

Single-seat license for basic package around £4K.

Formerly known as Pro/Engineer, this is not widely used in process engineering. It is far more popular with those who do 3D drawings such as product and mechanical designers and architects.

## 3D CAD

It is hard to find published unbiased comparative data on the merits of the various 3D CAD programs on the market, though it is easy to find such claims in sales literature. The following section is based upon comments received from a survey of users of 3D CAD for plant layout around the world carried out in 2015/2016, used in my update of Process Plant Layout (see Further Reading), where you will find a fuller version of it.

All 3D CAD programs allow for line and equipment lists; automated layouts; line routing; design validation and visualization, but they have some differences. The key issues affecting choice of 3D CAD program are as follows:

- plant size;
- scope of work;
- time available;
- budget;
- staff familiarity/ease of use;
- software training and technical support availability;
- interoperability with commonly used programs/client systems;
- sector-specific preferences;
- onshore or offshore;
- design company size;
- importance of buildings;
- drawing versus database priority; and
- plant owner data format requirements.

Table 4.1 summarizes the packages most suited to different project sizes.

**Table 4.1** 3D CAD software used for different project sizes

| Project size | | |
|---|---|---|
| **Small/medium** | **Medium/large** | **Large** |
| Autodesk Plant 3D<br>Intergraph Cadworx/PDS | AVEVA PDMS or Everything3D<br>Autodesk Plant 3D<br>Bentley OpenPlant and AutoPLANT<br>Intergraph CADWorx/PDS | Intergraph SmartPlant 3D<br>AVEVA PDMS and Everything3D<br>Cadmatic<br>TriCAD MS |

### *Onshore versus offshore*

AVEVA PDMS appears to be the industry standard for large offshore projects, while Intergraph's SmartPlant 3D and PDS are more commonly used for large onshore projects.

### *Drawings versus databases*

Drawing-based products, such as those offered by Autodesk and Bentley, tend to be quicker to set up and produce better drawings, but database centric programs such as those by AVEVA and Intergraph give better control of data consistency, and have a greater ability to automatically generate drawings, reports, and so on.

If drawings are the main deliverable and the database side is a lower priority, then drawing-based systems would be the preferred (and lower cost) solution. If the database side is more important, database-based products would be more favored, despite their greater setup and configuration requirements.

### *Commonly used programs*

#### Bentley Systems AXSYS.Process and PlantWise

The datasheet for these products states that they have been designed to allow rapid Front End Engineering Design (FEED) studies. This product has many useful features but does require Bentley's Microstation, a product which historically has been less popular, commercially, than AutoCad. As with all software, it is advantageous, from a collaborative perspective, to use the product which everyone else uses, irrespective of which is best.

#### AVEVA PDMS/AVEVA Everything3D

AVEVA PDMS is much favored by engineers on larger projects. It has a long and rich history of being used on complex plant designs across many industries. AVEVA PDMS has built up a large pool of competent users over many decades. AVEVA Everything3D (or AVEVA E3D) is AVEVA's leading multidiscipline plant design solution. It combines the latest 3D graphics and user interface technologies with state-of-the-art data management to deliver the most comprehensive, productive, and tightly integrated 3D plant design solution available today. The user interface throughout AVEVA E3D has been designed and developed using the latest user interface principles and practices, so that the product is as intuitive and easy to use as possible.

The opinion of users is well summarized by the following quote from a fellow engineer:

> *AVEVA ... has a software solution for most industries and projects. I've used ... PDMS and now use E3D on FPSO's/FLNG's, fixed and floating platforms, Refineries, LNG plants, Pharmaceutical plants and Nuclear plants and on projects ranging from small Brownfield modifications to full refineries and probably the biggest was a full LNG plant. The biggest challenge with the AVEVA software is getting it set up correctly at the start of the project with correct procedures in place.*

*From my point of view, AVEVA E3D [PDMS] is the best for plant layout. It can be used for all other depts. as well, not only for piping…. One small disadvantage is the administration of projects (one person's full-time job).*

#### Autodesk AutoCad Plant 3D

Plant 3D has the advantage of being an AutoCad product but is perhaps less favored by the pipers who do much of the plant/pipework layout in the traditional chemical engineering sectors. Users do, however, say that:

*I prefer AVEVA PDMS for large projects and Autocad Plant 3D for smaller [ones, but] Autocad Plant 3D has the advantage in the creation of catalogues, because you don't need 'special skill' to create … catalogue parts or piping specification.*

The biggest advantage of Autodesk Plant 3D is, arguably, that it comes from the AutoCad stable. The tools within the software appear suited to a slightly different market to PDMS, and possibly more suitable for process or mechanical/structural engineering applications.

#### Intergraph PDS

Intergraph claim in their literature to be the worldwide market leader across the board in all aspects of plant design, defined as "No. 1 overall worldwide provider of engineering tools for plant design based on revenue data reported by participating market providers in the ARC study." PDS is certainly a very popular 3D design program in traditional large chemical plant engineering, aimed toward owner-operators, and used extensively by EPC company staff. Intergraph now also provides the CADWorx and SmartPlant solutions as described below.

Much is made of compatibility but, like many other programs, it is mainly compatible with other software from the same vendor. It is clear from the features offered that this is a program intended for use by owner-operators in traditional oil and gas/heavy chemical engineering sectors.

#### Intergraph Smart 3D

Intergraph state that their Process, Power & Marine (PP&M) division "is the leading provider of enterprise engineering software for the design and operation of plants, ships, and offshore facilities."

The users I surveyed also indicated that this is the preferred solution globally for large offshore projects.

### *Model review software*

Almost every vendor has its own free model review software, but the most universally popular are Autodesk Navisworks, Bentley Navigator, Intergraph SmartPlant Review, and Siemens WalkInside. Review software is generally optimized for its own

applications. While Navisworks states it works with Bentley Microstation V8, for example, it only works with 2D. SP Review only works with exported formats. WalkInside is probably the most open product listed, though perhaps the least used.

#### Autodesk Navisworks

Navisworks is mainly used by layout engineers to share 3D models of a plant design within and (perhaps more importantly) outside the design team. There is a free Navisworks viewer which allows more or less anyone to look at the 3D model. The survey of users suggests that Navisworks is the most commonly used model review product across the board.

#### Intergraph SmartPlant Review/Enterprise/CADWorx Design Reviewer

SmartPlant is another product commonly used for model review, with a free viewer, which allows involvement outside the core design team.

It also offers an integrated suite of programs intended to provide an interface between engineering design and project management functions, as mentioned in the previous section, but the 3D modeling and visualization aspect is the main one of interest here.

As mentioned earlier, CADWorx also comes with free review software.

## Computer-aided design: process design

### *Bentley Systems Axsys.Process/PlantWise*

Single-seat license for basic package around £12K.

The suppliers say that it has been designed to allow rapid FEED studies, and they describe it as follows:

> *Interfaces with all the major process simulators, including HYSYS, AspenPlus, UniSim, and Pro/II, so you can use your system of choice and properly manage the resulting data. Data from multiple simulation runs can be easily compared and new design cases quickly generated*
>
> *Automatic creation of Process Flow Diagrams (PFDs) and Piping & Instrumentation Diagrams (P&IDs) using project-specific symbols and drawings that can be output to multiple drawing formats*
>
> *Integration with the major heat exchanger applications such as HTRI and HTFS for faster heat exchanger design*
>
> *Use of Microsoft Excel to provide easy data entry and generation of intelligent datasheets and reports in your specific formats*
>
> *A managed workflow that incorporates graphics, data, and work management for each user and tracks changes during the project, allowing users to revert to previous designs*

*Intelligent documents and data that can be transferred into detailed design products, including Bentley AutoPLANT and Bentley PlantSpace*

*Improved Front-End Engineering Design, which helps reduce capital expenditure as proven by users.*

It also allows automatic pipe routing. This sounds like a great product, so I'm not sure why I had never heard of it before I researched my layout book.

Having an integrated suite of programs which combine drafting and design with modeling and simulation outputs sounds like an excellent idea on paper (especially for those following the academic modeling-as-design approach), but I wonder if each of the bits does its job as well as a dedicated program, or a professional engineer.

## Computer-aided design: hydraulic design

Computational fluid dynamics (CFD) allows the visualization of complex patterns of fluid flow in a physics-based model. The output is often pretty but does not necessarily match reality that well.

CFD isn't much to do with whole-plant design in any case, but I'll mention them in passing for those who think it is.

There may be occasions where CFD might come in handy to design a particularly challenging element of the plant but you'd be wiser to buy the service in from a specialist, than learn on the job.

### *COMSOL Multiphysics*

This is one of the functionalities of the COMSOL product mentioned in an earlier section.

### *Matlab/Simulink*

You can write your own CFD program using Matlab. You probably shouldn't though.

### *Autodesk Simulation CFD*

This dedicated program seems to offer some of the same fluid flow and heat transfer analysis features as COMSOL Multiphysics and Matlab. Being an Autodesk product, it presumably integrates well with AutoCAD.

## Other

### *Microsoft Visio*

Single-user license £300.

Visio is flowchart software which is not intended for producing professional engineering drawings, but, like all MS products, it is easy to pick up, so it has become

commonly used in academia as a substitute for the professional drawing programs most academics can't use.

It does have a good-quality "export to dxf" feature which allows its product to be brought in to AutoCAD for professionalizing, so all is not lost if beginning designers can only use Visio, but I personally don't teach it at all, as it is much simpler to go straight to the far superior AutoCAD.

I have seen it used by professional engineers in some interesting ways, dependent on its ability to link to Excel, for example, producing dynamic hydraulic profiles which alter the relative position of drawing elements in response to underlying linked hydraulic calculations.

### *Microsoft Access*

Annual license from approximately £100.

Microsoft's database software, MS Access, can be useful for document control.

## Further reading

Erwin, D. L. (2014). *Industrial chemical process design*. New York, NY: McGraw Hill.

Institution of Chemical Engineers CAPE Working Group. (1999). *The use of computers by chemical engineers: Guidelines for practicing engineers, engineering management, software developers and teachers of chemical engineering in the use of computer software in the design of process plant*. London: IChemE.

Moran, S. (2016). *Process plant layout* (2nd ed.). Oxford: Butterworth-Heinemann.

# CHAPTER 5

# The future of process plant design

## The academics' view

### Academics as fortune tellers

Many academics believe they have a duty to teach the future of chemical engineering. As one correspondent wrote to me: "To restrict students to how things are at present is rather limiting. During their lifetimes no doubt technology will also change quickly along with ways of working." This is often the basis for justifying the inclusion of swathes of academic research in the engineering curriculum—after all, the cutting-edge research of today will be the everyday practice of tomorrow. Won't it?

However, in the 10 years or so I worked in them, I never met anyone else in a university chemical engineering department who ever designed a process plant. So, it is clear that a lot of academics do not know how process plant design is carried out in the here and now.

Furthermore, chemical engineering researchers are not known for their fortune-telling abilities. A case in point is my investigation of how plant layout practice had changed since 1985 (part of my background research for my update of Mecklenburgh's *Process Plant Layout*.) The most notable thing was the lack of change. Mecklenburgh was a bit of a futurist, and I had to edit out a lot of his speculation about how things were going to change, mostly because his predictions did not happen. I still however commonly hear my academic colleagues telling me that these very same changes are just on the horizon, as they were in 1985. This reminds me of Bill and Ted (of the Excellent Adventure), forecasting a future in which their own particular interests will become the very basis of society.

Ways of working across all engineering disciplines are at heart consistent and have endured for centuries. In fairness to academics, research interests -by contrast- can change quickly, and academics may have an unexamined assumption that professional engineering practice is the same. Most academic research, however, does not have widespread practical application. We practitioners may have our fashions, but the profession has changed little in the almost 30 years I have been practicing.

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00006-9
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My greatest bone of contention, however, is that academia leans on its perceived "duty" to teach the future as a justification for not teaching graduates the skills and knowledge they need to practice in the here and now.

> *Industry has always complained that Universities never produce the finished article. To that I would say, they never have.*
>
> *The most we can do is to educate students as to how to think for themselves and solve problems, to exhibit self and lifelong learning.*
>
> ***Anonymous Academics***

I often hear university staff complaining that it is not their job to produce so-called "oven-ready" graduates—those equipped with skills and knowledge relevant to current professional practice—an attitude which seems like covering up a lack of knowledge with intellectual elitism. Consequently, academics may consider it worthier to teach the mind-broadening possibilities of the future (based on their research) than the mundanities of the present. Personally, I am not supportive of the idea often voiced by these theorists that "industry" wants students to be given a purely functional rote instruction in mundane tasks. I've never met another professional engineer who was. The idea that this is what "industry" wants is a straw man only ever heard in academia, sometimes as the basis of an argument that if "industry" want this they should pay for it.

Furthermore, the idea that academia was always focused on research, and never produced useful graduates is quite a new one. It was normal as recently as the 1970s for most academics to see themselves primarily as teachers. The present system is an artifact of attempts to apply inappropriate business models and QA systems to academia.

## Process porn

Earlier I noted that academic staff never actually design working process plants. However, university chemical engineering departments often have staff with a research interest in something referred to as "Process Design." I call the approaches to process plant design developed by academics with no experience of the discipline "Process Porn," a term I have adapted from critics of modern physics.

> *In my intercourse with mankind, I have always found those who would thrust theory into practical matters to be, at bottom, men of no judgment and pure quacks.*
>
> ***John Smeaton***

Some areas of physics have, to outsiders, clearly lost themselves in abstraction. Paul Dirac may have started it when he wrote "it is more important to have beauty in one's equations than to have them fit experiment." Seduced by the beauty of higher

mathematics, theoretical physicists pursue things which seem to look right, even though they are piling unsupported speculation on top of itself many times over to get there.

> *The partial differential equation entered theoretical physics as a handmaid, but has gradually become mistress.*
>
> ***Einstein***

The theorists responsible have been advocating freedom from the requirement to prove any part of their theories empirically. They have argued that they should instead be allowed to pursue mathematics and philosophy where they think they lead, though since the first edition of this book there has been a backlash within physics too. Even theoretical physicists are now openly questioning whether the idea that math which is beautiful must be true might be a form of cognitive bias. As New Scientist pointed out in February 2018, "Our cosmos is failing to meet the rigorous beauty standards set by physicists. Is it time to face up to the fact we may live in an uglyverse?"

The problem is that mathematics and philosophy deal with what is plausible within their conventions, rather than the truth. Without a grounding in empiricism, physics of this type is pure self-indulgence, which is why the product of this lost school of physics is sometimes called "physics porn."

The philosophical tool which protects us against losing ourselves in abstraction in this way is the beefed-up version of Occam's Razor known colorfully as "Newton's Flaming Laser Sword": "what cannot be settled by experiment is not worth debating."

We seem to have developed a similar problem in process plant design. In a computer model's mathematical space, many things seem plausible, but we only find out what is possible when we actually build the plant. Some researchers are even generating things they call rules of thumb for design by repeated simulation, as if it had been proven that such models are reliable analogues of the real world.

This approach is similar enough to physics porn in its lack of empirical support that we might call it "process porn." In the resultant academic discourse on process design, it seems now to be considered axiomatic that the approach followed by all professional engineers is becoming hopelessly obsolete.

An approach based on higher mathematics, theoretical sciences, modeling and simulation programs, and network analysis techniques is now thought in academia to be the future of process design. Of course, as already discussed, this may have something to do with the fact that these disciplines and tools are those which academics know and, further, that the vast majority of chemical engineering lecturers worldwide have never designed a real process plant.

The idea that engineering is just applied mathematics and science is commonplace in academic circles, but this is an idea held only by those who have never practiced, or practitioners who have never reflected upon their practice.

Practitioners tend to find out sooner or later that much of what they were taught in university is worthless in practice, and much that would have been of value was not taught (the supposed exceptions to this rule are French engineers, who according to the old engineering joke ask "So eet works in practice but does eet work in theory?").

Universities feel that they have to staff their departments with scientific researchers, and few engineers want to do research—we mostly want to be engineers, not research scientists. Scientists are also cheaper than chemical engineers. All of this is fine as long as it is understood that scientists are there because practicing engineers are unavailable or unaffordable, but they have started making a virtue of their deficiencies.

As noted in a previous chapter, some research-led universities teach the following as a process plant design methodology:

- Look, in scientific literature, for bench-scale experiments which give possible process chemistry.
- Use these unproven techniques as the basis of a costing exercise which goes only as far as comparing feedstock and product prices.
- If the product sells for more than the feedstock, assume the process is economic.
- Use the unproven technique as the basis of a Hysys model.
- "Optimize" the Hysys model (which in this context means only getting recycles to converge).
- Grind through pinch analysis by explicitly defined rote methodology.
- Produce a short Word document which describes how they navigated the decision tree provided by the lecturer.

At the end of this time-consuming exercise, all we have is a worthless Hysys model based on bench-scale experiments without any scale-up consideration, limited in scope to a reactor and an associated separation process.

We have given no thought to whether the standard Hysys data and assumptions are valid in our case (they will probably not be), and we apparently think that getting recycles to converge in a computer model can be called optimization.

We have not required students to give any thought to cost, safety, or robustness, produced no engineering deliverables, and they have at no point been required to exercise the slightest judgment, imagination, or intelligence.

This state of affairs is not just useless-it actually teaches the opposite of professional practice, because:

- Engineers don't ever use lab research as the basis of full-scale plant design.
- Engineers don't ever use modeling in place of design.
- Engineers don't ever ignore cost considerations.
- Engineers don't ever ignore safety considerations.
- Engineers don't ever produce "designs" that no one (including them) really understands.
- Engineers design by producing recognizable engineering deliverables.

In direct contrast, this academic approach represents, as I understand it, best practice according to researchers in "process design."

It is ultimately based upon approaches originally intended to allow beginners with no experienced supervisor to attempt a certain rather unrealistic and outdated kind of process design; approaches which have been stretched far beyond their originally intended purpose.

Some parts of the approach do have limited use, mostly in optimizing existing plant in certain industries, but these too are used out of context and without validation in the real world.

So, let's unpick some of the ideas underlying the academic approach, and then consider some further questions about the future of plant design, bearing in mind how much of the core of process plant design is the same today as it has always been.

## Will first-principles design replace heuristic design in future?

In a word, "No." All is and always will be heuristic in the foreseeable future of engineering design.

We know this for sure because heuristic design is enshrined in law worldwide, and with good reason. Codes of practice and national and international design standards require heuristic design calculations to be carried out for safety purposes.

For example, in piping stress, the ASME code rules that apply in much of North America and other parts of the world rely on heuristic rules. You can do pipe stress analysis with FEA, but it is difficult to prove you also meet the heuristic rules. You should ensure that you do meet such rules. In Sean Brady's LinkedIn article on the failure of the Hartford Civic Center Stadium, Connecticut, in 1978, he writes

> *At 4:19 am that morning, with the arena empty, the 1,270 tonne space frame collapsed. Only six hours earlier more than 5,000 people had been sitting beneath it, watching a basketball game. . .. It would turn out that the design had been completely inadequate. The structure had begun failing almost as soon as it was completed—some of the members of the space frame were overloaded by more than 800%. So how did the designers get it so wrong?*
>
> *It would transpire that the problem was over-reliance on computer software. The design firm had convinced the city of Hartford to purchase a state-of-the-art software analysis package. They argued that using this package for the design would save half a million dollars in construction costs.*
>
> *But this software would introduce a number of serious deficiencies into the structure, which led to the inadequate design. We will not get into them here, but references discussing these deficiencies are provided below. The bottom line is that the software relied on a number of assumptions that were simply not applicable to the structure in practice, and these assumptions led to big differences between the predicted and actual behavior of the roof, and ultimately led to its collapse.*

Computers are no smarter now than in 1978. They are only faster.

*Computers have enabled people to make more mistakes faster than almost any invention in history, with the possible exception of tequila and handguns.*

***Ratcliffe***

Despite the hubris of some scientists, science has simply not advanced to the level where it can describe in sufficient resolution all the complexities of a proposed engineering design.

Companies also have their own design manuals which require heuristic design checks to ensure that designs include the company's know-how.

Some companies now use tailored simulation program blocks representing the unit operations they most frequently design to carry out this duty, but they build into these blocks in-house empirical information obtained from past designs. This is not first-principles design; it is empirically validated heuristic design. The program is just a container and vector for the empirical data, and its output is checked for sensibleness using further heuristics.

A process plant is too complex to be sufficiently fully described by any first-principles model simpler than the plant itself, and any sufficiently complex model would be too complex to understand.

The purpose of heuristic design is to produce a good-enough model of the plant encompassing the state of the art which the process designer fully understands. A model which is slightly more accurate than the good-enough one is actually worse than one which is slightly less accurate, because it will also be slightly less well understood.

## Will process design become a form of applied mathematics in future?

This is the process pornographer's ideal, but it's just not going to happen, for the reasons given in Chapter 4, Twenty-first century process plant design tools.

Process plant design will no more become applied mathematics than medicine will, as any practitioner understands, because:

*As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality.*

***Einstein***

## Will primary scientific research become the basis of engineering design in future?

The academic papers freely available within academia are usually too expensive to access for practitioners outside the paywall, but even if we had free access to the papers, we understand how many high hurdles there are between bench and plant.

Academics frequently mark student design based on bench-scale academic research very highly, as it satisfies their desire for radical novelty, but engineers know that few things scale up well from bench to plant. A correspondent corrected me on this:

> ***Good*** *engineers know. I have seen two examples in my career where companies built commercial scale plants based on bench scale experiments and failed miserably to scale them up properly. In fact, I have just recently seen a company provide a simulation file for a process plant that was built by their engineers for a small pilot plant (hardly more than bench scale) and ask for us to work up a full-scale version, complete with drawings and a cost estimate. The simulation models something that is fine for a short-term pilot experiment—but the inefficiencies and shortcuts that make sense in a pilot unit are foolish at full scale and we have had a terrible time explaining [this]. It's almost like the people at this company know design only from the academically taught version.*

In engineering, we do not give high marks for novelty—we give high marks for a working, safe, and cost-effective plant. We give low marks (i.e., fire you) for designing a novel but unsafe/unreliable/loss-making plant. The judiciary may also give you low marks in court.

So: No! Good engineers are not going to start spending millions of dollars to build a plant which scales a process up by a factor of 100 from a bench-scale experiment any time soon.[1]

## Will "chemical process design" replace process plant design in future?

The future of process plant design was envisaged by the IChemE in "Chemical Engineering Matters" as being to do with providing for human needs—food, water, medicine, and energy.

Douglas's original "Chemical Process Design" is based on a set of assumptions which do not hold in many of these sectors, and answers different questions to those asked of process designers in these areas. The school of Chemical Process Design developed from Douglas's ideas by other academics is less useful still in these sectors.

Some aspects of this approach are, however, finding favor in the petrochemical industry which matches most closely the basis of many of its embedded assumptions. This need not trouble us much in the developed world, as it is uneconomic to build new plants in this sector at our wage rates. The main uses for its component techniques and tools are still optimization, debottlenecking, and minor modifications to existing plant, *even in that sector*.

[1] The last sentence was true to the best of my knowledge when I wrote it in the first edition, but I have since completed an expert witness job in which a fresh graduate was allowed to do just that. It didn't go at all well.

## Will network analysis form the core of design practice in future?

Network analysis is all very clever, but it can only do one thing. Setting in stone the results of such an analysis early in the design process as the foundation of design is very unlikely to be optimal. This is because:

1. The more integrated a plant is, the less controllable (and by implication safe) it is, and the harder it is to start the plant up. This costs the client money in commissioning and maintenance engineers' time, the provision of back-up equipment for start-up and so on.
2. In the specific case of heat integration, it should be noted that heat exchangers are not free. Putting in enough heat exchange capacity to approach the theoretical maximum possible heat recovery (as many academic network analyses suggest) will never be economically sensible. The interpretation of sustainability which is used to support such an approach runs counter to that described in the IChemE's sustainability metrics.

Such approaches can have value in optimization of an existing plant, but in order to use them at the conceptual design stage, we have to apply them to "optimize" an unvalidated model. Since optimizing such a model does not necessarily optimize the plant which is built, this is an example of mismatch between a design technique and the resolution of the model to which it is applied.

## Will process simulation replace the design process in future?

Rather than being the future, this is a very old idea and the fond hope of academics since computers were first devised.

Simulations are made of mathematics. Mathematics is perfect, but the real world is made of rather more complex and imperfect stuff, and contains even less perfect, even more complex people.

Materials and feedstocks are never perfect. Equipment is never perfect and tends to become increasingly imperfect over time. Operators are never perfect and also tend to become increasingly imperfect over time unless well managed. Plants are never constructed exactly as per the original design.

I cannot find any research papers in which modeling and simulation programs are used in their straight-out-of-the-box format to design a plant, and the predictions of the model then validated against the real plant. The most impressive support I can see for the validation of this approach is that after such programs are "calibrated" with large volumes of full- or pilot-scale plant data, they can predict the performance of small sections of plant to a reasonable degree of accuracy.

This is, however, simply using the program to contain empirical data, with the program itself only filling in small gaps in the data, and even this approach has only

"worked" with a couple of linked unit operations at a time, rather than a complete plant. A professional designer could probably have produced the design of a complete plant in far less time than it took for even this limited success.

So even if it became possible to accurately model the full complexity of the real world, it would take longer to program the model than to simply design the plant, and the part of the process design which a simulation describes is at best the mass and energy balance, and process flow diagram.

Only someone who thought that safety, plant layout, hydraulic considerations, and cost were trivial side-issues would think it plausible that simulation could replace process design. Process design is in any case one small part of process plant design.

Even if this hurdle was overcome, plants designed by computer would be understood by no one. Plants understood by no one are not capable of verification as sufficiently safe, robust, and cost-effective. Following such an approach would be based on a misplaced faith rather than reasoned professional judgment.

The following anecdote from a fellow engineer, involved in writing simulation software after significant operational experience, is illustrative:

> *In 2002, I sat in a seminar at an Aspentech conference in Washington DC, where most of the presentations were from academics, although I recall BP Chemical presenting something. This would have been the beginning of what has come to be called "generative" design—whereby you give a computer model constraints and goals and let it come up with lots of options and solve towards an 'optimum'. They were presenting about using this kind of solver to come up with novel separation arrangements to reduce capital and operating costs, and lots of academic case studies on how this could be used. The chair of the session, a well-known professor from a highly regarded US university, lamented that industry wasn't adopting this technology and he didn't know why. I pointed out that the average engineer in industry didn't understand how the math worked and couldn't explain the resulting design. The presentation from BP Chemical even laid it out—they used the technology to devise a new separation scheme from some purification, but then still have to tear the result apart and use traditional design methods to validate that it could be done (and correct the places where the mathematical model provided something unworkable).*
>
> *I believe that generative design will have an impact on engineering—it already is in some other fields. But [in] every example I have heard of it being used, the first step after the computer comes up with something has been to TEST with real world models (be it novel machine part shapes, etc.). In process plant design, the place I foresee this being most useful is not the process design, but the fabrication and assembly—figuring out more efficient ways to build—not figuring out what to build.*

Even if all of these issues were overcome, these programs do not produce the engineering deliverables which are the immediate point of design. They are therefore not design tools.

## Will process plant design never change?

Surely this has to be a "No" too, but some things have been conserved from the very beginning of chemical engineering.

If the defining concepts of chemical engineering, that is, of unit operations, mass, energy and momentum balancing, quantification and analysis, and so on, are lost, the discipline will no longer exist, but they have proved useful for some time now.

Similarly, as long as resources come at some cost, there will be selection pressure to maintain the same stages of design as are common to all engineering disciplines.

As long as the limits on our knowledge of physical sciences and computing power cause process system complexity to prevent us from making a completely accurate model of a proposed plant, so the limits of human brainpower will prevent the understanding of models beyond a certain level of complexity; yet professional responsibility requires us to understand what we are proposing: modeling cannot replace heuristic design.

But, in my professional lifetime, we have produced many useful new design tools and, to a far lesser degree, useful new design techniques. Things will undoubtedly change, but when I look back to what we thought the world would be like in 2014 back in the 1960s, I am hesitant to predict how they will change. I hope it will be as surprising as that was, though I'd gladly trade the internet for a personal jetpack.

I am, however, happy to predict that when professional engineers do change how they work, they will change to something which gives a provably safer, cheaper, or more robust product within the real constraints we have to work under.

## How have things changed in process plant design?

Earlier in this chapter I mentioned my work on updating Mecklenburgh's 1985 book on Process Plant Layout. This process gave me an interesting insight on how process plant design has changed over the last three decades (and how it has not).

Mecklenburgh speculated—largely erroneously as it turns out—on the future of process plant layout, but his specific focus on plant layout may well have caused him to overlook the possibility of the biggest change which did actually happen, and which he might well have considered catastrophic. Mecklenburgh taught an entire module on plant layout at the University of Nottingham (United Kingdom), which continued for many years after his premature death. However, I am not aware of any UK university which still teaches a plant layout module. Research into and teaching of plant layout has not just changed over the last 30 years, it has more or less entirely disappeared, even though it is just as essential to practicing engineers as ever.

Technology—other than microelectronics—has changed relatively little. Vacuum drum filters with filter aid don't see a lot of new installations nowadays, and

membrane filters are a lot more common, but almost all of the equipment described in Mecklenburgh's 1985 book is still the bread and butter of process plant design. We still design and lay it out in the same way.

It is amazing to me that the desktop computers of Mecklenburgh's time—which must have had 6 Bit Intel 80286 processors—could do all of the things which the latest 64 Bit 80663 processor can. The modern chip is faster and has a larger memory, but it is no smarter. None of the things which Mecklenburgh forecast computers would be able to do in future in the field of layout have happened, and the things they can do are as constrained by data entry requirements as ever.

Microelectronics have however done two things which Mecklenburgh did not see coming: broadly networking and programmable logic controllers (PLCs), and the implications of these advances.

There is no mention in the book of a software engineering discipline in 1985. Starters and controllers were field mounted, and the instrumentation and electrical "departments" were responsible for designing and programming control loops. Control panels were dumb monitoring stations.

A number of things have changed in the professional world since then (though many of these are not reflected in academic syllabuses). Motor control centers now contain smart starters and instruments, each having far more computing power than Mecklenburgh's desktop 286 PC, or even his room-filling "mainframe." These smart starters are controlled by even smarter industrial computers called PLCs.

There are very few design offices in client companies any more, let alone subdepartments with process, electrical, and instrument design capability.

Far more profound has been the impact of networking in general, and the internet in particular. The most immediate impact has been that we can have a design office in another country if we like, which we can contact as readily as one on the other side of the building, whilst paying staff (cheaper) local wages. Drawings can be sent back and forth, shared in multiple copies, edited, and marked up in electronic format.

The second order effect of this networking has been a reduction of the cost of entering markets, which has meant that the only monolithic vertically and horizontally integrated companies nowadays are those trading in network goods. Ford doesn't make its own steel any more, and BP does not design its own plants, but Google and Facebook are huge. There are no design departments in operating companies any more, as there were in Mecklenburgh's day. Companies specialize in their core business.

So structural changes in the organization of engineering, originating in technology away from the discipline itself, have been far more significant to professional design practice than any new technology within the discipline.

Although they do like to try, academics are generally terrible at forecasting the future, as they are specialists. Academia is just a sideline for me, so I'm not going to

forecast how things will change. I have however noticed that engineering has changed far less than expected, and in ways which were not envisaged in Mecklenburgh's book.

The changes which have happened were driven by wider social forces, and this is how it should be. Engineers serve society—we don't tell society what to want as much as we make its dreams come true.

Similarly, it is the job of an engineering education to teach students how engineering is done. Academics will need to get a lot better at forecasting the future before they are in a position to teach what engineering is to become. As it has changed so little for the last 30 years (and for many decades before that), our first approximation must be that the practice of the future will be in essence very like today's.

What is particularly sad is that so many in chemical engineering education are still claiming that the near future will match the predictions of Mecklenburgh's time, with computers doing engineers' jobs rather than just helping.

It is also commonplace in academia to ignore some of the changes which have actually happened (as they do when they pretend that there is still no such thing as a software engineer, so chemical engineers will need to write their own control algorithms).

In my career, I have seen how things have changed since the early 1990s. But I think the most telling comment came from a fellow engineer who, in about 2008 or so, was nearing retirement. He observed that we now had the technology to run hundreds of simulation cases for a process plant, to consider various edge cases, operating modes, and perturbations to inputs. You would think this would give better designs. But the plants that were designed in the 1960s—when you would calculate a single heat and material balance (because it was too much work to do more)—worked.

I would argue that one thing that has changed in process plant design is that we are doing too much for very little benefit. Just because I *can* run Hysys with 32 different sets of inputs doesn't mean I *should*. I have rarely seen those extra cases help reduce cost, safety or robustness.

## Further reading

Alder, M. (2004). Newton's Flaming Laser Sword, or: Why mathematicians and scientists don't like philosophy but do it anyway. *Philos. Now.*, *46*, 29–32, May/June.

Institution of Chemical Engineers. (2013). *Chemical engineering matters*. Rugby: Institution of Chemical Engineers.

PART II

# Professional Practice

# CHAPTER 6

# Neglected industries and processes

## Introduction

There are a number of process industries which are off the radar of academia, with its tendency to focus on the traditional "chemical process industries" (CPI) of bulk organic chemicals. The boundaries of CPI are slightly variable, though the focus is usually on organic bulk chemical manufacture. Pharmaceutical production is, for example, sometimes included under the CPI banner, though its key characteristics are poorly served by university courses.

I have spent almost my entire career in water and wastewater process plant design, but many in academia still seem to think this is done by the civil/environmental engineers who predominated in this sector 30 years ago. Teaching methods and materials hardly ever reflect the key role played by process engineers in the design and operation of mineral processing, cement and energy from waste plants, nuclear reactors (including decommissioning and nuclear waste management), power generation (including gas, coal, renewables, etc.), military and defense, automotive and transport, health care, food and drink, semiconductors, and other plants which do not produce "chemicals."

Curiously, both academics and many practitioners in the traditional CPI seem to share the definition of "chemicals" used by green pressure groups, one which excludes "natural" things like food and drink. The consequence of this is that chemical engineering curricula are long on processes important to the CPI of the past, and academic research about a speculative future, but very short on entire industries, processes, and unit operations which have been important employers of chemical engineers as process designers and operations support for many decades.

## Neglected industries

Many of the same academics who think that research, teaching, and 3D printing are kinds of chemical engineering seem to think that the traditional CPI are all there is to "industrial chemical engineering." So "non-CPI" process engineering doesn't get so much airtime in most chemical engineering curricula, which are still focused on traditional CPI, even in countries whose CPI moved south-east decades ago. Perhaps this is because lecturers—mostly with no industrial experience—are delivering lectures

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00007-0
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handed down from their predecessors and updated only in respect of their own research interests and vision of the future.

It is notable that many of the neglected industries operate in the aqueous phase. There is a disconnect between the "green chemistry" initiatives of academic chemistry and chemistry engineering departments; and the process chemistry which they teach; which are still mostly organic chemistry carried out in organic solvents (and which safety and environmental legislation is making harder and harder to use as the basis of industrial process chemistry).

## Neglected processes

In summary, the effect of the academic focus on the "CPI" tends to mean that water, biochemical, solids handling, and batch process engineering are absent from many curricula.

These four deficiencies come together in the food/pharmaceutical/bioprocess industries, as they do in the water, food, and drink sectors, but they are still present even in traditional CPI.

## Water-based

Water is nonflammable, nonexplosive, and practically nontoxic. Water-based processes therefore tend to support inherent safety, when water replaces an organic solvent.

Chemists have become aware of this, and academics promote a kind of "green chemistry," the parts of which they borrowed from chemical engineering making good process sense. The three principles of "green chemistry" which unambiguously make sense to engineers are:

- *Safer solvents and auxiliaries* Auxiliary substances should be avoided wherever possible, and as nonhazardous as possible when they must be used.
- *Inherently safer chemistry for accident prevention* Whenever possible, the substances in a process, and the forms of those substances, should be chosen to minimize risks such as explosions, fires, and accidental releases.
- *Prevention* Preventing waste is better than treating or cleaning up waste after it is created.

The others are perhaps more questionable, especially in the hands of academics. (Look up the idea of "green engineering" to see why.)

Anyway, water is a great solvent, sometimes called the universal solvent. I'm still learning new things about water and water-based processes after almost 30 years of working with it, as I found when researching my third book (see Further Reading).

## Biochemical engineering

I was originally a biochemical engineer. When I design biological wastewater treatment plants I still am a biochemical engineer. Dealing with water chemistry and the constraints of a biologically based process are therefore reasonably straightforward for me. I have however trained many chemical engineers, from first-year undergraduates to experienced professionals, and biology is almost always their weakest science.

I think this is ultimately to do with the way we select entrants to chemical engineering courses. Based on the distances between subject areas in Fig. 6.1, chemical engineers are most like mathematicians, and they are also a lot more like chemists and physicists than biologists and architects. This tends to be reflected in what they have studied before going to university. Math, more math, physics, and chemistry tend to be what they bring with them, and these subjects are also a lot of what is taught in university.

That is a pity, because biology has a lot to show us about how complex, self-regulating systems can be made to work. It is also a handicap from the point of view of the budding water process engineer, because engineered biological systems are used in both clean and dirty water treatment.

You can't just assume that the biological part of a process plant is like a traditional chemical catalyst. It is alive, and if it dies it will stop working. A fellow engineer commented that the same is true for many chemical catalysts, but there is a key difference. If you treat biology nicely, it will replicate itself so efficiently that you will be

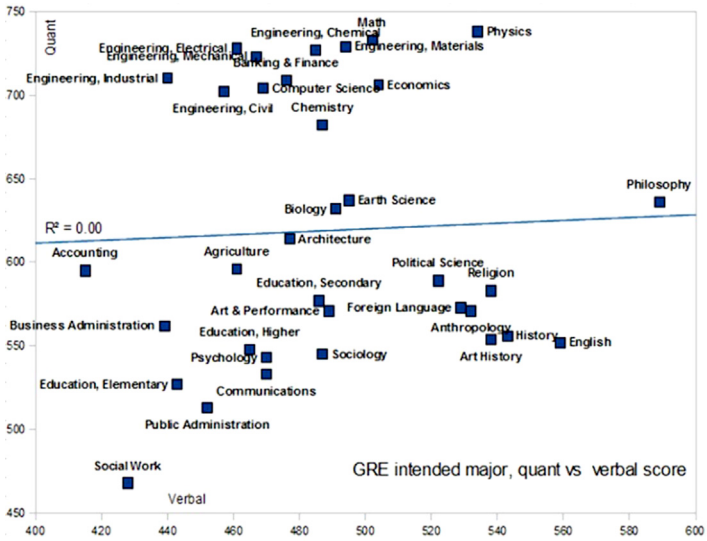


**Figure 6.1** Quantitative and verbal reasoning skills in entrants to US academic programs. *Courtesy: Razib Khan.*

presented with the problem of what to do with the surplus. It also tends to be a challenge from the point of view of handling, and often forms non-Newtonian fluids.

The organisms we use in water treatment are many kinds of bacteria, fungi, protozoa, algae, and also some higher organisms. The relative importance of these groups varies between types of treatment processes, but it is nearly always bacteria that are responsible for most of the work.

All bacteria belong to the group known as prokaryotes, "simpler" organisms without a cell nucleus. Eukaryotic organisms by contrast have a nucleus in the cell. Representatives of this group (colloquially known as higher organisms) important in wastewater treatment include protozoa and rotifers, algae, fungi, worms, snails, and insect larvae in some circumstances.

Wastewater treatment might be viewed as "dirty" biological treatment plant design. A mixed culture of all kinds of organisms (including pathogens) is present. This makes it practically impossible to analyze it rigorously from the point of view of first-principles approaches.

A cleaner version of biological design is important in drinking water treatment, but the hygienic design of food and drink/biopharma starts from a sterile set of kit and introduces just one type of organism or even a single component of an organism such as an enzyme.

Obtaining sterility requires an understanding of how to kill organisms in a controlled and reliable fashion, whilst growing them requires the related knowledge of how to promote their survival and reproduction (see Further Reading).

## Solids handing versus liquids

We can further split solids handling into dry and wet solids handling. Graduates tend to know little about either. Wet solids are often physically hard to handle as it is hard to predict rheology from their water/solids content, especially for biological solids. They commonly form variable, non-Newtonian fluids.

Dry solids (especially when finely divided) often present toxic, fire, and explosion risks, with the potential for major incidents with multiple fatalities. They also tend to not flow when and how we want them to. Making consistent homogeneous mixtures of powders is also very challenging.

## Continuous versus Batch Design

Traditionally, much process design was based on batch processes, but equipment tends to be better utilized in a continuous design, so there has long been a general trend toward continuous plant. Batch processing is still, however, very common in low-volume/high-value applications. I have made this section unusually long (with kind assistance from Keith Plumb from IChemE's Pharma subject group).

Although continuous processing is used to make the high tonnage materials produced by the oil and gas, bulk chemical, and water sectors, a far greater volume of materials is produced in batch processes than in continuous ones. In a recent survey carried out in a food ingredient factory, the company was using over 5000 different raw materials. All the small chemical plants using batch processes outnumber the total number of plants running continuous process many times over.

Specialty chemicals, pharmaceuticals, cosmetics, and food are nearly always made batchwise. Around 25% of chemical engineers work in these sectors, so batch processing is important to chemical engineers. For some process sectors it is critically important.

It is not easy to say why batch processing seems to be the poor relation of continuous processes with respect to design textbooks but this is undoubtedly the case. A quick scan of the index of Sinnott and Towler or Perry's Handbook shows how little space is given to this topic. Sinnott and Towler have three entries in the index, two paragraphs on batch distillation, and nothing on batch heat transfer. Perry does a little better with 14 entries in the index and several pages on some topics. However, this amounts to considerably less than 1% of the content of the handbook (as does this section of my book!).

## *Why use batch processing?*

### Apparent simplicity

On the face of it, batch processes appear to be simply a scaled-up version of the process that a chemist would use on a laboratory bench.

This makes batch processes attractive if you do not want to spend too much time and money on development work. It is easy to get from bench to commercial scale cheaply and quickly if all you are doing is making the kit bigger.

For some sectors, such as specialty chemicals and food processing, the huge number of products and, in some cases, the short product life cycle means that getting to commercial scale cheaply and quickly is very important.

For pharmaceuticals, getting a product on the market quickly is important because of the limited patent life. In general, at least half of the patent life is lost during clinical trials and process scale-up. Batch processes that can be scaled up quickly are at a distinct advantage.

However, once you look at a batch process in detail, it soon becomes clear that in practice it is not as simple as it first appears. The chemistry is frequently poorly understood and the nonsteady-state regime of batch processes makes them difficult to model.

Batch processes are therefore quick to scale up but difficult to optimize; and their efficiency is consequently usually far below that of continuous processes. But without substantial investment to understand the process (good old R&D), a company is trapped here.

### Flexibility

Flexibility is a great advantage of batch processes. If you have a generic set of batch processing equipment then it is often possible to make a wide range of products. Some batch plants make hundreds of different products using similar processing methods and plant.

Multipurpose plants can be designed for a generic group of products and are frequently designed without any knowledge of the actual products to be made.

This is achieved by using a facility equipped to work with temperatures in the range $-100°C$ to $250°C$, pressures from high vacuum to 6 bar g and pH from 1 to 14.

Such plants are often made from highly corrosion-resistant materials such as glass, graphite, and tantalum, to allow them to handle a wide range of chemicals, unknown at the design stage.

This great flexibility is the reason why multipurpose plants are subject to close monitoring—they could be used to make illicit drugs or chemical weapons as well as more benign products.

### Solids handling

Many products in specialty chemicals, pharmaceuticals, food, and cosmetics are solids or semisolids. These products can be difficult and expensive to handle safely and economically in continuous processes, particularly at a small scale, though the required handling of bulk volumes of solids in batch would tend to make it inherently less safe.

In the case of pharmaceuticals, even the smallest scale commercially available continuous solids handling equipment may be of the order of 10 times larger than required. Small-scale batch solids handling equipment is generally much cheaper, less complex, and easier to maintain than continuous equipment.

### Batch integrity

The major advantage of batch processing is that it is possible to identify when the processing of a given sample started and stopped. This means that if the material manufactured does not meet the specifications, it is possible to reject only the particular batch which failed without needing to reject other material.

This used to be a highly important part of quality assurance when we depended on end-of-batch analysis and testing for quality assurance. As online analysis becomes increasingly available, batch integrity is becoming a less important part of quality assurance and many products are released based purely on the online analysis. We will require a greater understanding of key performance indicators and how variation in them is likely to affect the end product before this is widely applicable.

However, there remains a business risk in relying solely on online analysis and many companies still like to retain batch integrity to minimize their exposure to the consequences of release to market of out-of-specification material.

## The main batch design requirements

There are two major differences between continuous and batch processes; the nonsteady-state nature of unit operations and the importance of time-related sequences of operations.

One of the major differences is that it is not possible to summarize the details of a process using a piping and instrumentation diagram, as you would with a continuous process. It is necessary to have other documents such as PERT or Gantt charts to indicate how the process changes with time.

The nonsteady-state nature of batch processing impacts on all unit operations. To illustrate the point, the most important aspects are examined in the next section.

### *Batch heat transfer*

If you heat or cool a batch of liquid in a vessel, the temperature difference between the heat transfer fluid and the batch of material changes with time and so does the outlet temperature of the heat transfer fluid.

If you have the simplified case of cooling a homogeneous batch of material with an internal cooling coil then the heat transfer equation becomes:

$$\ln\big((T_1 - t_1)/(T_2 - t_1)\big) = WC/Mc\big((K-1)/K\big)\theta$$

where:

$T1$ = the initial batch temperature;
$T2$ = the final batch temperature;
$t1$ = cooling fluid inlet temperature;
$W$ = the mass flow of cooling media;
$C$ = the specific heat of cooling media;
$M$ = the mass of the batch in the vessel;
$c$ = the specific heat of the batch;
$K$ = the eUA/WC;
$A$ = the heat transfer area; and
$\theta$ = the time.

Even for this relatively simply case, the equation is quite complex and, as can be seen, includes a time parameter. For the fairly common case of using an external heat exchanger and a liquid being fed into the vessel, the equation becomes very complex.

### *Batch distillation*

In the case of batch distillation, the concentration of the liquid in the reboiler (the batch) will be changing with respect to time as the more volatile components are driven off. This means that the temperature in the reboiler will rise over time and the concentration of components in the fractionating column will change with time.

To maintain the required product concentration at the top of the column, the reflux ratio has to be increased over time. A point will be reached where it is no longer possible to maintain the top concentration, and distillation will have to stop or the top product be diverted to a separate receiver.

Batch distillation can be used to produce multiple fractions, but instead of the flows being taken off at different points in the fractionating column, as they would be in a continuous process, the fractions are determined by time.

### *Batch reaction*

In a steady-state continuous-stirred tank reactor the conditions remain constant within the reactor, but in a batch reactor, concentration, temperature, pressure, viscosity, density, etc. can change with time. An agitator which was appropriate at the start of the process may be much less suitable at its end.

The contents of the vessel may be more heterogeneous than in a continuous process, and different parts of the batch will consequently see different reaction conditions during the period of the reaction. This is one of the reasons why apparently simple batch reactions are in fact very complex. This lack of homogeneity usually becomes more of a problem as the scale increases and it is increasingly likely that unexpected reactions occur that have a serious impact on product quality.

### *Batch sequencing*

To be able to calculate the capacity of a batch plant it is necessary to consider the sequence of operations and whether these operations take place in series or in parallel. Most batch processing plants have a number of parallel streams of the same series of operations.

The plant capacity is usually based on marketing demand forecasts for the products that the plant is being designed to manufacture. Keith Plumb tells me that the only thing that you can know with absolute certainty about such forecasts is that they will be wrong.

The design tools for batch sequencing and capacity calculations are similar to those used for engineering project management, that is, a combination of Gantt and PERT charts. However, instead of basing the charts on flows of resources, they are based on mass flows and document the mass and energy balance.

### *Energy balance and utility requirements*

The energy balance will be based on the heating and cooling requirements for reactions, distillation, and other unit operations, as is the case for continuous plants. However, the process sequence will determine where and when energy needs to be input to or removed from the system.

The input and removal of energy will be time-dependent and nonsteady-state, which makes energy recovery difficult. Heat integration techniques are even less appropriate to batch process plant design than continuous process design.

**Table 6.1** Summary of separation processes

| | Relative price | Process robustness | Safety concerns | Capacity range | Separation principle[a] | Product recovery per stage | Contaminant removal per stage |
|---|---|---|---|---|---|---|---|
| | H | M | Rapidly rotating equipment | | Sedimentation | M | M |
| Adsorption | M | M | | | Surface interaction | | VH |
| Distillation | H | L/M | Flammable/ toxic vapors, heat | | Differential vaporization/ condensation | L/M | M/H |
| Filtration | L | H | | | Physical exclusion of oversize particles | H | H |
| Distillation | H | L/M | Flammable/ toxic vapors, heat | | Differential vaporization/ condensation | L/M | M/H |
| Adsorption | M | M | | | Surface interaction | H | VH |
| Stripping | L | H | Flammable/ toxic vapors/ liquids | | Mass transfer from liquid to vapor phase | M | M |
| Filtration | L | H | | | Physical exclusion of oversize particles | H | H |
| Adsorption | M | M | | | Surface interaction | H | VH |
| Freeze-drying | H | M | Low temperatures | | Sublimation | H | VH |
| Filtration | L | H | | | Physical exclusion of oversize particles | H | H |
| Elutriation | M | M | | | Sedimentation | M/H | M/H |
| Cyclones | M | H | | | Sedimentation | M/H | M/H |
| Drying | M | H | Heat | | Evaporation, usually heat-assisted | VH | VH |
| Decantation | L | H | | | Sedimentation | M/H | H |
| Extraction | M | M | | | Mass transfer from one liquid phase to another | M | H |
| Membranes | M | L/M | | | Physical exclusion of oversize droplets | H | H |

(*Continued*)

**Table 6.1** (Continued)

| | Relative price | Process robustness | Safety concerns | Capacity range | Separation principle[a] | Product recovery per stage | Contaminant removal per stage |
|---|---|---|---|---|---|---|---|
| Chromatography | VH | L/M | | | Differential affinity | VH | VH |
| Crystallization | M | M | | | Mass transfer from solution to crystal | M/H | H |
| Coagulation | L | M/H | | | Destabilization of a colloid | M | M |
| Precipitation | L | H | | | Exceeding solubility limit | M/H | M |
| Flotation | M | M/H | | | Sedimentation effected by reducing solid or liquid density with gas bubbles | H | H |
| Ion exchange | H | M | | | Differential affinity | VH | VH |
| Electrolysis | H | H | Electricity | | Electrochemistry | H | H |
| Centrifugation | M | M | Rapidly rotating equipment | | Sedimentation | M/H | H |
| Hydrocyclone | M | M | | | Sedimentation | M/H | M/H |
| Magnetic separation | H | M | | | | VH | VH |
| Extraction/ Leaching | M | H | | | Mass transfer from solid to liquid phase | M/H | M/H |
| Chromatography | VH | L/M | | | Differential affinity | VH | VH |
| Membranes | H | M | | | Physical exclusion of oversize particles for coarser membranes, diffusion for RO | VH | H |
| Electrophoresis | VH | L/M | | | Electrochemistry plus drag effects | VH | VH |
| Classification | M | M/H | | | Sedimentation/adhesion/ electrostatic | M/H | H |
| Sublimation | M | H | | | Sublimation | VH | VH |
| Magnetic separation | H | M/H | | | Differential magnetic attraction | VH | H |

Note however that the list is not exhaustive, does not go beyond separations of two components, and does not mention the plethora of subtypes of the technologies listed.
In case not obvious: *L*, low; *M*, medium; *H*, high; *V*, very.
[a]These principles are major influencers of the separation process, but they are at best tools for analysis and partial understanding. Real-world separators differ from mathematical/theoretical ones in ways which usually make any first-principles design unworkable.

Even working out accurate predictions of working utility requirements is impossible, as the system is too poorly characterized for these to have any certainty.

The simplest (and least wrong) approach is to calculate the maximum utility requirements for the worst-case scenario of process steps coinciding and then apply a "diversity factor," basically a guess of how much of the maximum possible load will occur in practice based on practical experience of batch processes.

This is not always done well, and some plants are consequently constrained by lack of utility supply, requiring additional capacity to be retrofitted. In other cases, too large a capacity with insufficient turndown is supplied, leading to controllability and efficiency problems requiring remedy.

Despite there being many remaining problems in the field of batch design, it is still very popular in certain sectors, and there are a multitude of successful batch processes in operation today.

## Neglected unit operations

Many students leave university with knowledge of only six to ten separation processes, usually those most important in oil refining, and the knowledge they have of these processes is mostly at best engineering science.

Processes based in chemistry are overrepresented in university courses, as are liquid/liquid separations. The consequent lack of knowledge of options impoverishes the designer's imagination, and a lack of understanding of engineering design practice prevents practical use of technologies.

Table 6.1 summarizes some of the most important separation processes arranged by phases.

For a more extensive and exhaustive treatment of all unit operations, I recommend Couper (see Further Reading) as a first port of call.

## Further reading

Couper, J. R., & Penney, W. (2012). *Chemical process equipment—Selection and design*. Amsterdam: Elsevier Press.

Moran, S. (2018). *An applied guide to water and effluent treatment plant design*. Oxford: Elsevier Press.

# CHAPTER 7

# System-level design

## Introduction

As part of my research for updating Mecklenburgh's Process Plant Layout, I read a PhD thesis by one of Mecklenburgh's students on a computer program to lay out plant. The student started his explanation by splitting process plant design into process design and plant design, and I was reminded again of Pugh's Total Design.

It is hard to use the word "holistic" without feeling a bit like an alternative medicine salesman, who would also tend to describe science as "reductionist." Unfortunately, the primary criticisms I make of how process plant design is taught require the use of these concepts, but we should bear in mind that there is no "alternative" engineering, just as there is, in my opinion at least, no real "alternative medicine" (for, as Tim Minchin points out, alternative medicine which works is called simply "medicine").

Anyway, we can split process plant design into process design and plant design. We could split these further and further until we have produced versions of process and plant design which are just mathematical problems. But even when we do this, the final problems are very complex indeed, even as straight math problems.

To take the example of programming computers to lay out process equipment in space, there has essentially been no progress since the 1980s. That PhD thesis claimed to describe a fully functional computer program for plant layout in the 1990s, but the most recent reviews of the literature make clear that no-one has come up with an algorithm as good as a professional engineer, even to the simplified problem they are trying to solve.

This intractable problem is not how to best lay out plant at all. It is how to allocate the arrangement in planar space of objects with simplified characteristics in order to minimize the cost of materials transport between them.

Safety, operability, process robustness, and most cost considerations have to be removed in order to simplify to the point where engineering can become math. The space in which this exercise happens has to be perfectly flat, and adding a second floor seems to make the intractable impossible.

Whilst this has kept academics who think they are working on layout issues busy for 30 years or so, it has not been of the slightest use to professional engineers as far as I know. There were few takers for that PhD student's program.

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00008-2
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Alternatively, we might consider what has happened to process design over the same period. As I have said previously, many academics now think that process design is done in simulation programs and optimized with techniques such as pinch analysis for maximum energy recovery, ignoring cost, safety, and robustness entirely.

So, the stage that we are at now is that academics think that they have solved "process plant design" by splitting it in two, and then removing all of the uncertainties, ambiguities, and complexities from these two aspects.

Unfortunately, the bits they removed were the important ones, and the problems they have solved were not problems at all. Optimizing for any single variable—whether that be approximated materials, transport cost, or maximum energy recovery—is not smart. It wasn't even smart to try this, as computers can only solve "stupid" problems.

Now, we can—nominally—split the intrinsically holistic process plant design into parts, either for convenience when teaching, or for the practicalities of task allocation in professional life. There is nothing wrong with this, but if we mistake these artificial divisions for real ones, we will be terrible process plant designers. If we do not teach students that these are artificial boundaries, they will not understand that process engineering always crosses these boundaries at every scale of consideration.

Humans, however, evolved to see and manage patterns in complexity. Engineering is a creative, intuitive, imaginative activity. We don't need to dumb design down to the point where a computer can grind out an answer. We can intuit an answer and then apply math and science as tools to test its plausibility.

The very essence of process plant design, the thing people employ chemical engineers to do, is system-level design. By this I mean more or less the same thing as Pugh means by his term "total design," rather than the approaches called by similar-sounding names in academia.

It is integrative, though I do not mean by this the academic research area "process integration" (or the similar-sounding, but unrelated "process intensification"), I mean integration of the needs of all engineering design disciplines, and those who are to build and operate the plant.

It has a broad-ranging vision—a good process plant design considers all the elements of design given in this book, in order to produce an appropriately detailed set of documentation to allow decision making in early stages, and construction in the last stage (unless we are going to consider decommissioning as the last stage).

It is multidisciplinary, involving usually (as a minimum) civil and electrical engineers, as well as, to a lesser degree, construction stage staff, management, clients, and plant operators.

It is multidimensional, taking into consideration as an absolute minimum the cost, safety, and robustness implications of every decision.

It is iterative—a design evolves through successively better incarnations.

Lastly, the thing which makes it truly system-level design is that process plant designers see in their mind's eye a complex system working as a whole. This is why all partial approaches entirely miss the point—it isn't about optimizing any one variable. It is about being able to imagine a completely integrated system which no-one can fully understand, but that the designer understands well enough to make it do what they want it to do in the way they say it is going to do it. Process and hydraulic design, unit operation design and selection, plant layout, process control, instrumentation, costing, and hazard analysis must all be considered together and balanced against each other by professional process plant designers. They never optimize for less than three variables simultaneously. Those variables are broadly cost, safety, and robustness, but these are themselves complex.

So how do we do this?

## How to put unit operations together

The main tools for system-level design are the piping and instrumentation diagram (P&ID), process flow diagram (PFD), and general arrangement (GA) drawing (though, for larger plants, this is increasingly a 3D model rather than the GA alone). Taken together, these drawings represent a great deal of our design deliberation in a concentrated form. We can see from them, at a glance, most of the things we need to consider in making the components of our plant work together.

We use them in slightly different ways as design progresses, but the PFD encapsulates the integration of mass and energy balance, the P&ID system-level control and integration, and the GA the physical and hydraulic constraints.

They are not just records of the designer's thinking, though this is an important function to allow the review of designs by others. Producing these documents forces the designer to consider the issues described in the last paragraph, and allows him or her to visualize the effects of their proposed solutions. They are therefore design tools as well as records.

The academic methodologies intended to serve the purpose of process integration are hardly ever used in design practice because they are addressing a problem which professionals have already solved, in a more comprehensive and universally comprehensible way.

## Matching design rigor with stage of design

At the conceptual design stage, we have to get a broad idea at the very least of recycle ratios, as these can have a huge effect on main plant item sizing for certain types of unit operations, such as reactors and their often closely associated separation processes. This will involve generating a PFD and associated mass balance.

We need to get an idea of how physically large the plant is going to be, so that we can see if it is going to fit on the available site. We will need to produce a GA to do this, and carry out rough hydraulic calculations.

These hydraulic calculations will tell us whether we are going to have a completely pumped system, or make some use of gravity, a choice which will affect the plant layout and be seen on the GA. We will need to decide if we are going to use a batch or continuous process, a decision which will again affect layout and plant footprint.

The P&ID will be affected by these choices, and there are also choices to be made between software and hardware solutions to design problems, the solutions to which will appear even on early-stage P&IDs.

At this stage we are probably designing unit operations using rules of thumb, without checking whether the units we are specifying are commercially available. We probably have fairly sketchy design data, have made quite a few simplifying assumptions, and have been given only a few resources to get to the desired endpoint.

Our aim is to see if we can fit the plant on our site, and whether it is plausible from the point of view of cost, safety, and robustness. This is an initial rough screening, which the overwhelming majority of proposals fail. We cannot optimize such a design due to lack of definition, and we should not try, because we want to err on the side of caution.

If we are asked to produce a detailed design which we are willing to stand by as a fairly robust investigation, evaluation, and solution of the vast majority of design problems and tasks, then we need to look much harder. The same three drawings are, however, still going to be at the center of the exercise, but now they are primarily tools for collaboration with others.

System-level design optimizes the whole-plant design, considering the implications of design decisions for our civil and electrical partners, installation and commissioning engineers, plant operation and maintenance staff. We can send drawings (especially the GA which almost everyone can understand) back and forth with our design collaborators, installation contractors, and so on to take on board their opinions.

We can use the drawings to conduct design reviews with all interested parties. This is not to imply committees produce good designs, they do not. A plant "improved" by including layers of afterthoughts, or features which allow people to feel they contributed, is very likely to be a suboptimal design.

The process plant designer needs both a strong vision and a willingness to challenge any suggested design modifications, inviting anyone making such suggestions to prove that they are improvements from the point of view of whole-plant cost, safety, and robustness. A plant "improved" in a way which, for example, maximizes profit or minimizes risk for the civil or electrical partner alone is unlikely to be optimal. Only genuine improvements should get past the designer, but they should not be closed to the idea of needed change.

## Implications for cost

There are many ways to consider the capital and operating cost implications of designs. "Least capital cost" is probably the most popular method, despite its shortcomings, but there are also evaluations based on whole-life cost, total cost of ownership, and net present value, among others.

A well-integrated design considers cost in the same way the designer is asked to consider cost by the client. We need to set aside our preferences and prejudices and give them what they want if it is possible to do so.

We can design a least-cost plant which operates for the defect liability period plus 1 day, or a plant with an excellent whole-life cost. We can design a plant based on the technologies the client's staff are used to even though there have been better technologies for decades.

None of these are the wrong approaches, if they are the preference of the people who are paying. We may attempt to persuade clients to use another evaluation basis, but if it is not in some way cheaper, we are unlikely to succeed.

Generally speaking, from a capex point of view:

- More robust plant and materials may cost more;
- More automated plants cost more;
- Add-on safety equipment (but not inherently safe plant) costs more.

From an opex point of view:

- More robust plant and materials generally cost less to operate;
- More automated plants cost more to maintain, but save on operator time;
- Add-on safety equipment (but not inherently safe plant) costs more.

Note that from the point of view of both capex and opex, simplicity saves money.

## Implications for safety

We tend to consider safety issues based on legal responsibilities and professional codes of practice rather than client preferences in the first instance.

As discussed in the last section, afterthought safety (or "tinsel safety," as I used to call it back when my students used to "complete" a plant design with no consideration of safety and then decorate it with pretty safety features) costs money (it also reduces robustness), but system-level thinking eliminates risk using techniques such as inherent safety.

The system-level approach might actually save more money—by eliminating unnecessary layers of add-on safety features—than the cost of the required safety measures controlling the risks which remain after minimization, substitution, and moderation of risks inherent in the design, and limiting the effects of adverse events.

Making the design error-tolerant and simple may also be included under the heading of inherent safety, but these to me are basic design principles with effects beyond the realm of safety.

Any optimization which is carried out at the conceptual design stage needs to address these paramount issues.

## Implications for robustness

I was originally going to say here that robustness costs money, which is I think what most practicing engineers would say without a break for reflection, and is often true at the level of components, but is not necessarily so at the level of systems.

For example, which is better, a Daihatsu or a Bentley? Well, the Bentley looks pretty slick, but the Daihatsu has a reliability index of 40, and the Bentley 582 (average reliability is 100, and the lower the number, the better—see Further Reading for source).

So, robustness may be thought by many people to always cost money, but the robustness of simplicity, and well thought-out integration of complex systems always saves money, and can trump the usually higher costs of robust components.

Clients may specify directly a period of operation of a plant, and/or they may give tender evaluation criteria which make clear whether they want a low capex, low opex, or low whole-life cost plant. Professionalism would prevent us offering a plant below certain standards, though these would be pretty low.

We could, if asked, design a plant intended as a display of wealth, like a Bentley, showing that you just don't care how much it costs to run, because you can afford not to care. This is, however, much less popular in process plant design than in car design.

We can offer the same plant availability by using multiple cheap low-robustness units, or a smaller number of more robust items. The latter is often better from the point of view of whole-life cost, if not from a capex point of view.

## Rule of thumb design

Rules of thumb are one of our main easy-to-learn tools in managing complexity. Real rules of thumb incorporate knowledge of the limits of operability, safety, and economics. They tell us where a working solution is likely to lie. They also tell us which approaches are likely to fail.

By "real" rules of thumb I do not mean those things with the same name now being generated using repeated computer modeling exercises. Real rules of thumb crystallize experience with real full-scale plant, which is very similar indeed to the plant being designed. Computer modeling is theoretical first-principles design unless the model has been validated against real full-scale plant. You cannot generate experience from theory, only from practice.

It should be noted that all rules of thumb are specific to a set of circumstances, and contain implied assumptions. They should not be applied outside these specific circumstances without the greatest of caution. Ideally, they should not be applied outside their specific case at all but, practically, we may have to bend the rules a bit on occasion. If we do this, we need to know that we are doing it, and reflect this in our degree of confidence in our answer. Complacency has led to disaster on many occasions in engineering.

## First-principles design

This is not how professional process plant design is done, because anything designed from first principles is essentially a prototype, and its operators are test pilots.

If we are forced to carry out first-principles design, there will undoubtedly be teething problems. Such a plant may not be safe, is unlikely to be robust, and will probably not be cost-effective.

So, this is not a professional design approach, and there is a fair chance that its product cannot be made to work at all. This will come as a great disappointment to the client who spent large sums of their money on what they thought was a competently executed design.

This is not to say that there will not be occasions on which you are asked by a client to do something novel without being given the resources to characterize the problem well enough to avoid first-principles design. This happens to me occasionally, and can lead to some difficult conversations. The following should be markers for possibly crossing a line in this area:

- Being asked to scale up a process by a factor of more than five;
- Being asked to design a unit operation (or worse still a whole plant) based on bench-scale tests of kit for which there are no full-scale references;
- Building the first plant of any type or at significantly increased scale.

I am not saying that you should never design a prototype (I have designed a few myself), but that you need to know that is what you are doing, and not confuse this R&D activity with normal professional process plant design. Technological innovation is fine, but needs to be managed in the correct way.

The oil and gas industry has a concept of technical readiness levels, defined in API 17N and summarized in Table 7.1.

There is also the related idea of technology qualification as set out in DNV RP A-203. "Qualification is the process of providing the evidence that the technology will function within specific limits with an acceptable level of confidence." This mainly differs from the API standard above in providing detailed advice on how to do the assessment, rather than being a high-level definition term.

**Table 7.1** Technical readiness levels

| TRL number description | Criteria |
|---|---|
| TRL 0 Unproven concept (basic R&D, paper concept) | • Basic scientific/engineering principles observed and reported<br>• Paper concept<br>• No analysis or testing completed; no design history |
| TRL 1 Proven concept (proof of concept as a paper study or R&D experiments) | • Technology concept and/or application formulated<br>• Concept and functionality proven by analysis or reference to features common with/to existing technology<br>• No design history; essentially a paper study not involving physical models but may include R&D experimentation |
| TRL 2 Validated concept Experimental proof of concept using physical model tests | • Concept design or novel features of design are validated by a physical model, a system mock up or dummy, and functionally tested in a laboratory environment<br>• No design history<br>• No environmental tests; materials testing and reliability testing are performed on key parts or components in a testing laboratory prior to prototype construction |
| TRL 3 Prototype Prototype tested (system function, performance and reliability tested) | • Item prototype is built and put through (generic) functional and performance tests; reliability tests are performed, including: reliability growth tests, accelerated life tests and robust design development test program in relevant laboratory testing environments; tests are carried out without integration into a broader system<br>• The extent to which application requirements are met, assessed, and potential benefits and risks are demonstrated |
| TRL 4 Environment tested (preproduction system environment tested) | • Meets all requirements of TRL 3<br>• Designed and built as a production unit (or full-scale prototype) and put through its qualification program in simulated environment (e.g., hyperbaric chamber to simulate pressure) or actual intended environment (e.g., subsea environment) but not installed or operating; reliability testing limited to demonstrating that prototype function and performance criteria can be met in the intended operating condition and external environment |
| TRL 5 System tested (production system interface tested) | • Meets all the requirements of TRL 4<br>• Designed and built as a production unit (or full-scale prototype) and integrated into intended operating system with full interface and functional test but outside the intended field environment |
| TRL 6 Field qualified System Installed (production system installed and tested) | • Meets all the requirements of TRL 5; production unit (or full-scale prototype) built and integrated into the intended operating system; full interface and function test program performed in the intended (or closely simulated) environment and operated for less than 3 years<br>• At TRL 6 new technology equipment might require additional support for the first 12–18 months |
| TRL 7 Field proven (production system field proven) | • Production unit integrated into intended operating system, installed and operating for more than 3 years with acceptable reliability, demonstrating low risk of early life failures in the field |

## Design by simulation program

Many simulation programs now come with rough costing data built in, but unless you add your own safety and robustness elements, they are not considered, and you can easily "design" plants you don't understand very well with no safety factor.

Any such functionality is normally based on a very small data set and is thus often poor quality, as many companies (operators, suppliers, or EPC contractors) just won't share these data with a "software company."

There is no need for a simulation program user to keep the plant simple enough to understand it, or to have a model of any part of the system in their head. There is no need to consider the requirements of other disciplines or stakeholders, nor any tools in such programs to produce collaborative documents.

These factors should give us grounds for grave doubts about the use of such programs in anything other than the most tightly constrained circumstances. I simply cannot disapprove strongly enough of their use for "process optimization" at the conceptual design stage, ignoring most of the important factors in true system-level plant optimization.

Simulation and modeling programs can, however, be of use for equipment suppliers to specify standard products, assemblies of standard products, or standard package plants. In this application, the default values in the program are replaced by users with real operating, thermodynamic, and costing data, so that the program is really operating as a convenient dynamic repository of empirical data.

There can still be some limited use of imagination and even a little innovation under these circumstances, but we are in my opinion shading into a modeling program operator/salesman role here.

## Sources of design data

### Client documentation

Usually our client will give us some documented idea of what they want and may well have gathered some data to assist us in our design. Clients, however, frequently attempt to disavow any responsibility for the information they supply and try to pass on all design responsibility to design companies.

I have seen this approach tried many times in my expert witness engagements, and all it succeeds in doing is enriching lawyers and expert witnesses in the event that things go wrong. No contract can deem people to know things they cannot know.

Designers need to exercise due diligence in checking that client data are correct. There are potential opportunities here as well as problems. Sometimes the correct information or approaches can be more competitive than the suggested ones, or an alternative endpoint can be better, safer, or cheaper than the one the client asks for.

Commercially minded engineers (which should be all of us) should be on the lookout for these ways to get ahead of less flexibly minded competitors.

## Design manuals

It is common that companies will specialize in designing certain sorts of plants and will have codified their know-how in in-house design manuals. These are often mandated as the source of information and approaches to be used by the company's designers.

Going off-piste is at the designer's own risk and is frequently a sackable offence. It also exposes designers to the possibility of legal action in future.

That said, I have worked at places which had bad design manuals based on modeling program output and felt a professional obligation to challenge the manual. This does not always go down well, but we are not automata. Professional judgment is required of professionals.

## Standards

Governments, national and international standard institutes, and trade bodies also codify know-how about what works and what does not (especially with respect to safety issues) in standards and codes of practice. Failure to adhere to codes and standards may be more serious in some jurisdictions than failure to follow design manuals. It may be illegal and even imprisonable, though different countries have different degrees of codification, and some (such as the United States) are moving from a highly codified approach towards a more outcome-based one.

National, regional, and international standards may well have conflicting requirements. The choice of which ones to follow is often dependent on the sector which the plant falls into, or conventions with respect to the type of equipment being specified. For example, the oil industry works largely to the American Society of Mechanical Engineers (ASME) and American Petroleum Institute (API) standards, and air pollution control equipment suppliers may look to German TA Luft standards.

Make sure you are following the most up-to-date version of codes and standards, and don't follow codes and standards blindly. Exercise professional judgment. Partial compliance with a written standard for a good reason is better than slavish compliance where it is inappropriate.

Don't play mix and match to get around a tough standard and have a consistent philosophy from the conceptual design stage on issues like the acceptable size of fugitive emissions. Make it a good one, as it is expensive to change it later. Consistency of philosophy makes for ease of comprehension by operators and other engineers later in the design process.

Note that in countries with a well-developed regulatory environment, regulatory authorities may specify codes and standards to be followed and offer their own

statutory guidance. In less-regulated countries, the minimum standards consistent with professional ethics are applicable.

I have included at Appendix 5 a short list of standards which are commonly applicable to process plant design.

## Manufacturers' catalogues and representatives

This can be a rich source of knowledge. In order to produce a design integrated at depth, you need to have a very detailed knowledge of the parts of the thing you are designing (or know someone who does). Equipment salesmen are not merely an annoyance as some designers think. You can work with them to produce very well-integrated designs.

## More experienced engineers

For philosophers, the argument from authority is a logical fallacy, but I'm not going to worry about the opinions of people who doubt whether the sun is going to rise tomorrow.

For new engineers, discussing ideas with someone who has a feel for design through long experience is far better input than the most rigorous mathematical modeling exercise. A fellow engineer told me "This is highly cultural ... in the West we try and get engineers to think and challenge, in China etc. the practice is very hierarchical and younger engineers will be told what to do." This may well be generally true, though I have encountered some Chinese engineers who are happy to challenge authority figures!

We old guys might seem a bit negative to newcomers, as so much of experience is knowing what doesn't work, and the practical constraints on plant design, commissioning, and operation.

As neophytes ("noobs") become more experienced themselves, they come to see that the constraints are not stifling but are the rules without which the game would be no fun.

## Pilot plant trials/operational data

Sometimes we have the luxury of information on the operation of an existing very similar plant at the proposed site, or at least a similar type of plant at a similar site.

Sometimes we may have data from a similarly sized pilot plant of the proposed type at the proposed site. Sometimes the data we have are for less similar plants.

We need to be cautious with such data, and to be honest with ourselves about how much trust to put in it. Scale effects need to be considered. A pilot plant less than say 20% of the rated capacity of our plant might not be that strong a guide as to the constraints on operation of a full-scale plant.

Such data may be used to validate a computer model. Where this is done well (as it is done, e.g., by Air Products) this is a great aid to the designer. A validated model is, however, only true for the plant whose data have been validated. It is no more capable of predicting the operation of a plant 10 times as large as a physical pilot plant would be—quite possibly less so.

Other sites and other technologies may be less similar than we think to our proposed site and technology. I once undertook an expert witness engagement where a technology which worked at a small scale on one kind of effluent outdoors in Canada failed to meet expectations with a different kind of effluent entirely indoors in the Caribbean.

## Previous designs

The same companies which have enough experience to have good design manuals also probably have staff who have designed previous similar plants, and commissioning engineers who have commissioned such plants. These are the people who know what does and doesn't work.

There will in such companies be access to drawings and calculations used to design previous plants, costing data, and an opportunity to improve on the last design based on commissioning and operational experience.

That is why clients like to buy from companies with a track record, and new designers would be wise to try to work for such companies.

## The Internet

The internet looks quite different outside academia, as professional engineers rarely have free access to scientific papers. This is not, however, a big problem: most scientific papers are about experiments at too small a scale to be of much use to full-scale plant designers anyway.

A far more valuable use of the internet is the free 24/7 access to manufacturers' data, literature, and drawings. Nowadays we can choose unit operations based on detailed information and insert an accurate AutoCAD version of the chosen kit into our drawings without even talking to manufacturers.

A word of caution: the internet is undiscriminating in its content. A feel for the reliability of internet sources has to be developed. If a page looks like it was produced by a barely literate teenager it is usually obvious that it is not a reliable source of information. Obvious puff pieces for equipment manufacturers abound in Wikipedia articles as well as on their own websites. The most useful questions to interrogate web pages with are "Says who?" and "Based on what?" If you cannot see solid backing for claims, it is best not to rely upon them.

One more thing: I would advise you not to go on web forums asking more experienced engineers the most basic details of how to design the thing you are designing. They will wonder which Muppet asked you to design that thing when you have no clue where to start. This reflects badly on both you and your employer.

## Libraries

Large public libraries often still carry handbooks and textbooks which are of use to the designer. It is also usually possible for alumni to get free in-person (but not the far more convenient remote, electronic) library access at the university they attended. Sometimes it is cheaper to take a trip than to buy a copy of a technical resource, as these can be very expensive.

## Further reading

BNP Paribas Warranty Direct. (2018). *Reliability index*. Available at <http://www.reliabilityindex.com/manufacturer>. Accessed 23.10.18.

# CHAPTER 8

# Professional design methodology

*Aeroplanes are not designed by science, but by art in spite of some pretense and humbug to the contrary. I do not mean to suggest that engineering can do without science, on the contrary, it stands on scientific foundations, but there is a big gap between scientific research and the engineering product which has to be bridged by the art of the engineer.*

***British Engineer to the Royal Aeronautical Society***

## Introduction

Each of the stages of design produces increasingly precise deliverables. We start with broad sketches and rough back-of-the-envelope calculations and we get down to drawings accurate to the millimeter and calculations good enough to purchase expensive equipment which will reliably do a specific duty.

So, each stage of the design process has a natural resolution, or granularity. It will be excessively resource-intensive to produce a more precise definition of the design at any given stage than is conventional, and the additional precision will be of no benefit to those commissioning the exercise. It will be wasted effort (and therefore money).

One of the mistakes made by early-career designers is to attempt to design unit operations in great detail at the conceptual design stage, as they were required to do at university. They often find that the information they need to do the calculation as they were taught at university (at best, as set out in Sinnott & Towler) is simply not available.

Both information and design challenges are generated during each stage of design. Much of the information needed to carry out detailed design of unit operations may never be publicly available, but specialist suppliers and licensors will usually have it, or an alternative design methodology which does not need it.

Newcomers to this approach, coming from the certainty of mathematics and pure science based degree programs, may find it a little odd, even a bit flaky. Why not

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00009-4
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institute a scientific research program to resolve all the uncertainties and collect all the missing data? Why not produce a simulation based on this program so detailed that the design process is more or less just a process of interrogating the simulation?

Why not? Because this would cost a great deal more, take far longer, and produce less good results than just having professional engineers design and build the plant, and no one is going to pay you to do that. For example, a company I used to work for tells me that they are producing a reliable, empirically validated model of a single unit operation. After 2–3 years of development, it is almost (but not quite) as good as the 30-year-old rule-of-thumb-based design approach which they are still using to actually design plants.

So, if you are going to use modeling properly, your competitors can give the client the information he or she needs for a tiny fraction of the resources you propose to use, probably even as a "free" favor. Process plant design is a commercial activity. Any methodology which does not recognize that will remain at best an academic curiosity.

## Design methodologies

There is really only one design methodology in all design activity: the iterative staged approach described in this book.

However, designers may use discipline-specific design techniques, design philosophies, and design support tools. In circles where no one designs plants for a living, all kinds of "design methodologies" can grow up.

Setting aside the academic "chemical process design" methodology discussed previously, there is a handy list of examples of "Design Methodologies" in Koolen's book "Design of Simple and Robust Process Plants" (see Further Reading) as follows:

- Inherently Safe Design;
- Environmentally Sound Design;
- Minimization of Equipment;
- Design for Single Reliable Components;
- Optimize Design;
- Clever Process Integration;
- Minimize Human Intervention;
- Operational Optimization;
- Just in Time Production;
- Design for Total Quality Control.

Koolen essentially proposes rolling all of these into one in order to obtain "an optimally designed safe and reliable plant operated hands off at the most economical conditions."

Koolen's background is plant operation, rather than design and, in common with many academic approaches, his is a technique for design of modifications to hydrocarbon processing plants with extensive operational data supporting a modeling exercise.

Many of the things he calls "design methodologies" are used in professional practice, but none of these are really design philosophies or methodologies, nor are they all universally applicable or without conflicting interactions.

To take one example: "Minimization of Equipment" has the subcategory "Avoidance of more reactor trains by development of large reactor systems." Theorists, researchers, and idealists will always favor scale-up (making one big novel reactor) over scale-out (having lots of small proven reactors). Professional designers will, however, also consider the time and expense of the implied development program. Scale-up needs to balance the turndown of one large reactor against two or three smaller reactors. You can achieve a larger turndown with two or three smaller reactors by turning some off. If the market for your product reduces, and the single larger reactor has insufficient turndown, the site which went for scale-up rather than scale-out may close. Notice also the clash between this approach and Inherently Safe Design's desire for small reaction masses. There is simply no way to avoid the need to apply professional judgment.

There are of course many problems apart from turndown—logistics are key for many sites and too large a piece of equipment simply cannot be transported due to size or weight. Larger vessels also need thicker walls, which can create welding difficulties and limit the number of potential suppliers, making this a more expensive option than one subjected to truly competitive tendering.

I mention Koolen's book because I have far more sympathy for his approach than those proposed by academics without operational experience. None of his "design methodologies" are terrible ideas in all settings—they all have their place, though for some of them it is in process optimization rather than design.

It seems a clever approach to the problem it sets out to address, producing a hydrocarbon processing plant as simple to operate as a washing machine. I don't know if this problem has ever actually come up, let alone if anyone has actually applied the methodology to it, but it looks (to someone who has never been asked the question) as a decent place to start answering it.

There are approaches used in operational companies to carry out "designs" of sufficient quality to allow operational companies to supervise detailed designs done by contractors on their behalf. These are the foundation of the approach used in Koolen's book, as well as any industry input to academic design approaches. This is not, however, process plant design as I define it. This is optimization of an existing design by operating company staff.

I know that there are many theoretical approaches in academia and in operational companies for the activity they call plant design, but in professional process plant design practice there is one basic methodology, used worldwide and across sectors. In the remainder of the book, I will describe this approach in enough detail to hopefully allow a beginner to master the basics.

## The "is" and "ought" of process design

Process design deals with what ought to be. It is not a scientific description of something which already exists, but a practical creative activity aimed at bringing into being something thought desirable.

Much of the academic discussion of process design is to do with how design ought to be done, rather than how it is done. Such discussion is normative, rather than descriptive. Without claiming that what is, is what ought to be, I will offer an approach based on a description of what I believe to be the modern consensus approach.

What process design ought to be is a way to imagine, select, evaluate, and define safe, cost-effective, and robust solutions to the problems inherent in the design problem we have been asked to address. All ways of achieving this are good. We are paid to be engineers, not ethicists, nor social reformers.

## Right versus wrong design

There is no entirely right design, but there are an infinite number of wrong ones. Being sufficiently right really matters if someone is going to spend millions of dollars on the thing you have designed.

Engineers tend to only design things for construction which they really understand. You might think you can grind through BS PD5500 or EN 13445 and design a pressure vessel as well as the next person, but if you tell a supplier to make such a vessel to your specification, you are taking responsibility for the integrity of an item made by others. This is why we tend to make those who supply equipment responsible for its design.

We need to be able to do enough design to give suppliers' proposals a quick check over for reasonableness, but they are far more likely than us to have the know-how to make a specialist item in a safe and cost-effective way.

## Interesting versus boring design

> *A good scientist is a person with original ideas. A good engineer is a person who makes a design that works with as few original ideas as possible.*
>
> ***Freeman Dyson***

You need a damn good reason to be interesting as an engineering designer. "Interesting" or revolutionary design is nowhere near as likely to work as boring old "normal" design, where there are only incremental changes in design approaches which are known to work.

Academia, on the other hand, tends to value interesting design, as the research quality is judged to a large extent on its interestingness. Practitioners, however, need something which will definitely work, rather than an interesting research project.

Vincenti gives a number of examples of this phenomenon in his book "What Engineers Know and How They Know it" (see Further Reading), most notably the case of the development of the jet engine in Germany and the United Kingdom.

After early success with centrifugal engines, the Germans designed an axial-flow engine years ahead of its time, very similar to modern jet engines. There were few suitable materials to make such an engine at the time, even if they had been working under peacetime conditions. The German Junkers engine consequently had a life in service of around 12 hours, before it needed replacing with a new engine. It was a terrible waste of resources. Cost, safety, and robustness had been ignored in favor of novelty and elegance (Fig. 8.1).

The British jet engine designed at the same time was ugly, but it was designed to be produced under the prevailing circumstances. It was a "boring" design, but it had a very long service life, and went on to set world speed records (Fig. 8.2).

As with all in engineering, there is a balance to be struck. Dyson says "as few original ideas as possible." He doesn't say "no original ideas."

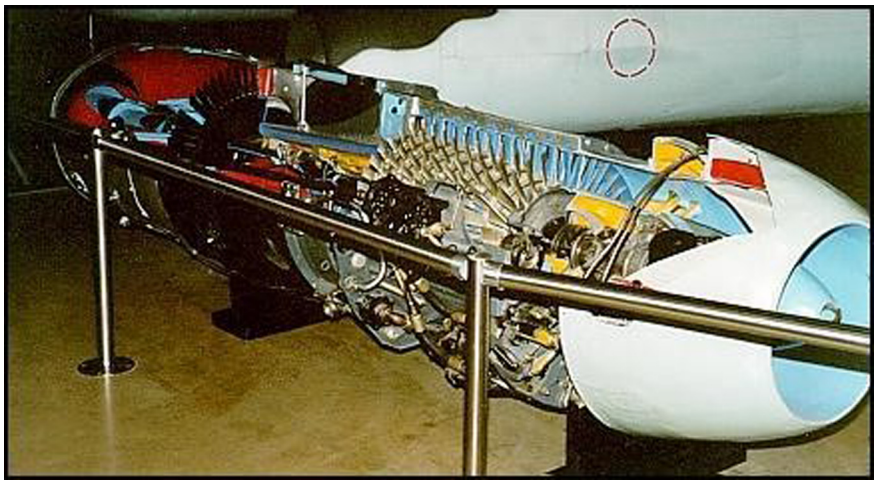

**Figure 8.1** The Junkers Jumo 004 engine. *Courtesy: National Museum of the US Air Force.*

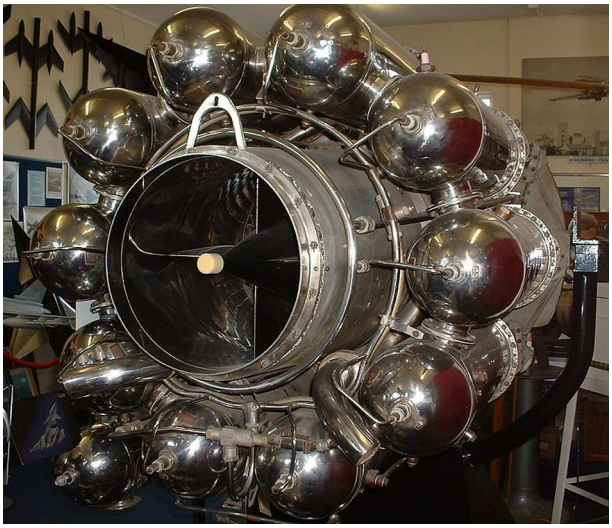

**Figure 8.2** The Whittle W2-700 engine.

## Simple/robust versus complicated/fragile design

There are so many quotes about the importance of this that I am spoilt for choice, but how about starting with someone considered by many to have been the first engineer?

*Simplicity is the ultimate sophistication.*

***Leonardo Da Vinci***

Koolen says, in *Design of Simple and Robust Process Plants*: "A process plant should meet the simplicity and robustness of a household refrigerator." This might be a bit over the top in most cases, but good designs are (in a phrase widely attributed to Einstein) as simple as possible but no simpler. This is not, as some think, quite the same thing as Occam's Razor—it contains an additional note of caution against oversimplification. (This is a very important consideration in offshore projects: complex plants often require more maintenance and thus more manning which carries more opex and has inherent safety risks.)

Complex designs shouldn't be ruled out-sometimes they are needed, but they should be evaluated bearing in mind the fact that simple plants are easier to understand, easier to analyze, more robust, more likely to be getting to the root of design challenges rather than piling afterthoughts on top of each other. More operable, more maintainable, more commissionable, more reliable, more available, more robust. What's not to like?

A classicist turned computer scientist puts it well:

> *There are two ways of constructing a ... design: One way is to make it so simple that there are obviously no deficiencies, and the other way is to make it so complicated that there are no obvious deficiencies. The first method is far more difficult.*
>
> ***C.A.R. Hoare***

There is an unexamined axiom in the "simple and robust" approach similar to that in academic approaches, the optimization of a small number of variables. Do we really need all process plants to be operable by the general public? Or are we shooting for a simpler design than is necessary if we blindly apply this approach?

Like the typical engineer, Koolen proposes to quantify simplicity with a view to allowing it to be systematically reduced. Do we really need to quantify simplicity? I have designed a few small package process plants which are to be operated by the general public, and I did not apply Koolen's mathematical/theoretical approach to attain the necessary simplicity. I know simple when I see it, and (like enlightenment):

> *It seems that perfection is reached not when there is nothing left to add, but when there is nothing left to take away.*
>
> ***Antoine de Saint Exupéry***

## Lessons from the slide rule

Before computers or even electronic calculators, engineers had slide rules. They couldn't easily use them to add and subtract and they had to guess where the decimal point was. This meant that engineers needed to be quite adept at mental arithmetic, and only worked to three significant figures.

My students get nervous when, like most engineers of my generation, I round up figures, do rough sums in my head, etc. Many believe that all 10 of the figures on their calculator displays are significant, even when I have set them a problem with two significant figures in the question data.

Often process engineers mistakenly specify to a level well beyond the manufacturing tolerance of equipment. It's also important to factor in equipment degradation in the design specification as this is often allowed by code. This is usually given as a percentage, for example, 4%–6%, which makes a mockery of spuriously precise figures.

Process plant design engineers are probably kidding themselves if they think that they are working beyond three significant figures. Their underlying data are probably at best to this degree of precision. The extra decimal places on calculator and computer screens are spurious precision.

A feel for the sensibleness and reliability of our numbers is what really matters. Our modern tools seem to be taking this judgment away from new engineers. Perhaps universities need to start using the QAMA calculators you can get now that require you to estimate the answer before they will give it to you.

## Estimation/feel

> *He ... insists that no mathematical formula, however exact it may appear to be, can be of greater accuracy than the assumptions on which it is based, and he draws the conclusion that experience still remains the great teacher and final judge.*
>
> ***James Kip Finch***

A feel for the potential error associated with your answer, and its consequent meaningful precision, is very important in engineering (even those who are not Finch's assumed "he"). It is related to the margin of safety and turndown required to make a plant which will work.

New Scientist magazine conveniently gave us a word for this discipline, "olfactorithmetic," or the ability to notice if a number "smells" wrong. It will come with practice, but you can start to get it by always remembering the compounded uncertainty of your sources of data, the imprecision of your heuristics, and the probability of error.

As a rule of thumb, remember that every engineering design method is based on assumptions and simplifications; your original design data have an associated degree of uncertainty, as do any chemical/physical data you are using. If you have not identified, verified, quantified, and multiplied these assumptions, simplifications, and degrees of uncertainty, your calculations are at best very rough.

There is nothing wrong with rough calculations, as long as they are combined with professional judgment. If I have sized a piece of equipment using three independent rough sizing methods which have a decent track record of success in professional use and used professional judgment to make sense of the answers, I am far happier that I have a robust solution than if I had commissioned a 5-year bench-scale research study.

So, avoid spurious precision—be honest with yourself about how much you really know, and specify equipment with a margin of safety plus turndown to match the design envelope.

## Setting the design envelope

We might call much of what is taught in university "Training Wheels Design." Just as we teach kids to ride a bike by minimizing the complexity of the task with a couple

of ancillary wheels, we minimize the complexity of the design task for beginners with an assumption of "steady state"—all parameters (flow, composition, temperature, pressure, etc.) are assumed to be constant during the life of the equipment.

A real plant operates for most of its life within bounds set by the effectiveness of its control system; a significant part of its life in commissioning/maintenance conditions outside these bounds; and has to be sufficiently safe when operating well out of bounds in an emergency situation. In addition, the maintenance and emergency conditions we need to accommodate may well have a larger effect on the limits of plant design than the requirements of quasi-steady state normal operation.

So, we have to design a plant which will handle normal variations for extended periods of time, maintenance conditions for shorter periods of time, and extreme conditions for short, but crucial, periods.

Real plant design may have dozens of parameters at each stage, each of which has a range of values, rather than the single value it has in the steady state case. The range of values will be associated with a range of probabilities, similar to a confidence interval. If our design is good, extreme values will be experienced with a low probability, and average values will be commonplace.

We frequently use confidence intervals to decide on the upper and lower bounds of incoming and outgoing concentrations of key chemicals. Performance trials are frequently statistically based, so we are in effect already working to a confidence interval in our product specification. We do not, however, design to the specified confidence interval: many engineers usually go up at least one standard deviation, such that a 95% confidence interval specification from the client leads me to work to a 99% confidence interval design.

We then need to permutate these ranges of parameters to generate design cases, representing the best, average, and worst cases we can imagine across important permutations.

For example, if I am designing a sewage treatment works, it needs to work in the middle of the night when no one is flushing a toilet and most factories are closed, as well as at peak loadings. It needs to work during dry weather, and during a 100-year return period storm. It needs to work sufficiently well even when crucial equipment has failed.

When it rains hard, we can initially get a sharp increase in solids and biological material coming in through sewer flushing, and afterwards we get large volumes of weak sewage, mostly rainwater.

So, I need to design to a low-probability/high-strength/high-flow scenario, a medium-probability/high-flow/low-strength scenario, a medium-probability/low-flow/high-strength scenario, and a high-probability/medium-flow/medium-strength condition.

I can imagine those who believe chemical engineering to be petrochemical engineering thinking this only applies to water and sewage treatment, but this is just a specific example of a general condition: oil is a natural product too, whose production is subject to wide variations in flow and composition. In petroleum refining, very few refineries continue to run the crude they were initially designed for. Even in the Middle East, the properties of indigenous crudes change over time, often increasing in specific gravity and giving less distillate product. Sometimes the reservoir drops below the bubble point, leading to gas breakthrough.

In offshore oil and gas design, only a small number of test/appraisal wells are drilled, and good engineering judgment has to be applied to evaluate the impact of the uncertainty of the data obtained from well fluid analysis on production, operation, and flow assurance. This analysis only gives an initial composition, and composition will change with time, often leaning out or souring, and these changes needs to be factored into design. A fellow engineer recently described to me his first-hand experience to support this from the Chevron Frade FPSO off Brazil. The wells were initially designed for 30% water cut and almost no solids, but the wells actually produced 70% water cut with a high suspended-solids content.

Even simple bought-in chemicals are supplied with a specified range of properties, rather than a single value. There is, in short, no such thing as steady state. We need to construct a range of realistic design scenarios, and our designs need to work in all of them. It may be that our provision for less probable scenarios leads to a shorter service life or requires more operator attention than in the normal running case, but the plant has to be reasonably safe and operable under all foreseeable conditions.

That said, we often chase these scenarios unnecessarily. Designing for all the extreme cases as if they occur all the time adds cost. It is better to do a statistical analysis of the inputs to figure out what a reasonable operating envelope is for design, and whether shrinking the envelope is a good idea. I find it curious that many engineers happily do this with issues like ambient conditions (designing cooling systems for the 2.5% summer high temperature, not the 1% or 0.1%), but not for things like inlet condition ranges or feedstock composition ranges. Similarly, I find it worrying when I am told that a feedstock will meet exactly the composition/pressure/temperature when no one has control over it.

## Summary statistics

In real design scenarios there are often have too little data to generate statistically significant design limits. We get a feel for the data by generating summary statistics: means, maxima, minima, confidence intervals, and so on. You can, incidentally, download a plug-in for MS Excel which helpfully generates this set of "summary statistics."

The lack of a formally statistically valid data set doesn't usually mean you get out of designing the plant. Sensitivity analysis can be used to see how much it matters if your data are unrepresentative.

The all-too-likely lack of rigorously valid data as a design basis should be something the designer is conscious of throughout the design. Those who claim that arrogance in process design can usefully be measured in nanomorans may be surprised to see me use the word, but we need to demonstrate humility.

For example, the well samples discussed in the last section are limited in number and will not be fully representative for many reasons. Types of sampling methods, reservoir condition, insufficient well conditioning prior to sampling collection, inappropriate sample collection and storage methods, limitation of laboratory testing, contamination of sample by drilling mud, methanol, and so on may contribute to error. Different laboratories have been shown to produce a wide inconsistency in compositional analysis even for the same sample.

All these uncertainties may affect the surface facility design further downstream, such as pipelines and onshore terminals. Among the examples of impacts are incorrect sizing of separator, compressor, pumps; overprediction or underprediction of liquid holdup in pipelines, slug catcher capacity, fuel gas systems, and so on.

It is therefore crucial that the design parameters are not too tight and that a sufficient design margin is provided.

## Implications of new design tools

Computer-based tools allow us to do more brute force calculations, so we don't have to design a plant in such a way as to make analysis simple. We should not, however, take advantage of this capability—our professional responsibility is to understand our plant. We also need to be careful not to be carried away by the precise-looking outputs of these programs.

An associate recently reported to me:

> *... [I once] came across a program for PSV sizing that the contractors I was working with tried to use for an LNG Import Terminal. The software couldn't handle the cryogenic conditions in the equation of state thus the results were badly wrong. Even worse, the ... engineers couldn't tell me that they were wrong as they didn't understand how to size the PSVs correctly as per API RPs. They instinctively "blindly trusted" the software.*

We should not use modeling and simulation programs as a substitute for design—by the time we have taken the usually rather flimsy design data and run it through a black box program written by someone who has never designed a plant, outputs are at best merely informative, and can easily be highly misleading.

There is more specific comment on these issues elsewhere in the book, but, in summary, many of the techniques taught in university are not really design, and many of the tools used are not used by professionals, with good reason.

## Importance of understanding your design

Recent stock market crashes have been at least contributed to by automated stock market modeling software, in many cases written by physical science and engineering grads based on models derived from the physical sciences very similar to those in process simulation software.

Your calculations, whether done by hand, in a spreadsheet, or a simulation program, are a model of the proposed system. It is infinitely better to have a simpler model which you understand well than a more complex one which you don't really understand.

In Henry Petroski's books, many of his engineering disasters come about as a result of people who thought they understood well-established design methodologies cutting safety margins and applying techniques to areas where their underpinning assumptions did not hold.

My advice is not to take responsibility for anything you don't understand well enough. This can make you unpopular if there is a lot of time pressure to get calculations signed off, but engineering is hard, and the stakes are high. Literally life and death in many cases!

There's no shame in asking someone to show you why they think they have a design nailed down if you can't see how they have, and our professional responsibility means we have to imagine defending our actions in court later. Don't allow yourself to be pushed around by management. Their aims may be different from yours, which leads to a necessary tension in design.

## Manager/engineer tensions in design

There are several kinds of manager, but the most common are those who wish to minimize capital expenditure to allow them to get through capital approval (and then wonder why they have to spend so much later on "maintenance"). There are far fewer who wish to minimize operating cost, and never mind the capex. There are hardly any who wish to maximize flexibility and hence market responsiveness, except perhaps in research/science-led sectors like pharmaceuticals.

Managers and engineers have to some extent different pressures upon them and different aims to meet during the design process, and the inevitable tension arising

from this needs to be managed. An old engineering joke illustrates the differences in outlook between engineers and managers:

*A man in a hot air balloon realized he was lost. He reduced altitude and spotted a man below. He descended a bit more and shouted, "Excuse me, can you help me? I promised a friend I would meet him half an hour ago, but I don't know where I am."*

*The man below replied, "You are in a hot air balloon hovering approximately 30 feet about the ground. You are at approximately 53 degrees north latitude, and at 1 degree 13 minutes west longitude from the Greenwich meridian."*

*"You must be an engineer," said the balloonist.*

*"I am," replied the man, "but how did you know?"*

*"Well," answered the balloonist, "everything you told me is technically correct, but I have no idea what to make of your information, and the fact is I am still lost."*

*The man below responded, "You must be a manager."*

*"I am," replied the balloonist, "how did you know?"*

*"Well," said the man, "you don't know where you are or where you are going. You made a promise which you have no idea how to keep, and you expect me to solve your problem. The fact is you are exactly in the same position you were in before we met, but now, somehow, it's my fault."*

## Manager/engineer Tensions I: risk aversion

There is a tension between external design consultants and product managers in client organizations, but even when the designer and product manager are within the same organization, there may be a tension. Designers are usually risk averse, and management are often more risk tolerant.

In essence, management usually wants to get a product to market as soon as possible, and with the absolute minimum possible margins of safety, and highest possible profit margin. Designers don't want to design things which don't work, they have a good idea of the limits of their analytical techniques, and they know that all design relies on approximation and heuristics.

When nondesigners look at our calculations and drawings, it all looks very mathematical, very sharp-edged, but these are precise-looking calculations of approximate values, and those straight lines on the drawing might be different in 10,000 ways.

I hear that management are now asking engineers to justify adding any margins of safety at all to designs done substantially using modeling programs, but that engineers are subsequently being asked to carry out debottlenecking of plants which have been designed in this way.

So, there will always be a tension between engineers and management. The Scotty Principle addresses this tension with respect to timescales:

> *Scotty Principle (n.) The de facto gold star standard for delivering products and/or services within a projected timeframe. Derived from the original Star Trek series wherein Lt. Cmdr. Montgomery "Scotty" Scott consistently made the seemingly impossible happen just in time to save the crew of the Enterprise from disaster.*
>
> 1. *Calculate average required time for completion of given task.*
> 2. *Depending on importance of task, add 25%—50% additional time to original estimate.*
> 3. *Report and commit to inflated time estimate with superiors, clients, etc.*
> 4. *Under optimal conditions the task is completed closer to the original time estimate versus the inflated delivery time expected by those waiting.*
>
> ***Urban Dictionary***

However, margins of safety are not just about gaining a Scotty-style reputation as a miracle worker. When things are uncertain, designers should err on the side of caution, "underpromise and overdeliver." Occasionally you will lose out to those who are willing to gamble, but winning in that way makes them lucky, not good. Let's not trust to luck when so much is at stake. This is particularly important in offshore engineering, where delays in "sailaway" may lead to unavailability of heavy-lift vessels, missing an installation window (due to sea states and seasons) or work having to be completed offshore at great expense if the choice is taken to sailaway incomplete, all of which can create serious difficulties for the offshore project manager.

## Manager/engineer Tensions II: The Iron Triangle

One other point of potential conflict between designers and management is covered by a trilemma sometimes known as the Iron Triangle; "Fast, Good, or Cheap—pick any two."

It is common in my experience for managers and clients to want three out of three, but it just can't be done. Scotty knew about this too: "I cannae change the laws of physics, Jim"—neither can we change the iron laws of design.

## Manager/engineer Tensions III: "Technicism"

There are engineers, engineer/managers, and there are pure man-managers. Although (as James Trevelyan has pointed out) all engineers are, to some extent, informal managers, career man-managers see projects very differently from "subject matter experts," that is, engineers. This is the case whether or not managers have degrees in engineering or worked as engineers before they became managers.

*A group of man-managers were given an assignment to measure the height of a flagpole. So, they go out to the flagpole with ladders and tape measures, and they're falling off the ladders, dropping the tape measures—the whole thing is just a mess.*

*An engineer comes along and sees what they're trying to do, walks over, pulls the flagpole out of the ground, lays it flat, measures it from end to end, gives the measurement to one of the managers and walks away.*

*After the engineer has gone, one manager turns to another and laughs. "Isn't that just like an engineer, we're looking for the height and he gives us the length."*

## Other engineer/nonengineer tensions in design

Setting aside managers, there can also be tension between engineers and market development ("Make me the perfect sample now, so I can go and find out what the spec should be with market tests"); tension between engineers and QA "Well this is what I can measure with the time/equipment available, so you'll have to live with it"; tension between pilot plant operators and designers ("Taking that sample is a real pain, so we modified the approach"); and tension between engineers and R&D ("I know you want to freeze the design, but we're still trying to understand the impurity profile").

All such tensions are however mediated through management, so see above. A fellow engineer with a lot of modeling/pilot plant operations experience commented to me on researchers as follows:

*The researchers . . . are all about solving an elegant problem and doing cool science and while it doesn't quite work now, if they just have a little more time. . .. The business developers usually fall in love with the market potential and the margin that they think they can make based on the cost estimate that the original research team pulled together on very rough numbers and without a process design. They never want to hear about cost increases, dismissing them as "engineers' padding." Piloting engineers tend to be very "can-do" and will always be keen to demonstrate their prowess in "getting it done," but might take shortcuts (e.g., using more catalyst, neglecting heat integration targets, . . .) that make the apparently successful demonstration actually uneconomic. . .. the design engineers tend to be a more pessimistic bunch, being tied to the capital estimate, but too often their response is "well this is what it's going to cost, the business guys just need to recognize that."*

*Then there are the marketing guys:*

*I once made the mistake of including the marketing guy on a tour of the analytical lab—he later came back and dug through the past samples to find the "Goldilocks" one—just the right color and consistency. He took that out to a customer who loved it and promptly demanded more. Unfortunately, he'd removed the ugly label from the bottle so it was a pain to find what the sample was, and when we did it was from a completely infeasible operating point. The business development folks tend to be motivated by developing the market and excitement about the new stuff, and often feel that the engineering team are dragging their heels or putting up unnecessary barriers.*

*The lab analysts also have a view:*

*I've had plenty of discussions with analytical around QA specs. The lab chemist's argument is that it's difficult to identify, say, an unknown peak on an HPLC and even harder if that peak is actually two components coeluting with one of them identified. Perfectly true and reasonable, but if that peak (or worse one pair in a coeluting couplet is unknown) has a big impact on product quality, then it's important to differentiate it. I've forced the lab to switch out instruments and/or resins to be able to identify key impurities (always with grumbling about those idiots from Research wanting unnecessary detail). I say HPLC here, but pick your measurement, really—particle size, slurry viscosity (if that means anything for a non-Newtonian fluid), ion balance, ... A specific example? When you hydrolyze corn starch into glucose, you break the polymer down through the dimer maltose (that can be metabolized by many organisms), then form isomaltose (another dimer that's mostly nondigestible). Both show up as a "DP2" peak on a typical chromatogram, but if isomaltose ends up being a bad actor in a downstream reactor, then it's important to differentiate the two molecules (which you can do if you set up a second resin in your HPLC).*

## Whole-system design methodology

Our initial conceptual design process needs to do more than just select broad technologies—such a decision-making exercise on its own isn't really engineering design at all. A conceptual design needs to give us an approximate size and shape of unit operations and associated pipes, pumps, and so on.

They need to allow us to price at least all main plant items (a term used in approximate costing functionally close to identical with unit operations). We need to lay all the kit out on a general arrangement (GA) drawing to make sure it will fit on the site available. Ideally, we would have some idea of how long it will take to build, and what it will cost to run it.

The sizing of unit operations for this purpose will be based on easy rules of thumb. We only need to know roughly how big they are. We will need to do a rough mass and possibly energy balance to allow us to size the units, as recycles can make flows far larger than are obvious by simple inspection.

We cannot optimize this rough design, and we should not try to. Conceptual design should underpromise and overdeliver. We should make very conservative assumptions, and err consistently on the side of caution. Things always take longer than you think, cost more, and have problems which are not immediately apparent. Save a bit of fat for later—you'll need it.

Detailed designs will need to address a number of issues which were disclosed but not resolved by the conceptual design stage. Rather than looking to scientific literature or modeling programs for answers, professional process plant designers usually look to the know-how of experienced engineers and equipment suppliers/licensors.

They may need to carry out slightly more rigorous design than at the conceptual stage to do this, and they will certainly need to get their P&ID, mass and energy balances tightened up considerably to do so. Again, this tightening-up should be based upon commercially available kit.

At this stage (if not earlier), the designer will need to supply the other engineering disciplines involved with the information they require to carry out their design.

Civil engineering designers will need to be provided with equipment weights, locations, and so on. Electrical engineers will need motor sizes and preferred starter types. Software engineers will need a control philosophy and a P&ID. They will all usually be in a hurry to get this information, but they will complain if it changes too many times during the design process.

The other disciplines (and sometimes the client) will come back with suggestions for how the overall design might be changed in ways which make it better, cheaper, and easier to build (or whatever). The plant designer needs to evaluate, negotiate, and, fairly frequently, modify their process design to accommodate these changes.

Design for construction has to specify every detail, right down to the numbers and types of bolts used to connect pipe flanges. This stage is not merely the dull scheduling and documentation stage envisaged by theorists. Many design challenges remain—the devil is in the detail.

## Design stages in a nutshell

Table 8.1 summarizes the design stages, based on generalized consensus practice. However, additional disciplines and deliverables feature in certain sectors—see "Variations on a theme" section below.

## Variations on a Theme

I was going to include here a big diagram showing all the stages of an ideal design methodology, but that might give you the impression there was such a thing. The truth is that the contents of the preceding chapters represent a core common approach, but that there are great variations between sectors, between companies, and between countries in a number of key issues, even if we stick to the whole-plant "grassroots" design which this book is about.

Operating companies, contracting/engineering, procurement and construction (EPC) companies, and consultants of various kinds will all do a thing which they call design. The meaning of the term will vary, as will their understanding of terms like conceptual design, detailed design, and so on.

The job titles of the people involved in design, the tools they use, and the deliverables they produce will differ. There are many additional sector-specific deliverables

**Table 8.1** Summary of design stages

| Stage of design | Purpose | Features |
|---|---|---|
| Conceptual design | Purpose: To identify the design philosophy, the most promising technologies, rough cost, and footprint, then select the one or two most promising technologies | Construct design envelope |
| | See the conceptual design section of later chapters for details of safety, costing, layout, materials and equipment selection, process control, and hydraulics aspects | Produce process flow diagram (PFD), P&ID, GA, unit op design, mass and energy balance, rough costing, and preliminary safety study |
| FEED | To choose subtechnologies, design approaches produce good-quality costing and layout documentation to allow evaluation and quite possibly to place an order for construction for long lead time items such as compressors | Produce more detailed PFD, P&ID, GA, unit operation design, mass and energy balance, control philosophy, detailed costing, robust safety study, obtain quotations and specifications from suppliers for equipment, and have mechanical, civil, control, and electrical design progressed in tandem |
| | See the intermediate design section of later chapters for details of safety, costing; layout, materials and equipment selection, process control, hydraulics, and optimization aspects | |
| Detailed design | Design of plant to be built | To produce the PFD, P&ID, GA, unit operation design, mass and energy balance, control philosophy, detailed costing, robust safety study, datasheets, schedules, obtain exact specifications and prices for equipment to be purchased, finalize technical bid evaluation, and have mechanical, civil, control, and electrical design progressed in tandem |

I have not covered here, in the interests of simplicity. There are also sector-specific roles such as the petrochemical industry's control/instrument engineer.

The contents of the preceding chapters are true to the best of my knowledge for all sectors, as far as they go. There is, however, an infinite amount of detail which I have "omitted for clarity" as we engineers say.

## Further reading

British Standards Institute. (2002). *European standard for unfired pressure vessels*. BS EN 13445.
British Standards Institute. (2012). *Specification for unfired, fusion welded pressure vessels*. PD5500.
Koolen, J. L. A. (2001). *Design of simple and robust process plants*. Weinheim: Wiley-VCH.
Trevelyan, J. (2014). *The making of an expert engineer*. Boca Raton, FL: CRC Press.
Vincenti, W. G. (1993). *What engineers know and how they know it: Analytical studies from aeronautical history*. Baltimore, MD: Johns Hopkins University Press.

# CHAPTER 9

# How to do a mass and energy balance

## Introduction

Although nobody graduates in chemical engineering without having acquired some knowledge of mass (aka material) and energy balance, I am aware that this book has been used to teach basic process engineering to nonchemical engineers so I have included an outline description of what mass and energy balance is about.

The basic idea of a mass balance is that since mass is neither created nor destroyed in a process plant (unless you are designing a nuclear reactor), all of the masses going into and out of the plant add up over time, unless there is a store of mass within the plant whose contents are increasing or decreasing over the period of time being considered (which we call the basis).

It is also the case that all of the masses going into and out of any area of the plant you draw a boundary around on the PFD will follow the same rule. Finding out all of the masses of stuff moving around on the plant can then be worked out by a process rather like doing sudoku.

Similarly, energy in is equal to energy out across the plant or any boundary on the PFD defining a subsection of the plant.

It gets slightly more complex when there is a reaction going on as, whilst the overall mass of stuff and the number of each kind of atoms remains the same, the masses of various reactants and products change over the reactor. It gets more complex still when we recycle streams from the outlet of a process stage to its inlet, as we often do to improve product yields. There are also other causes of complexity in real-world mass and energy balance exercises, which may come as news even to chemical engineering graduates, so a reality check is in order.

## Reality check

Most universities teach chemical engineering students to carry out mass and energy balances in steady-state scenarios in order to simplify the process for beginners. In the real world there is, however, no such thing as steady state.

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00010-0
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Real plants are dynamic, with variable flows, compositions, temperatures, pressures, and so on. They have to produce product(s) to specification under all of these conditions, though it should be noted that "to specification" also implies a range of acceptable compositions rather than a single one.

Producing a model which accurately and dynamically models the operation of a plant which has not yet been constructed is practically impossible. We can, however, produce a number of steady-state models across the design envelope, which allow us to generate performance curves and sensitivity analyses which give us confidence that the design will work (where the meaning of "work" is not perfection, but that implied by the brief) across all reasonably foreseeable conditions.

We need to exercise engineering judgment in deciding which scenarios we need to consider. In designing a water treatment plant we might, for example, look as a minimum at high-flow and low-flow scenarios, permutated with high contaminant and low contaminant levels.

We would also consider scenarios in which key process equipment is out of service for backwashing or maintenance, variations in feed temperature, degradation in dosed chemical quality, and so on.

This is almost always done in practice using a spreadsheet program, and the required permutation of scenarios becomes quite easy to achieve (and just as importantly, verify) if we structure our spreadsheet in a certain way.

## Unsteady state

If you have an opportunity to view the "trends" screens on a supervisory control and data acquisition (SCADA) system, the dynamic nature of plant operation becomes very obvious (Fig. 9.1).

Everything varies with respect to time on a process plant at some scale of resolution. Feedstock quality varies, as does product quality. Plant throughput varies both because we call for a different flow rate from the system, and because equipment degrades over service intervals, so that the same control inputs may produce different responses over time.

Other parameters vary for similar or different reasons. When we take off our steady-state "training wheels," we need to understand the range of possible values which we can encounter in all parameters. A robust design works under all of these conditions.

It is often the case that the range of parameters we consider has an associated probability. If we have been provided with data which we are to use as a basis for design, the upper and lower limits of confidence intervals may well carry more weight than the maximum and minimum figures in the data.

**Figure 9.1** Unsteady-state SCADA screen. *Courtesy: Process Engineering Group, SLR Consulting Ltd.*

So, we are (consciously or not) designing a plant that will only probably work. Usually the required probability of success is implied by the performance tests we have to pass to have the plant accepted (though our design's probability of success should always be higher than that required by the test).

## Implications of feedstock and product specifications

Most of the things I have designed which have actually been built have been water and effluent treatment plants. The feedstock for such plants is a very variable flow of water with very variable levels of contamination. Drinking water plants ramp up and down production to match demand. Sewage and industrial effluent treatment plants have to reliably treat the often highly variable flows and compositions they are given.

Drinking water has to meet very tight absolute maximum allowable value specifications for more than a hundred parameters. Effluent treatment product specifications are less complex, and may be probabilistic—95% compliance with specification might be fine.

What is true in water is true in all sectors: a plant needs to handle the worst feedstock it might encounter as well as the specification says it has to, producing the product to the specification required as reliably as is required.

There is no benefit in exceeding required performance, and it costs money to do so, but the plant has to meet required performance as specified, or for practical reasons a little better.

## Stages of plant life

When setting out our design scenarios, we need to consider all stages of the plant's life. This is especially important if we have attempted to design in integration of systems.

If there is a stage of the plant's life, such as commissioning, start-up, shutdown, or maintenance, when we will need to run the plant in a different way, or need additional services, the full implications of this need to be considered in our mass and energy balance.

The petrochemical industry mounts campaigns called turnarounds where staff carry out more or less all the maintenance for a plant in a short sharp program. Is this how your plant will be maintained, or will it be little and often? The designer needs to know, and to take this into consideration from the stage of initial mass balance generation.

## Handling recycles

Frequently, there are process streams on a plant which are returned directly or indirectly to the feed of the unit operation which they came from, and these are known generically as recycles.

As their introduction modifies the stream going into the unit operation, and the product of an operation is almost always affected by its feed stream, recycles affect themselves and, having been affected, affect themselves further, and so on. This may not be obvious during "steady-state" operation, but it will be obvious to the designer.

Back when I was a student, we used to have to resolve this issue using iterative calculations done by hand. This was very dull indeed, the time-consuming nature of the approach meaning that nested recycles (recycles within recycles) were avoided.

Nowadays we have MS Excel, which offers us a number of ways to carry out iterative calculations in seconds, and without the mistakes borne out of loss of attention which used to appear in hand calculations.

## How to set out a mass and energy balance in MS Excel

Here is how I set it out, which is similar to the way most other professionals do. You don't have to do it the way I do, but you do need to address all the problems at least as robustly as my method does. Much of what professional engineers do habitually is intended to systematically avoid error, and make it easy to spot any residual errors.

Mass and energy balances like these are pretty complicated process models, which are very hard to hold in your head as a completely unified whole. Even the best examples will need rigorous double-checking by a second competent engineer, and you should assume that there will be mistakes before such checking.

I like to make my spreadsheet look like the engineer's calculation pads we used back when we did hand calculations, and I teach my students to do this as well. Otherwise, they tend to hand in spreadsheets which are hard to follow, with bits of calculation over in some obscure corner of the spreadsheet which no one notices.

Forcing the calculations into a succession of virtual sequential A4 sheets makes it easy to set out an annotated logical argument, and to follow the argument being made. So, I recommend a vertical stack of these virtual pages be set out on each Excel tab (Fig. 9.2).

I start with a header tab which sets out the given and assumed design parameters and gives an overview of the whole spreadsheet. All uses of these design parameters throughout the spreadsheet should be linked directly back to this header page. This makes it easy to vary the parameters to generate different scenarios.

If the cells containing the parameters have been labeled with descriptive names (see Fig. 4.1), the designer and the checker will not need to keep flicking back to the header to see what parameter a cell address refers to when it is encountered on other sheets. I would in fact recommend that all cells whose values are copied across into calculations are so labeled to reduce errors and facilitate checking.

Each subsequent tab has a stack of pages which represent the design of a unit operation. I like to follow the order of the process flow on the piping and instrumentation

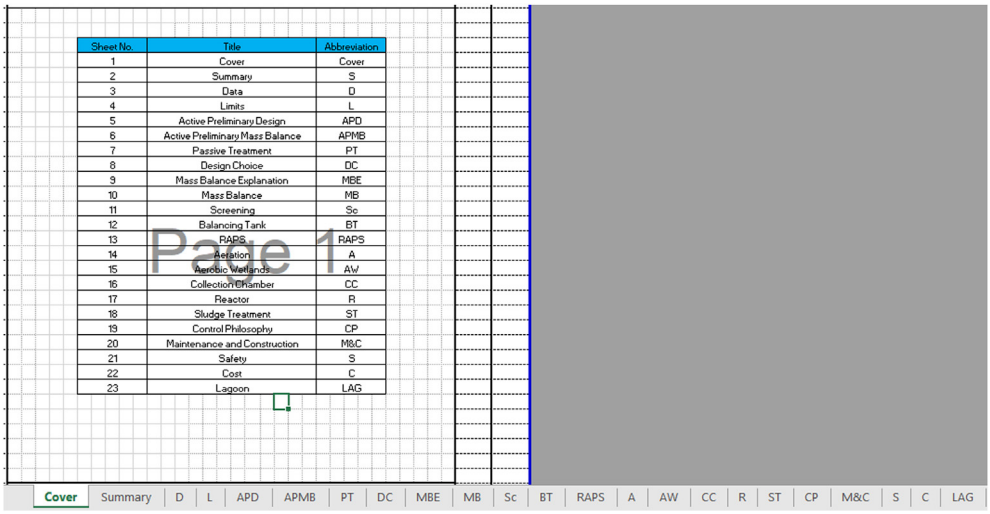


**Figure 9.2** Stacked mass and energy balance calculations in MS Excel.

diagram (P&ID) in my virtual stack of Excel tabs. The mass and energy flows (with the exception of those requiring the breaking of a recycle to avoid circular calculation errors—see later) out of each unit operation should be directly linked to the inputs to the downstream operation.

This makes the spreadsheet capable of self-modifying to handle the various scenarios which it will be used to balance, removing the possibility that the designer will forget to change cells.

Each of these tabs will have what I call "checksums," calculations arranged so that they will be zero if the unit operation's mass balance is correct. These checksums will be carried across to the header tab, where they will appear as a single table, along with checksums for mass and energy balance checks at scales above the single unit operation.

Behind these mass and energy balance/unit operation sizing tabs I usually have a few sheets of hydraulic calculations, so that I can include dynamic pump calculations based on the flows from the mass and energy balance in the spreadsheet for convenience. I have standard single-tab Excel spreadsheets (verified by an independent third party and then locked) which I insert for this purpose.

I also have such standard spreadsheet tabs for the more common unit operations which I design, saving time and reducing errors. Going to the trouble of producing such standard spreadsheets and having them validated is, however, only worthwhile if you are going to use them many times.

## Using MS Excel for iterative calculations: "Goal Seek" and "Solver"

Microsoft Excel has a suite of commands known as "what-if analysis" tools (under the "Data" tab). Process plant designers find two of these particularly helpful: Goal Seek and Solver.

Goal Seek allows us to vary the number in a spreadsheet cell until the value of a cell whose contents are calculated from the first cell's value is a number we specify. Solver is more sophisticated, and allows us to minimize or maximize a value in a target cell.

I use Goal Seek for the following purposes:

- Resolving recycles in mass and energy balances—use Goal Seek to make the difference between two mass balance formulae equal zero, and you have resolved the recycle;
- Dealing with iterative calculations, especially those with too many unknowns—I use this a lot for hydraulic calculations based on the Darcy–Weisbach equation and Colebrook–White approximation, as described in Chapter 10, How to do hydraulic calculations.

Solver, on the other hand, is well suited for optimization exercises such as sensitivity analysis and reactor design problems.

It may be useful to break the chain of calculations in nested recycle calculations with a cell whose value can be set manually, prior to the "what-if" command being run. This avoids "circular argument" error messages, but great care should be taken that all results yielded by such an exercise are sensible, as there is a greater probability of nonsensical results from this technique.

# CHAPTER 10

# How to do hydraulic calculations

## Introduction

> *I am an old man now, and when I die and go to Heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics and the other is the turbulent motion of fluids. And about the former I am rather more optimistic.*
>
> ***Sir Horace Lamb***

At university, all chemical engineers study fluid mechanics, which is a kind of applied mathematics, usually combined with a bit of applied dishonesty.

The truth is that no one really understands the turbulent motion of fluids, or can predict it with a high degree of precision. Consequently, even the most basic fluid mechanics courses have to handle a transition from first principles mathematics to the rough heuristic of the Moody diagram.

This is the point where an honest lecturer should admit we can't actually use Bernoulli's equation to solve any useful problems, and we are consequently bringing in a chart based on empirical relationships determined by experiment to fill the gaps in our understanding with a fiddle factor.

Not all lecturers are so honest or insightful and students may leave university thinking that they understand something which no one does—until someone asks them to size a pump.

Hydraulics is the more practical cousin of fluid mechanics, which we mainly use to specify pump and equipment sizes as accurately as required for practical purposes. Engineers don't have to completely understand things in order to exercise sufficient control to achieve a given aim.

## Matching design rigor with stage of design

Right at the start of a design project, we need to know, for example, whether we intend to move fluids around our plant by gravity, or by pumping. Even to do the most basic layout we need to know approximate pipe diameters.

The nature of hydraulic calculations is essentially iterative. We need to know a pipe diameter and pipe length to work out the headloss down a pipe. We need to know the headloss to know the economic pipe diameter. We need to know static and dynamic head to know how big our pump needs to be. We need to know how physically large our pump is to know how long the pipe needs to be.

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00011-2
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We have to start this circular process somewhere. The method used by most process engineers is described in the following sections. Levels 1/2 are used at the conceptual design stage, and levels 2/3 at detailed design. Level 4 is used only in rare cases of complexity.

Hydraulic calculations have three main components: static head (the elevation from reservoir to point of discharge, plus any atmospheric pressure difference between reservoir and point of discharge), straight run headloss (headloss due to friction at operating flowrate due to straight pipe sections), and fittings headloss (headloss due to friction at operating flowrate due to bends, tees, valves, etc.).

In water process engineering, we make a fair amount of use of open channels, and I consequently have to do quite a lot of open channel hydraulics. However, I am going to leave that out of this book, as it can be quite complicated and there isn't very much of it in most other process sectors.

I am also going to leave out calculations for multiphase flow and water hammer (conditions I like to design out), though I offer later in this chapter rough calculations you can use to screen for the potential for water hammer problems. I suggest you look at Donald Woods' book (see Further Reading) for guidance on shortcut methods for these though, in practice, you might want to call in a specialist if your rough calculations make you think these conditions likely.

## Level 1—superficial velocity

Superficial velocity is the same thing as average velocity (i.e., the volumetric flowrate in $m^3/s$ divided by the pipe's internal cross-sectional area in $m^2$—its units are, in this example, m/s).

A very quick way of starting our hydraulic calculations is to use the following rules of thumb from acceptable superficial velocities:

- Pumped water-like fluids $<1.5$ m/s;
- Gravity-fed water-like fluids $<1$ m/s;
- Water-like fluids with settleable solids $>1$, $<1.5$ m/s; and
- Air-like gases 20 m/s.

By "water-like" fluids, I mean those which have a density and viscosity between half and twice that of water, which includes many organics. I know, by the way, that Sinnott considers pumped liquids to be less than 3 m/s and gases to be less than 30 m/s; and also that with clean, dry, regasified LNG, velocities of up to 45 m/s are routine. However, I think it's always better to start out conservative, as head loss increases with the square of velocity.

Two-phase flow is hard to predict, and should be designed out if at all possible—headlosses can be 1000 times that for single-phase flow, and consequently it creates problems with pumps, valves, and instrument functions.

These rules will usually give sensible headlosses for the sort of pipe lengths normally found on process plants.

## Level 2—nomograms, etc.

The most difficult part of a headloss calculation is determining the straight run headloss. It isn't really that difficult, but we have to do it many times, so a quick method is handy at earlier stages of the design.

### *Liquids*

Pipe manufacturers and others produce tables and nomograms which can be used to quickly look up headloss due to friction for liquids (Fig. 10.1).

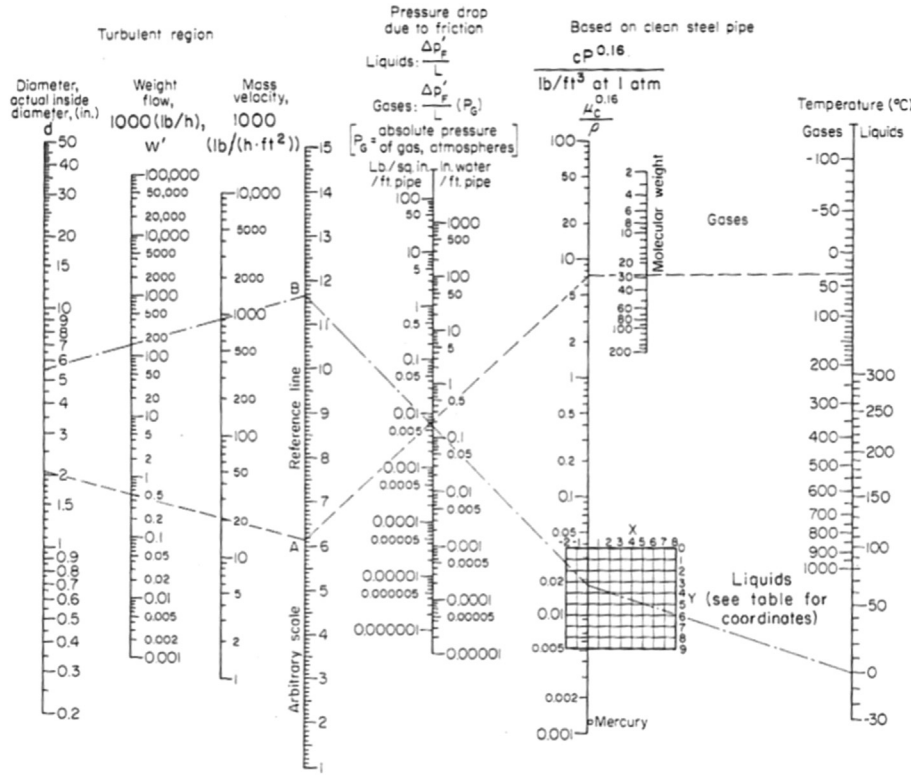


**Figure 10.1** Pipe flow chart nomogram.
**Legend:** *Courtesy: Sandler, H. J., & Luckiewicz, E. T. (1987).* Practical process engineering: A working approach to process design, New York, NY: McGraw-Hill.

| | x | y | | x | y |
|---|---|---|---|---|---|
| Acetaldehyde | −0.3 | 3.7 | Glycerol, 100% | 6.9 | 1.8 |
| Acetic acid, 100% | 1.0 | 4.0 | Glycerol, 50% | 3.0 | 3.7 |
| Acetic acid, 77% | 2.6 | 3.8 | Hydrochloric acid, 31.5% | 1.1 | 4.2 |
| Acetic anhydride | 0.7 | 4.3 | Linseed oil, raw | 3.4 | 1.8 |
| Acetone, 100% | 0.9 | 3.4 | Mercury | See chart | |
| Acetone, 35% | 2.7 | 3.7 | Methanol, 100% | 0.8 | 3.3 |
| Ammonia, anhydrous | 0.9 | 3.6 | Methanol, 40% | 2.8 | 3.6 |
| Ammonia, 26% | 1.9 | 3.6 | Methyl acetate | 0.0 | 4.2 |
| Aniline | 2.5 | 3.4 | Methyl chloride | −0.8 | 4.3 |
| Benzene | 0.6 | 3.6 | Nitric acid, 95% | 0.8 | 5.8 |
| Butanol | 2.6 | 2.6 | Nitric acid, 60% | 1.5 | 4.8 |
| Calcium chloride brine, 25% | 2.6 | 4.2 | Nitrobenzene | 1.7 | 4.4 |
| Carbon disulfide | 0.0 | 5.6 | Octane | 0.4 | 2.7 |
| Carbon tetrachloride | 0.7 | 6.0 | Phenol | 2.4 | 3.4 |
| Chloroform | 0.0 | 6.0 | Propionic acid | 0.6 | 3.8 |
| Chlorosulfonic acid | 1.5 | 5.8 | Sodium chloride brine, 25% | 2.1 | 4.4 |
| Cyclohexanol | 5.3 | 2.2 | Sodium hydroxide, 50% | 5.3 | 3.7 |
| Diphenyl | 0.0 | 3.5 | Sulfur dioxide | −0.2 | 6.1 |
| Ethyl acetate | 0.2 | 3.9 | Sulfuric acid, 110% | 3.7 | 4.7 |
| Ethyl alcohol, 95% | 1.9 | 3.0 | Sulfuric acid, 98% | 3.5 | 4.8 |
| Ethyl alcohol, 45% | 3.6 | 3.4 | Sulfuric acid, 78% | 3.2 | 4.8 |
| Ethyl chloride | 0.2 | 4.3 | Tetrachloroethylene | 0.3 | 6.2 |
| Ethyl ether | −0.3 | 3.2 | Toluene | 0.4 | 3.6 |
| Ethylene glycol | 3.5 | 2.9 | Trichlorethylene | 0.1 | 5.9 |
| Fluorocarbon, F-11 | 0.0 | 6.2 | Turpentine | 1.1 | 3.1 |
| Fluorocarbon, F-12 | −1.2 | 5.9 | Vinyl acetate | 0.4 | 4.2 |
| Fluorocarbon, F-21 | −0.4 | 5.9 | Water | 2.0 | 4.2 |
| Fluorocarbon, F-22 | −1.7 | 5.5 | | | |
| Fluorocarbon, F-113 | 0.9 | 6.2 | | | |
| Formic acid | 1.5 | 4.5 | | | |

We can then calculate fittings headloss by the $k$ value or equivalent diameter method (obtaining a count of valves, etc. from the piping and instrumentation diagram (P&ID), and bends, tees, and so on from the general arrangement (GA) drawing), and work out the static head from heights measurable from our GA, plus vessel pressures read from our process flow diagram (PFD). This is one of the reasons why even quite early-stage designs need to produce all three of these drawings.

It may be seen that once we have carried out the hydraulic calculations, our pump and possibly pipe sizes will need to change, as might minimum and maximum operating pressures at certain points in the system. There might even be a requirement to change from one pump type to another, or to change from a fan to a blower or from a blower to a compressor.

Therefore there is a stage of design development which takes a set of preliminary drawings and modifies them to match likely hydraulic conditions across the design envelope. This stage requires us to do lots of approximate hydraulic calculations before the design has settled into a plausible form.

We consequently do the quickest and the least rigorous calculations which meet the needs of this stage of design development as described in this section.

### Net positive suction head

Even at an early stage, I also recommend obtaining a prospective pump's required net positive suction head (NPSHr) from the pump manufacturer and calculating the net positive suction head available (NPSHa), as these can affect much more than pump specification. The NPSHa of the system should always exceed the NPSHr of the pump by 15% to avoid cavitation in the pump.

I recommend creating a MS Excel spreadsheet that uses the Antoine equation (Eq. 10.1) to estimate the vapor pressure of the liquid at the pump inlet and then calculates the NPSHa at that vapor pressure.

$$\log(Pv) = A - \frac{B}{C + T}$$

where

$Pv$ = vapor pressure of the liquid at the pump inlet (mmHg)

$T$ = temperature (K)

$A$, $B$, $C$ are coefficients (obtainable from the NIST database among other places, see Further Reading).

**Equation 10.1** Antoine equation.

An example for water at 30°C is shown in Table 10.1.

The available net positive suction head (NPSH) is given in Eq. (10.2).

$$NPSHa = hSp + hSv + hSs - hSf - Pv/\rho g$$

**Equation 10.2** Available NPSH.

**Table 10.1** Example Antoine equation calculation in MS Excel

| Material | Density (kg/m$^3$) | ANT A | ANT B | ANT C | Temperature (°C) | VP (mmHg) | VP (Pa) |
|---|---|---|---|---|---|---|---|
| Water | 1000 | 18.3036 | 3816.44 | −46.13 | 40 | 54.7542132 | 7298.736615 |

Pump manufacturers will provide curves which allow the NPSHr of any pump to be determined, of which more later.

Note that NPSH is calculated differently for centrifugal and positive-displacement pumps, and that it varies with pump speed for positive-displacement pumps rather than with pressure as for centrifugal pumps. The equations above should only be used with centrifugal pumps.

### *Gases*

If we are working with an air-like gas, we can use the charts of friction losses in ducts for air which are readily available to estimate straight run headloss (Fig. 10.2).

If headloss due to friction is less than 40% of upstream pressure (as it usually is), we can ignore compressibility effects for gases at level 2, and use the same method as suggested for liquids above.

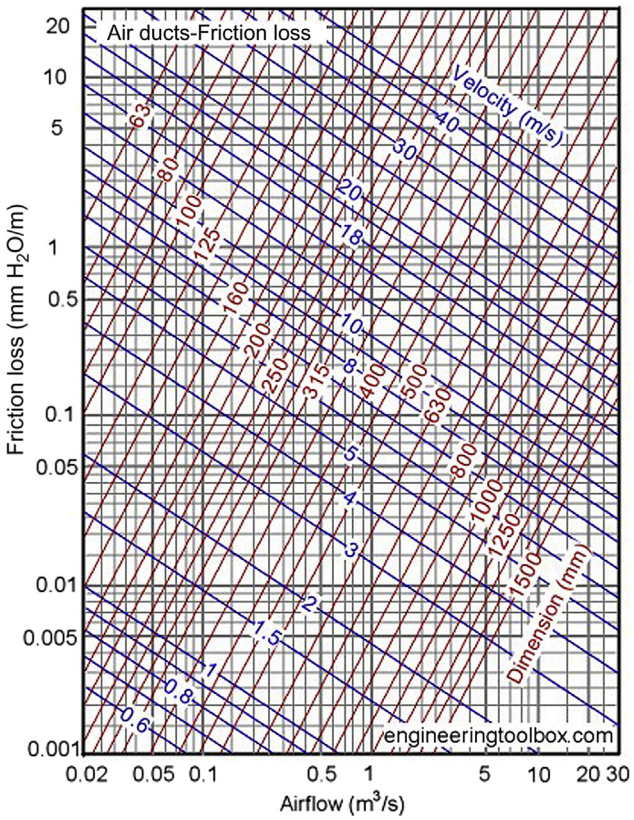


**Figure 10.2** Gases: duct chart. *Courtesy of www.engineeringtoolbox.com*.

## Level 3 (now superseded)—Moody diagram

Students are mostly taught to calculate straight run headloss using a Moody diagram, which is a summary of empirical experiments (and essentially an admission of defeat on the part of the mathematicians and scientists responsible for fluid mechanics—they couldn't make their sums work without these fiddle factors taken from experimental data).

The Moody diagram is one of the things superseded by MS Excel. As Excel can't read charts, we use curve-fitting equations which approximate the Moody diagram's output.

While this is an approximation, it might well be closer to the true experimental value than is read by the average person from an A4 copy of a Moody chart. In any case, it's a fiddle factor.

## Level 3 (updated): spreadsheet method

### *Liquids*

I personally use the Colebrook–White approximation to give me the fiddle factor which I would once have read from the Moody diagram, and I plug this into the Darcy–Weisbach equation to work out straight run headloss, with an iterative method based on Excel's Goal Seek function which I cover in Chapter 9, How to do a mass and energy balance. (If you use another equation, make sure you use the correct friction factor for the equation you use—the Darcy–Weisbach is 4 × Fanning.)

I have seen a paper (see Further Reading) which suggests there are new and more accurate curve-fitting equations, and I might have got around to modifying my standard hydraulic calculation spreadsheet if I hadn't gone to all the trouble of having it validated. So if you are producing your own spreadsheet for this purpose, I suggest you look into the Zigrang and Sylvester or Haaland's equations, which this paper recommends, to generate your fiddle factor.

Whichever equation you use, this Excel-based approach allows you to calculate straight run headloss to the degree of accuracy required for more or less any practical application.

Static head and fittings headloss can then be calculated as in level 2, and it can all be added up to generate a delivery side headloss.

Suction side headloss and NPSH should also be calculated, and all of this used to generate an approximate pump power rating for a centrifugal pump using Eq. (10.3)

$$P = Q\rho gh/(3.6\times10^6)\eta$$

where

$P$ = power (kW)
$Q$ = flowrate ($m^3/h$)
$\rho$ = density of fluid ($kg/m^3$)
$g$ = acceleration due to gravity (9.81 $m/s^2$)
$h$ = total pump head (m of fluid)
$\eta$ = pump efficiency (allow 0.7 if you don't have a figure).

**Equation 10.3** Centrifugal pump power rating.

The manufacturer will give you the precise power ratings and motor size, but the electrical engineers will need an approximate value of this (and pump location) quite early on in the design process, to allow them to size their power cables. You should err on the side of caution in this rating calculation, as the electrical engineers will be a lot happier with you if you come back later to ask for a lower power rating than if you ask for a higher one.

### *Gases*

Compressibility can make this all get a bit complex, but we can simplify matters. Crane, the valve manufacturers, proposed a simplified method in a technical paper first published in 1942 (see Further Reading).

If headloss is greater than 40% of upstream pressure (as it usually is), gas compressibility can be ignored, and we can use the Darcy–Weisbach equation/*k*-value method to determine headloss. The gas density used should be consistently either that upstream or downstream for headloss less than 10% of upstream pressure.

For headloss of 10%–40% of upstream pressure, use the density at the average of upstream and downstream conditions. If it is greater than 40% of upstream headloss, we will need to consider compressibility and use the Weymouth, Panhandle A, and Panhandle B equations. It should be clear that this will require an iterative design process.

## Level 4—Computational fluid dynamics

I have never had to carry out a computational fluid dynamics (CFD) study, though I know other professional engineers who have, so it isn't ridiculously theoretical and impractical.

It is, however, rare enough that it is more likely that you will go out to a specialist subcontractor to do it for you rather than buy the software and learn to use and validate it for a one-off exercise.

## Hydraulic networks

The previous sections are about how to calculate the headloss through a single line, but what about the common situation where we have branched lines, manifolds, and so on?

Each branch is going to take a flow proportional to its headloss, and its headloss will be proportional to its flow. Producing an accurate model can become complex very quickly. Things which are at all hard to model/understand are generally not of a robust design unless this represents the only workable approach.

My approach to this is to reduce complexity and improve design as follows:

- Avoid arrangements of manifolds which give a straight-through path from feed line to branch. Entry perpendicular to branch direction is preferred.
- Oversize manifolds such that superficial velocity never exceeds 1 m/s at the highest anticipated flowrate.
- Step the manifold diameter along its length to accommodate lesser flows to further branches.
- Include a small hydraulic restriction such that branch headloss is 10–100 times that from one end of the manifold to another.
- Design in passive flow equalization throughout the piping system wherever possible by making branches hydraulically equivalent.

I then do headloss calculations for each section of the plant at expected flows to find the highest headloss flow path through my simplified design.

I use this path to work out the required pump duty. I will test it at both average flow with working flow equalization, and at full flow through a single branch. Usually these don't differ all that much, and as I know that the more rigorous answer lies between them, I don't worry about it. Only if the results of this approach seem problematic will I do a more rigorous analysis.

To do a more rigorous analysis, I create an Excel spreadsheet based on the Hardy Cross method to solve for individual pipe flows. Excel's "Solver" function can be used to find the change in flow which gives zero loop headloss.

There are many computer programs available to do these calculations, but I would personally always rather produce a simple model in MS Excel—which I completely understand—than use black box programs.

## Screening for water hammer

Water is both heavy and incompressible, and water engineering infrastructure can be very large. Water flowing through a pipe has a large momentum so, if a valve suddenly closes in front of it, that energy has to be dissipated somewhere—usually in the form of removing the valve from its previous physical location. Water engineering can therefore potentially involve large forces produced by the rapid acceleration and deceleration of thousands of tons of water. Transient pressures of hundreds of bar are readily produced by inexpert hydraulic design of water pipework. A rigorous analysis of transient pressure spikes in pipelines can be incredibly challenging and time-consuming. There is, however, a shortcut method.

Much of the effort of a rigorous analysis goes into finding an exact answer to the maximum size and duration of pressure spikes, but we do not actually need to know this. What we need to know as engineers is if there are likely to be conditions under

which it is likely that our design will subject pipes to pressure greater than their rating, even transiently.

So we can carry out two calculations, representing the boundaries within which the rigorous answer will lie.

First we need to calculate P0, the steady-state total pressure (dynamic and static head) for the pipeline by the usual method, expressing our answer in psi.

Then we calculate transient pressure assuming incompressible conditions according to Eq. (10.4).

$$P1 = 0.07 \times V \times {}^{L}/_{t} + P0$$

where

$V$ = fluid velocity in ft/s

$L$ = pipe length in ft

$t$ = valve closing time in s

**Equation 10.4** Transient pressure equation in incompressible conditions.

Then we calculate transient pressure assuming compressible conditions, *P*2. This is a two-step process as set out in Eq. (10.5).

1. Calculate wave speed (celerity)

$$\text{Celerity} = \sqrt{((1/(1/Ef + D(W*Ep)/\rho))}$$

where

Ef = modulus of elasticity of fluid

D = pipe diameter

w = pipe wall thickness

Ep = modulus of elasticity of pipe

ρ = density kg/m $^{3}$

2. Apply the result as follows:

$$P2 = Celerity \times \rho \times ({}^{\Delta v}/10000)$$

where

$\Delta v$ = steady state velocity

**Equation 10.5** Transient pressure equation in compressible conditions.

If $P1$ and $P2$ are both lower than the pipe pressure rating, no surge protection measures are required. If such measures are required, the system can be reanalyzed by this means to check if they are likely to be sufficient, though it might be best to carry out a more rigorous analysis at the design for construction stage.

## Pump curves

A notable omission from university courses is the development of an understanding of how to read a pump curve, which is an essential requirement to do what we are probably going to do with the head/flow pairs we calculated across the design envelope.

The most frequent use of pump curves is for the selection of centrifugal pumps, as the flow rate of these varies so dramatically with system pressure. Pump curves are used far less frequently for positive-displacement pumps.

A basic pump curve plots the relationship between head and flow for a pump at a given supply frequency. On more sophisticated curves, there may be nested curves representing the flow/head relationship at different supply frequencies or rotational speeds, with different impellers or different fluid densities. The pattern is that curves for larger impellers or faster rotation lie above smaller impellers or slower rotation, and lower specific gravity lie above high for centrifugal pumps.

Let's start with a basic curve (Fig. 10.3).

Along the horizontal axis we have increasing flow ($Q$), and along the vertical axis, increasing pressure ($H$). The curve shows the measured relationship between these variables, so it is sometimes called a $Q/H$ curve. The intersection of the curve with

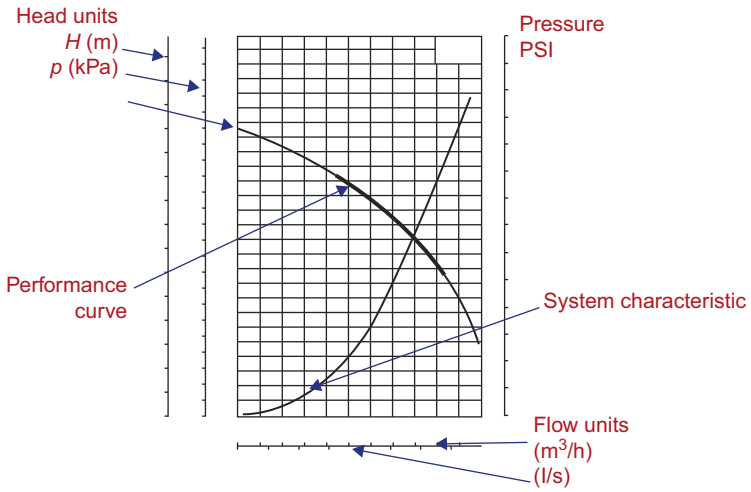


**Figure 10.3** Basic pump curve. *Courtesy: Grundfos.*

the vertical axis represents the *closed valve head* of the pump. These pumps are generated under shop conditions and ideally represent average values for a representative sample of pumps.

We can use our calculated flow/head pairs to plot a system head on the same axes, and see where our system head meets the $Q/H$ curve. This will represent the operating or *duty point* of the pump.

We will have a system head curve for the expected range of flows at a given system configuration. Throttling the system will give a different system curve. We will need to produce a set of curves which represent expected operating conditions, generating a set of duty points.

That's it as far as our basic curve is concerned, but it is common to have efficiency and motor rating curves plotted on the same graph (but not the same vertical axes) as in the example in Fig. 10.4.

Thus, we can draw a line vertically from the duty point to the efficiency curve, and obtain the pump efficiency at the duty point by reading the vertical axis at the point of intersection. Similarly, we can draw a vertical line to the motor duty curve, and obtain a motor power requirement.

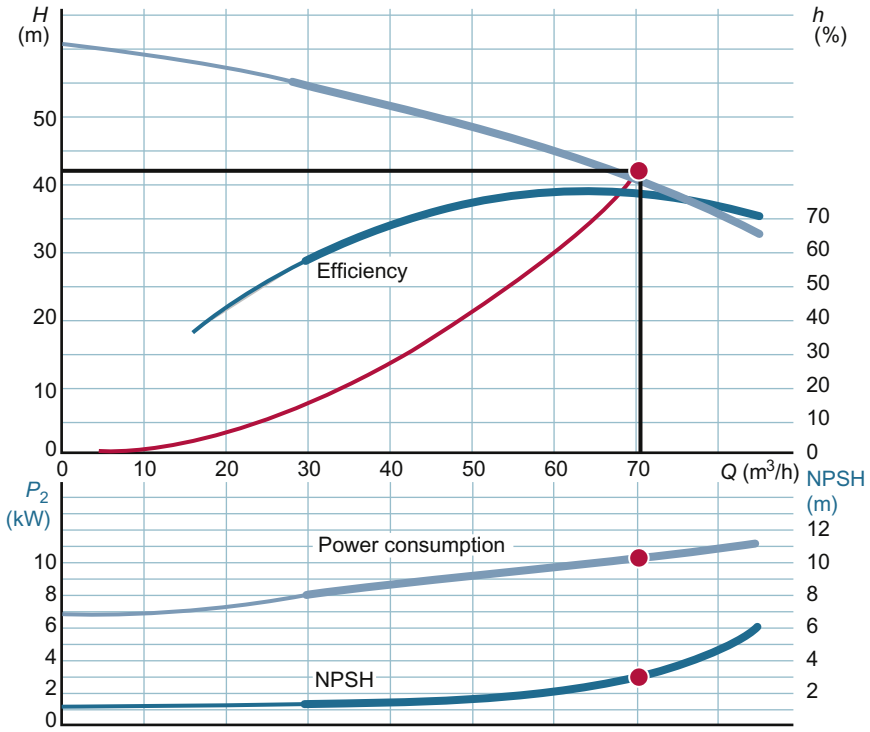


**Figure 10.4** Intermediate pump curve. *Courtesy: Grundfos.*

Having tackled these basic and intermediate curves, we can look at the common format of professional curves, incorporating efficiency, NPSH, and impeller diameters like this (Fig. 10.5).

These start to look a bit confusing, but the thing to bear in mind is that, just as with the simpler examples, the common axis is always the horizontal one of flowrate. So the corresponding value on any curve is vertically above or below the duty point.

These more advanced curves usually come with efficiency curves, and it is usually visually obvious that these curves seem to bound a region of highest efficiency. At the center of this region is the *best efficiency point* or BEP.

We will want to choose a pump which offers good efficiency across the range of expected operating conditions. Note that we are not necessarily concerned with the

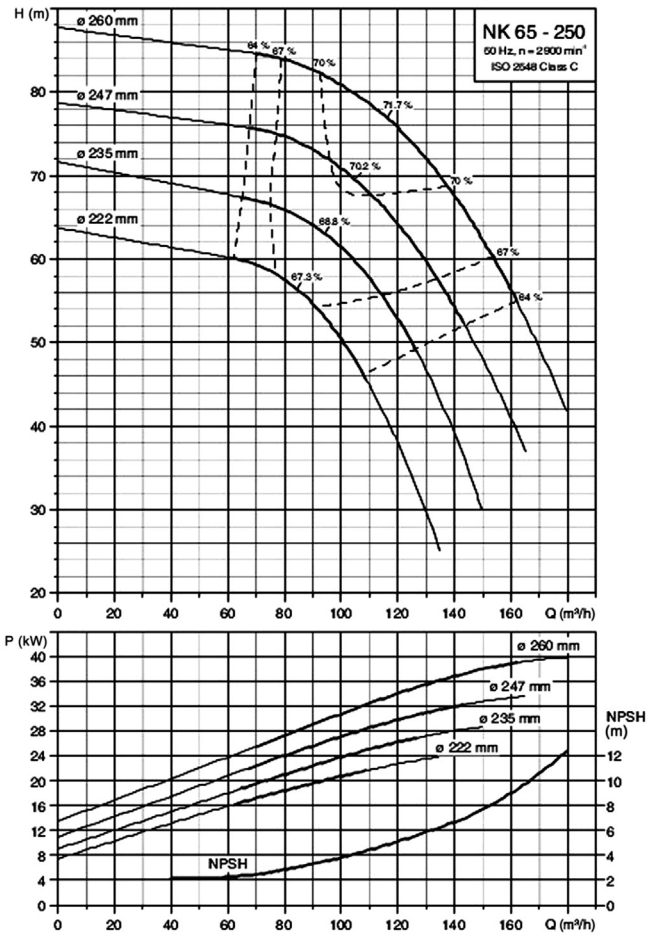


**Figure 10.5** Complex pump curve. *Courtesy: Grundfos.*

whole design envelope here—it is not crucial to have high efficiency across all conceivable conditions, just the normal range.

A well-selected pump will have a BEP close to the duty point. If the duty point is way over to the right of a pump curve, well away from the BEP, this is not the right pump for the job. Try another.

These are the basics of centrifugal pump selection. If you are in a position to influence which pump is purchased, any pump supplier's representative would be happy to talk to you about pump selection for as long as you are willing to listen. Probably buy you lunch too, though obviously that wouldn't affect your choices.

Even with the most cooperative pump supplier, the curves you want in order to make a pump selection may not be available, as is commonly the case when we want to use an inverter to control pump output by speed. We can, in this case, generate the required curves for ourselves using pump affinity relationships. The laws are:

- $\text{Flowrate}_2/\text{Flowrate}_1 = \text{Impeller diameter}_2/\text{Impeller diameter}_1 = \text{Pump Speed}_2/\text{Pump Speed}_1$
- $\text{Dynamic Head}_2/\text{Dynamic Head}_1 = (\text{Impeller diameter}_2/\text{Impeller diameter}_1)^2 = (\text{Pump Speed}_2/\text{Pump Speed}_1)^2$
- $\text{Power Rating}_2/\text{Power Rating}_1 = (\text{Impeller diameter}_2/\text{Impeller diameter}_1)^3 = (\text{Pump Speed}_2/\text{Pump Speed}_1)^3$
- $\text{NPSH}_2/\text{NPSH}_1 = (\text{Impeller diameter}_2/\text{Impeller diameter}_1)x = (\text{Pump Speed}_2/\text{Pump Speed}_1)y$

where $_1$ designates an initial condition on a known pump curve, and $_2$ is some new condition.

The NPSH relationship is a lot more approximate than the others. $x$ lies in the range $-2.5$ to $+1.5$, and $y$ in $+1.5$ to $+2.5$. A worst-case estimate can be established using the maximum quoted $x$ and $y$ figures if the impeller speed or diameter is to be increased, and the lowest figures if it is to be decreased.

## Further reading

Crane Co. (2018). *Flow of fluids through valves, fittings, and pipes*. Crane Technical Paper 410, US.

Cross, H. (1936). Analysis of flow in networks of conduits or conductors. *Engineering Experiment Station*, Bulletin No. 286.

Generaux, R. P. (1937). Fluid-flow design methods. *Industrial & Engineering Chemistry*, *29*, 385.

Genić, S., Arandjelović, I., Kolendić, P., Jarić, M. S., Budimir, N. J., & Genić, V. (2011). A review of explicit approximations of Colebrook's equation. *FME Transactions*, *39*, 67–71.

Woods, D. R. (2007). *Rules of thumb in engineering practice*. Weinheim: Wiley-VCH.

PART III

# Low Level Design

# CHAPTER 11

# How to design and select plant components and materials

## Introduction

> *Engineering is the art of modeling materials we do not wholly understand, into shapes we cannot precisely analyze so as to withstand forces we cannot properly assess, in such a way that the public has no reason to suspect the extent of our ignorance.*
>
> ***A.R. Dykes.***

The selection of the basic subcomponents of process plants is an essential part of what plant designers do. There is often a fundamental misunderstanding in academia of what constitutes the elements of a process plant. Process plants are not made of ideas, or (at an engineer's usual resolution of vision) even of chemicals. Process plants are made of commercially available products. We are not usually employed to select process chemistry, but to specify the pumps and valves, pipes, and tanks used to construct the plant in which those chemistries occur.

As a result of the composition of university departments, taught chemical engineering often overemphasizes science and mathematics to the point where graduates lack the broad overview of available technologies which allows them to make such a selection.

Such qualitative knowledge may seem less intellectually rigorous than science and mathematics, but it is actually far more sophisticated to exercise multidimensional judgment in a mental space of the qualities of various process options than to grind through a rote calculation which a computer could beat you at.

In this chapter I will attempt to offer broad guidance on the selection of common items which are missing from many chemical engineering programs.

## What process engineers design

The essence of process engineering is the integration of complex systems, but in order to integrate systems, the designer has to have some knowledge of those characteristics of such systems which affect integration.

To be more specific, certain types of materials are more suited to a given range of pressures, temperatures, and chemical and physical compositions than others. Matching the ranges of these parameters in the plant design envelope to suitable materials is usually thought of as the process plant designer's job. Similarly, the selection of pumps,

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00012-4
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heat exchangers, instrumentation, valves, and so on is usually thought to be part of process plant design.

The information required to make these selections is largely absent from chemical engineering degrees, justified by the idea that it is mere qualitative data which is insufficiently intellectually demanding for a university-level education.

Similarly, the qualitative criteria used to choose between separation processes and other technologies are frequently thought of as too shallow and easy to be worth a student's time. Students mostly concentrate on a few processes, selected to illustrate scientific principles or mathematical techniques.

Practitioners understand that qualitative knowledge is actually capable of forming the basis of quite subtle and sophisticated multidimensional reasoning, and that providing such judgments is one of the basic expectations of a process plant design engineer.

This chapter includes matrices showing a number of dimensions which may be used to choose between options for materials of construction, valves, pumps, blowers, compressors and fans, separation processes, and heat exchangers. It also includes information on the specification of electrical components and instrumentation.

## Matching design rigor with stage of design

At the conceptual design stage it is often important to know, at a category level, what kinds of components we are thinking of using. Whether we are going to use rotodynamic or positive-displacement pumps, membranes or distillation, globe or butterfly valves, carbon steel or plastic is usually known to the process plant designer by the time their initial drawings are done. All of these decisions affect the fundamental characteristics of the design and have implications for cost, safety, and robustness.

Experienced professionals might not even know they are making some of these choices (which might be strongly affected by custom in the sector and personal preference), but the beginner has to make conscious choices. There may be little formal documentation of some of these choices at this early stage, but the designer has to make many of them to carry out even a conceptual design.

At the detailed design stage, we are selecting specific commercially available items of equipment. We produce datasheets which set out the detailed specification of the item or incorporate our choices in the case of materials of construction. Equipment suppliers may, on sight of these datasheets, feed back to us information which allows us to refine or reconsider our choices.

More generally, a more detailed analysis may show some of our conceptual design choices to be less than ideal, so we might change our minds. If someone else did the

conceptual design, it can be a good idea to ask them why they chose the component which you want to change. They may have had a good reason to choose it based on factors you are unaware of. If that is not possible, the project design philosophies may be of assistance.

Design for construction generates a lot more detailed documentation, and experienced engineers will be likely to review your design choices before this is finalized. They may ask for changes based on their experience of what works, or more importantly still, what does not.

## Materials of construction

*When in doubt make it stout, out of stuff you know about*

***Holman's Homily (Anon)***

Plant designers need to know which materials are going to be suitable for the duty to which they intend to put the plant, as well as the duties to which it might (intentionally or unintentionally) be put. This is not determined so much by material science as by practical experience, and 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 is carbon steel in the oil and gas industry, and plastics in the water industry—even highly corrosive water is transported in carbon steel piping in the oil and gas industry. Whilst carrying water in carbon steel seems odd to a water specialist, it is not wrong, 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 (Table 11.1).

An aside—it should be borne in mind that just because a steel has a higher chromium or nickel composition doesn't necessarily mean it is better suited to severe conditions than carbon steel. For example, stress corrosion cracking occurs in austenitic stainless steel, but not in ferritic stainless steel, low-chrome alloy, or carbon steel materials.

## Scaling and corrosion

Prediction of the scaling or corrosive nature of fluids impacts on many areas of design from the selection of tube or shell side duty on a heat exchanger of a fluid to fouling factors and corrosion allowances. There is a lot to this subject, but I will confine myself to covering a few key aspects in outline.

**Table 11.1** Materials of construction

| | Relative price | Temperature rating | Pressure rating | Water resistance[a] | Organic solvent resistance | Acid resistance | Alkali resistance | Abrasion resistance | Chloride resistance | UV resistance | Hardness | Toughness |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Metals*** | | | | | | | | | | | | |
| Cast iron | L | H | M/H | M | H | L | L/M | H | L | VH | H | M/H |
| Carbon steels | L | H | H | L | H | L | L | M/H | L | VH | H | H |
| Stainless steels | M | H | VH | H | H | L | L/M[b] | VH | L/M[b] | VH | H | VH |
| Bronzes | M | M/H | H | L | H | L | L | M | M | VH | M | M |
| Brasses | M | H | H | H | H | L | VL | M | M | VH | M | M |
| Hastelloy | VH | VH | VH | VH | H | H | M | H | H | VH | H | H |
| Tantalum | VH | VH | M/H | VH | H | VH | M | H | H | VH | H | VH |
| Inconel | VH | VH | VVH | VH | H | M/H[b] | H | H | M/H[b] | VH | H | H |
| Aluminum | M/H | M/H | M/H | H | H | L | L | M | L | VH | H | H |
| Titanium | H | H | M/H | H | H | M | L | H | VH | VH | H | H |
| Precious metals | VVH | H | L/M | H | H | M/H | VH | L/M | VH | VH | L/M | L/M |
| ***Plastics*** | | | | | | | | | | | | |
| PVC | L | VL/L[b] | M/H[b] | H | M[b] | H | H | M | H | VL | M | H |
| ABS | L | VL | L | H | M | H | H | M | H | M | M | H |
| PP/PE | L | VVL | VL | H | L | H | H | L/M | H | H | L | M |
| PS | L | VL | L/M | H | L | H | H | L | H | H | L | H |
| Acrylic | M | L | L/M | H | | H | H | H | H | H | | H |
| Nylon | M | L/M | M | M/H | L/M | M | H | H | H | H | M | H |
| Polybenzimidazole | H | M/H | M | H | H | L/M | L | H | H | H | M | H |
| ***Fluoropolymers*** | | | | | | | | | | | | |
| PTFE | H | M | VL | H | H | H | H | M | H | H | M/H | M |
| PVDF | VH | M | L/M | H | H | H | H | M | H | H | M/H | M/H |
| ***Other*** | | | | | | | | | | | | |
| Ceramics | M | VVH | VVH | H | H | L/M | L | VH | H | VH | VH | L |
| Graphite | H | H | L/M | H | H | H | L/M | L | H | H | L | L |
| Glasses | M | M | L/M | H | VH | H | M | H | H | H | VH | L |
| Rubber | L | L | L/M | H | L/M | L | H | H | H | H | L | H |
| Composites | H | L | H | H | M/H | L/M | H | M | H | M | M | H |

*L*, Low; *M*, Medium; *H*, High; *V*, Very.
[a]Corrosive water by Langelier index (LSI).
[b]Varies by grade.

Corrosion allowances are dependent upon temperature, pressure, and internal and external chemical environment, and limited life stipulations may be needed for pressure vessels in corrosive environments.

Effects such as erosion by entrained solids, galvanic corrosion, stress corrosion cracking, hydrogen embrittlement, cavitation, vibration, thermal expansion/contraction, and water hammer may all cause the premature failure of metal components. New processes especially might need extensive testing of materials. Materials specialists may be needed to assess the suitability of materials of construction at the detailed design stage. For earlier stages of design, Table 11.2 (from "Practical Process Engineering") may be useful.

Various indices are used to predict whether water is going to be scaling or corrosive, but they are at best quite rough heuristics. There is a lot more about this in my book on water and effluent treatment but, in broad outline, I usually favor the Langelier index (LSI) for historical reasons although, for carbonate-buffered systems, the Ryznar/Carrier stability index (RSI) is supposedly more empirically based.

The Larson–Skold index predicts corrosion of mild steel and, since it considers sulfate and chloride as well as bicarbonate, is commonly used to predict corrosivity of once-through cooling seawater.

The Oddo–Tomson index allows for water, gas, and oil phases, and the effect of pressure on $CO_2$ saturation, to satisfy oil and gas industry needs.

## Mechanical equipment

The average new graduate knows very little about pipe specification and so on, so this section focuses on qualitative information for the most important items of mechanical equipment, the design of which is largely untaught in chemical engineering degrees. These items are, in my opinion, fluid transport machinery, flow control devices, and heat exchanger selection.

## Fluid transport machinery (pumps/blowers/compressors/fans)

Fluid transport machinery generally comes in two main varieties—rotodynamic or positive displacement. Each of these comes in many subtypes, but beginners have often not been taught the crucial differences between the two broad types.

Later, I provide a table giving you some ideas on how to choose between the commonest types of liquid and gas moving equipment, but first let's see how we choose between the broad varieties of pumps (Table 11.3).

**Table 11.2** Corrosion table

| | Brass | Bronze | Alloy 20 | Hastelloy C | Monel | 304 stainless steel | 316 stainless steel | Titanium | Silicon iron | Tantalum | Copper | Aluminum | Carbon steel | Butyl rubber | Epoxy | Hypalon | Natural rubber | Neoprene | Nitrile rubber | Nylon | Phenolic | Polyethylene | Polypropylene | PVC | Silicone elastomer | TFE | Ceramic, alumina | Graphite |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Acetaldehyde | | | A | A | | | A | A | A | A | | | N | | N | N | A | A | | N | | | B | N | | A | A | A |
| Acetic acid, 20% | C | C | A | A | B | A | A | A | A | A | A | A | N | A | A | A | C | C | | N | | C | A | A | A | A | A | A |
| Acetic acid, 80% | C | C | A | A | B | A | A | A | A | A | A | A | N | A | B | A | C | A | | N | | C | A | C | | A | A | A |
| Acetic acid, glacial | C | C | A | A | B | | A | A | A | A | A | A | N | A | B | N | C | C | A | N | A | C | B | N | | A | A | A |
| Acetic anhydride | C | C | B | A | | A | B | A | | A | A | A | C | | | A | | A | | N | B | A | A | N | | A | A | A |
| Acetone | A | A | A | A | A | A | A | A | A | A | A | A | A | C | C | C | N | C | N | A | A | A | C | N | N | A | A | |
| Aluminum chloride | C | C | C | A | N | N | C | C | C | A | C | C | N | A | A | A | | A | N | N | A | A | A | A | C | A | A | A |
| Aluminum sulfate | C | C | C | A | C | C | C | A | A | A | C | C | N | | A | A | C | A | | C | A | A | A | A | | A | A | A |
| Ammonia, 10% | N | N | A | A | N | A | A | A | | | N | C | C | C | C | A | N | A | N | A | | | A | A | | A | A | A |
| Ammonium chloride | N | N | C | A | C | C | C | A | C | A | N | C | C | | A | A | N | A | N | N | A | A | A | A | A | A | A | |
| Ammonium nitrate | N | N | A | C | N | A | A | A | A | A | N | A | C | | A | A | A | A | | N | A | A | A | A | | A | A | A |
| Ammonium phosphate | N | N | A | A | N | | A | A | A | A | C | C | C | | C | A | A | A | | C | A | A | A | A | | A | A | A |
| Ammonium sulfate | N | C | A | A | C | A | C | A | A | A | C | A | C | A | A | C | N | A | N | N | A | A | A | A | A | A | A | A |
| Amyl acetate | | | A | A | A | | A | A | | A | | | | | B | N | N | N | | C | | N | N | N | | A | A | A |
| Amyl alcohol | B | | A | A | | A | A | A | A | A | A | A | | | | C | B | A | | A | | A | A | C | | A | A | A |
| Amyl chloride | B | | A | A | A | A | B | | A | A | | N | | | C | N | B | | | C | | N | N | N | | A | A | A |
| Aniline | N | N | A | A | A | A | A | A | C | A | N | N | A | | B | B | N | N | | | B | N | B | N | | A | A | A |
| Aqua regia | N | N | N | C | N | N | N | A | N | A | N | N | N | | N | C | | N | | N | | B | N | N | | A | A | |
| Arsenic acid | N | | B | B | B | B | B | A | C | | | N | | | | | A | A | | N | | B | A | A | | A | A | A |
| Barium chloride | A | A | A | A | A | B | B | A | A | A | A | N | | A | A | B | C | A | A | A | A | A | A | A | A | A | A | |
| Barium sulfate | A | A | A | A | A | A | A | A | A | A | A | A | | A | A | A | C | A | N | A | A | | A | A | A | A | A | |
| Beer | | | A | A | | A | A | A | | | A | A | C | | A | A | | A | | N | | A | A | A | | A | A | A |
| Benzaldehyde | A | A | A | A | A | A | A | A | A | A | A | A | | | N | N | N | N | | A | B | A | B | N | | A | A | A |
| Benzene | A | | A | A | A | A | A | A | A | | A | A | A | N | B | N | N | N | N | A | A | N | B | N | N | A | A | A |
| Benzoic acid | | C | A | A | | C | A | B | A | | | | | A | A | N | A | N | N | C | A | C | A | A | N | C | A | A |
| Borax | A | A | A | A | C | A | A | A | A | A | A | N | | | A | A | A | A | | A | | A | A | A | | A | A | A |
| Boric acid | N | A | A | A | A | A | A | A | A | A | C | A | N | A | A | A | A | A | N | A | A | A | A | A | N | A | A | A |
| Bromine water | C | C | N | A | C | N | N | A | N | | C | N | N | | B | N | | N | | N | | N | N | B | | A | A | N |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Butyl acetate | A | | C | A | A | C | C | A | A | A | A | B | | | B | N | N | | | A | N | N | N | N | | A | A | A |
| Butyric acid | B | A | A | A | A | C | A | B | A | A | A | B | | | C | N | A | N | | N | | N | A | C | | A | A | A |
| Calcium bisulfate | N | A | C | A | N | C | C | C | N | A | A | A | | A | A | A | N | A | A | | A | A | A | A | N | A | A | A |
| Calcium chloride | | A | A | A | | C | A | A | A | | | | C | A | A | A | C | A | A | N | A | A | A | A | N | A | A | A |
| Calcium hypochlorite | C | A | C | C | C | C | C | A | A | A | C | C | C | | B | A | B | N | | N | | A | A | A | | A | A | A |
| Furfural | A | C | A | A | A | C | C | A | A | A | A | A | A | | B | | B | N | | A | A | N | N | N | | A | A | A |
| Gasoline | A | A | A | A | A | A | A | N | A | A | A | A | C | N | C | N | N | N | A | A | A | N | N | B | C | A | A | A |
| Glycerine | A | A | A | A | A | A | A | A | A | A | A | A | A | A | A | C | A | A | N | A | A | A | A | A | A | A | A | A |
| Heptane | A | A | A | A | A | A | A | A | A | A | A | A | A | | C | C | B | C | | | A | N | B | A | | A | A | A |
| Hexane | | | A | A | A | A | A | A | | | | A | | | B | C | B | A | | A | | N | B | B | | A | A | A |
| Hydrobromic acid, 20% | N | N | N | A | N | N | N | A | N | A | N | N | N | | C | A | N | C | | N | | A | A | A | | A | B | A |
| Hydrochloric acid, 0%–25% | N | N | N | C | C | N | N | C | A | A | C | N | N | C | A | A | N | A | C | N | A | A | A | A | C | A | B | A |
| Hydrochloric acid, 25%–37% | N | N | N | C | C | N | N | C | A | A | C | N | N | C | A | A | N | A | C | N | A | A | A | A | N | A | B | A |
| Hydrocyanic acid | N | N | A | A | A | A | A | | A | A | N | N | N | | A | | A | | | | | A | A | A | | A | B | A |
| Hydrofluoric acid, 10% | N | N | B | A | A | B | B | N | N | N | N | N | N | A | A | A | A | A | N | N | | A | A | B | A | A | N | A |
| Hydrofluoric acid, 30% | N | N | B | A | A | B | B | N | N | N | N | N | N | A | A | A | A | A | N | N | | A | A | B | C | A | N | A |
| Hydrofluoric acid, 60% | N | N | B | A | A | B | B | N | N | N | N | N | N | A | A | C | A | N | N | N | A | A | A | C | N | A | N | A |
| Hydrogen peroxide, 30% | N | N | A | A | C | C | A | A | C | A | C | C | C | | B | A | N | C | | N | | A | B | A | A | A | | A |
| Hydrogen peroxide, 50% | N | N | A | A | C | C | A | A | C | A | C | C | C | B | | A | N | C | | N | | N | B | B | C | A | | A |
| Hydrogen peroxide, 90% | N | N | A | A | | C | A | A | C | A | C | C | C | N | | C | N | N | A | N | A | B | B | N | C | A | | A |
| Hydrogen sulfide, aqueous | N | N | A | A | N | C | A | A | A | A | N | A | C | A | A | A | N | A | A | | A | A | A | B | A | A | | A |
| Iodine in alcohol | | N | A | A | | | A | N | N | | | | | N | | N | N | N | N | | | N | B | N | C | A | A | |
| Kerosene | A | A | A | A | A | A | A | A | A | A | A | A | | | A | N | N | N | | | A | N | C | A | | A | A | A |
| Lactic acid | A | A | A | A | | B | B | A | A | A | A | A | N | | A | A | A | A | | C | | A | A | A | | A | A | A |
| Lead acetate | | | A | A | | A | A | A | A | A | | A | | | A | N | A | N | | A | | A | A | A | | A | A | A |
| Magnesium chloride | C | C | A | A | A | A | A | A | A | | C | C | C | A | A | A | A | A | N | A | A | A | A | A | C | A | A | |
| Magnesium nitrate | A | | A | A | | A | A | A | | | | | | | A | A | C | A | | A | | A | A | A | | A | A | |
| Magnesium sulfate | A | | A | A | A | A | A | A | A | | A | C | C | | A | A | A | A | N | A | A | A | A | A | C | A | A | |
| Maleic acid | A | | A | A | | A | A | A | C | | | | | | A | A | | | | | A | A | A | A | | A | A | A |
| Methanol | A | A | A | A | A | A | A | A | A | A | A | A | | | A | A | A | A | | A | B | B | A | B | | A | A | A |
| Methyl chloride | | C | A | A | A | A | A | A | A | A | | N | | N | | N | N | N | C | | C | N | N | N | N | A | A | A |

(*Continued*)

**Table 11.2** (Continued)

| | Brass | Bronze | Alloy 20 | Hastelloy C | Monel | 304 stainless steel | 316 stainless steel | Titanium | Silicon iron | Tantalum | Copper | Aluminum | Carbon steel | Butyl rubber | Epoxy | Hypalon | Natural rubber | Neoprene | Nitrile rubber | Nylon | Phenolic | Polyethylene | Polypropylene | PVC | Silicone elastomer | TFE | Ceramic, alumina | Graphite |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Methyl ethyl ketone | A | A | A | A | A | A | A | A | A | A | A | A | A | A | B | N | | N | | A | N | A | B | N | | A | A | A |
| Methylene chloride | N | N | A | A | N | A | A | A | A | A | N | | | | | N | | N | | N | | N | N | N | | A | A | A |
| Napthalene | A | | A | A | A | A | A | A | A | A | | A | | | A | N | N | N | | | A | A | B | N | | A | A | A |
| Nickel chloride | N | N | A | A | A | A | A | A | A | A | | N | | A | A | A | A | A | N | A | A | A | A | A | C | A | A | A |
| Nickel sulfate | | C | A | A | A | A | A | A | A | | | N | | A | A | A | A | A | N | A | A | A | A | A | C | A | A | A |
| Nitric acid, 10% | N | N | A | A | N | A | A | A | A | A | N | B | N | A | | A | B | N | N | N | | N | A | A | | A | A | A |
| Nitric acid, 20% | N | N | A | A | N | A | A | A | A | A | N | B | N | A | | A | B | N | N | N | | N | A | A | | A | A | A |
| Nitric acid, 50% | N | N | A | A | N | C | C | A | A | A | N | B | N | N | | N | N | N | N | N | C | N | B | A | N | A | A | N |
| Nitric acid, anhydrous | N | | A | A | N | C | C | A | A | A | N | B | N | N | | N | N | N | N | N | | A | N | N | N | A | A | A |
| Oleic acid | A | A | A | A | A | A | A | A | A | A | C | A | C | | | C | | C | | N | | A | B | A | | A | A | A |
| Oxalic acid | A | A | C | A | A | C | B | A | A | A | C | C | C | | A | A | A | | | N | | A | C | A | | A | A | A |
| Phenol | A | | C | A | A | C | C | A | A | A | N | B | N | | C | N | B | N | | A | | | A | B | | A | A | A |
| Phosphoric acid, 0%–50% | C | C | A | A | C | C | C | B | A | A | C | N | C | | A | A | C | A | N | N | A | A | A | A | | A | A | A |
| Phosphoric acid, 50%–100% | C | C | A | A | C | C | C | B | A | | C | N | C | | C | A | C | A | N | N | A | A | A | C | N | A | A | A |
| Potassium bicarbonate | | | A | A | A | A | A | A | | | | | | | A | A | | A | | A | | A | A | A | A | A | A | A |
| Potassium bromide | A | | A | A | | A | A | A | A | A | A | N | | | A | A | B | A | | C | | A | A | A | | A | A | A |
| Potassium carbonate | A | A | A | A | A | A | A | A | A | N | A | N | | A | A | A | A | A | C | A | A | B | A | A | C | A | A | A |
| Potassium chlorate | N | | A | A | A | A | A | A | A | A | | A | | A | | A | C | A | N | C | A | A | A | A | C | A | A | |
| Potassium chloride | C | C | C | A | A | C | C | A | A | A | A | A | | A | A | A | A | A | N | C | A | A | A | A | C | A | A | A |
| Potassium cyanide | N | N | A | A | A | A | A | A | A | A | N | N | | | A | A | A | A | | A | | A | A | A | | A | A | A |
| Potassium dichromate | N | N | A | A | | A | A | A | A | A | N | A | | | A | A | A | A | | N | | | A | A | | A | A | A |
| Potassium hydroxide | N | N | A | A | A | C | C | C | N | N | N | N | C | A | A | C | C | A | C | A | A | A | A | A | A | A | N | A |
| Potassium nitrate | N | A | A | A | A | A | A | A | A | A | A | A | | A | A | A | A | A | N | C | A | A | A | A | A | A | A | A |
| Potassium permanganate | A | A | C | A | A | C | C | A | A | A | A | A | | | A | A | | A | | N | | A | A | A | | A | A | A |
| Potassium sulfate | C | C | A | A | A | A | A | A | A | A | A | A | C | A | A | A | A | A | N | C | | A | A | A | A | A | A | A |
| Propyl alcohol | A | A | A | A | | A | A | A | | A | A | A | | | | A | | A | | | | | B | B | | A | A | |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sodium acetate | | | A | A | A | A | A | A | A | A | A | A | | | A | A | A | A | | A | | A | A | A | | A | A | A |
| Sodium bicarbonate | A | A | A | A | A | A | A | A | A | A | A | A | | N | A | A | C | A | N | A | A | A | A | A | N | A | A | A |
| Sodium bisulfate | N | C | A | A | A | A | A | A | A | N | C | C | N | A | | A | C | A | N | C | A | A | A | A | C | A | A | A |
| Sodium bisulfite | A | A | C | A | A | C | C | A | N | A | A | A | | | A | C | A | A | | C | | A | A | A | | A | A | A |
| Sodium carbonate | A | A | A | A | A | A | A | A | A | N | A | N | A | N | A | A | A | A | N | A | A | A | A | A | N | A | A | A |
| Sodium chlorate | A | | C | C | | C | C | A | A | | | | | A | A | C | C | A | N | C | A | A | A | A | C | A | A | |
| Sodium chloride | | | C | C | | C | C | A | A | | | | C | | A | A | A | A | | A | A | A | A | A | | A | A | A |
| Sodium cyanide | N | N | A | A | A | A | A | A | | | N | N | A | | A | A | | A | N | A | A | A | A | A | C | A | A | A |
| Sodium hydroxide, 20% | N | C | A | A | A | A | A | A | N | N | C | N | A | A | A | A | C | A | A | A | C | A | A | A | A | A | N | A |
| Sodium hydroxide, 50% | N | C | A | A | A | A | A | A | N | N | C | N | A | A | A | C | C | A | A | A | C | A | A | A | A | A | N | A |
| Sodium hypochlorite | N | C | C | C | C | C | C | A | N | A | C | N | N | A | | A | C | C | N | N | A | A | A | A | C | A | A | A |
| Sodium nitrate | C | C | A | A | A | A | A | A | A | A | A | A | A | A | A | A | C | A | N | A | | A | A | A | C | A | A | A |
| Sodium silicate | A | A | A | A | A | A | A | A | A | A | A | A | | | A | A | A | A | | A | A | A | A | A | A | A | A | A |
| Sodium sulfate | A | A | A | A | A | A | A | A | C | A | A | A | C | A | A | A | C | A | N | A | A | A | A | A | C | A | A | A |
| Sodium sulfide | N | N | A | A | C | C | C | A | A | N | C | N | C | A | A | A | C | A | N | A | A | A | A | A | C | A | A | A |
| Stannic chloride | N | | B | C | C | N | N | A | N | A | | N | N | | A | C | C | A | N | | | A | A | A | N | A | A | A |
| Stearic acid | A | A | A | A | B | A | A | A | A | A | A | A | | A | A | C | N | C | | | | A | B | A | | A | A | A |
| Sulfuric acid, 0%–10% | N | A | A | A | C | N | N | B | | A | N | N | N | N | A | A | N | A | N | N | A | A | A | A | | A | A | A |
| Sulfuric acid, 10%–75% | N | A | A | A | C | N | N | C | N | A | N | N | N | N | B | A | N | N | N | N | C | C | A | A | N | A | A | A |
| Sulfuric acid, 75%–100% | N | A | A | C | C | N | N | N | N | A | N | N | N | N | N | C | N | N | N | N | C | C | B | B | N | A | A | A |
| Tannic acid | A | A | A | A | A | C | C | A | A | A | A | N | | | A | A | A | A | | N | | A | A | A | | A | A | A |
| Tartaric acid | C | C | A | A | C | A | A | A | A | A | A | A | | | A | A | A | A | | | | A | A | A | | A | A | A |
| Tetrahydrofurane | | | A | A | | A | A | | | | | | | | | | | | | A | | N | B | N | | A | A | |
| Toluene | A | N | A | A | A | A | A | A | A | A | A | A | A | N | C | N | C | N | N | A | A | N | B | N | N | A | A | A |
| Trichloroethylene, dry | A | N | A | A | A | A | A | A | A | A | A | A | A | N | A | N | N | N | N | N | C | N | B | N | N | A | A | A |
| Turpentine | C | C | A | A | A | A | A | A | A | A | C | A | C | N | B | N | N | N | C | A | A | N | B | A | N | A | A | A |
| Urea | | | A | A | | A | A | A | | | | A | | | A | A | | A | | | | A | A | A | | A | A | A |
| Xylene | | | A | A | | A | A | A | | | | | | | C | N | | N | | A | A | N | N | N | | A | A | A |
| Zinc chloride | N | N | A | A | A | A | A | A | A | A | N | N | N | A | A | A | C | A | N | N | A | A | A | A | A | A | A | A |
| Zinc sulfate | C | A | A | A | A | A | A | A | A | A | C | | C | A | A | A | C | A | N | C | A | A | A | A | A | A | A | A |

*A*, acceptable; *B*, acceptable up to 80F; *C*, caution, use under limited conditions; *N*, not recommended; blank space, effect unknown.

Source: Reproduced from Sandler, H. J., & Luckiewicz, E. T. (1987). Practical process engineering: A working approach to plant design. New York, NY: McGraw-Hill.

**Table 11.3** Pump selection (general)

| | Rotodynamic | Positive displacement |
|---|---|---|
| Head | Low—up to a few bar | High—hundreds of bar |
| Solids tolerance | Low without efficiency losses | Very high for most types |
| Viscosity | Low-viscosity fluids only | Low- and high-viscosity fluids |
| Sealing arrangements | Rotating shaft seal required | No rotating shaft seal |
| Volumetric capacity | High | Lower |
| Turndown | Limited | Excellent |
| Precision | Low—discharge proportional to backpressure | Excellent—discharge largely independent of backpressure |
| Pulsation | Smooth output | Pulsating output |
| Resistance to reverse flow | Very low | Very high |
| Reaction to closed valve downstream | No damage to pump | Pump damage likely |

In very brief summary, we tend to use positive-displacement pumps for metering duties, and centrifugal (rotodynamic) pumps for moving large volumes of flow at relatively low pressures. More detailed choices are given in Table 11.4.

## Flow control devices (valves)

We can think of valves in a number of broad categories. It can incidentally be helpful, when first constructing a piping and instrumentation diagram (P&ID) of a process, to add them using these categories in turn.

The most common types on a process plant are the valves which allow every item of equipment to be capable of isolation from the rest of the plant for maintenance purposes. The (usually manually operated) valves we use to do this can be called isolation valves. They are usually set to either their fully open or fully closed position, rather than being used at intermediate degrees of opening for flowrate modulation. These are usually tagged on a P&ID as MV—manual valve (though some think that this clutters the P&ID, and do not tag MVs).

A variant on isolation which can be useful (but carries a significant risk) is a bypass valve, which allows a unit operation to be bypassed. If complete or partial bypassing of a unit operation carries safety or performance implications (as it usually does), the designer needs to think about how to protect the plant from accidental or deliberate bypassing of a unit operation by operators. Valves can be locked out, or a section of pipe known as a spool piece can be left out and kept under lock and key to make sure that bypassing is only done deliberately and under management control.

Bypassing of actuated control valves via a manual control valve is more akin to a manual standby unit and is far less risky from a process point of view than bypassing of

**Table 11.4** Pump selection (detailed)

| | Relative price | Environmental/ safety/operability concerns | Robustness | Shear | Maximum differential pressure | Capacity range | Solids handling capacity | Efficiency[a] | Seal in−out | Fluids handled[b] | Self-priming? |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Rotodynamic*** | | | | | | | | | | | |
| Radial flow | M | Cavitation | H | H | M/H | L-VH | M | H | M | Low viscosity/ aggressiveness | N |
| Mixed flow | M | Cavitation | H | H | M | M-VH | M | H | M | Low viscosity/ aggressiveness | N |
| Axial flow | M | Cavitation | H | H | M | M-VH | M | H | M | Low viscosity/ aggressiveness | N |
| Archimedean screw | H | Release of dissolved gases | VH | H | L | M-VH | H | L | N/A | Low viscosity/ aggressiveness | N |
| ***Positive displacement*** | | | | | | | | | | | |
| Diaphragm | M | Overpressure on blockage | VH | L | M/H | VL-M | H | L | H | Low/high viscosity/ aggressiveness | Y |
| Piston diaphragm | H | Overpressure on blockage | M | L | VH | VL-M | L/M | M | H | Low/high viscosity/ aggressiveness | Y |
| Ram | H | Overpressure on blockage | H | M | VH | M-H | H | M | H | Low/high viscosity/ aggressiveness | Y |
| Progressing cavity | M | Overpressure on blockage | M | VL | H | M-H | H | H | H | Low/high viscosity/ aggressiveness | Y |
| Peristaltic | H | Overpressure on blockage | L | VL | M | VL-M | H | M/H | M | Low/high viscosity/ aggressiveness | N |

(*Continued*)

**Table 11.4** (Continued)

| | Relative price | Environmental/ safety/operability concerns | Robustness | Shear | Maximum differential pressure | Capacity range | Solids handling capacity | Efficiency[a] | Seal in−out | Fluids handled[b] | Self-priming? |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Gear | L | Overpressure on blockage | L | M | VH | VL-L | L | L | H | Low/high viscosity. Low aggressiveness | Y |
| Screw | L | Overpressure on blockage | L | M | VH | L-M | L | L | H | Low/high viscosity. Low aggressiveness | Y |
| ***Other*** | | | | | | | | | | | |
| Air lift | L | | VH | VL | VL | L-M | H | L | L | Low viscosity, low/high aggressiveness | N |
| Eductor | M | Blockage of eductor | M | M | VL | L-H | M | H | M | Low viscosity, low/high aggressiveness | Y |

[a]Centrifugal pump efficiency reduces as viscosity increases, but PD pump efficiency increases. Centrifugal pump efficiency is more to do with impeller type than anything else, impeller type is determined by process conditions such as any solids handling requirement.
[b]Aggressiveness is related to the presence of abrasive particles, undissolved gases, or unfavorable LSI.

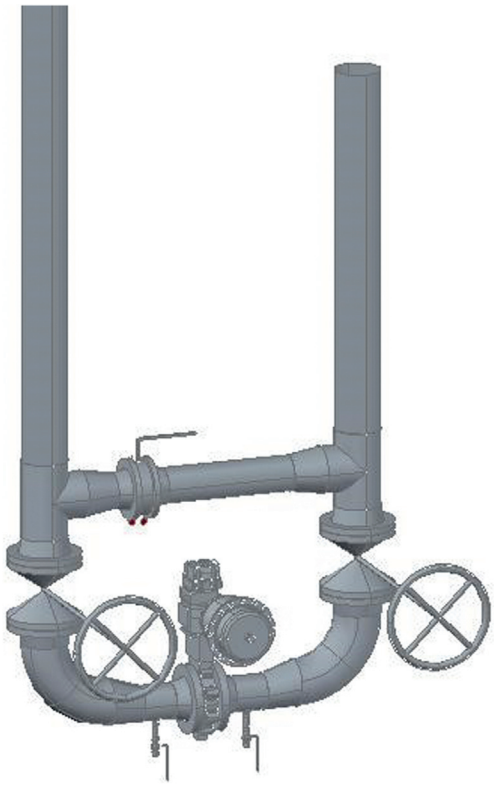

**Figure 11.1** Typical actuated valve station. *Courtesy: Paul Bowers, Society of Piping Engineers and Designers.*

unit operations. Bypass arrangements are normally made into a standard layout known as a valve station (Fig. 11.1).

A smaller number of valves on a plant are used to control flow (control valves). They may be used for on/off control, or they may be used to modulate flow by intermediate degrees of opening. The setting of these valves may be manual, or more frequently nowadays they are moved by means of motors known as actuators, controlled by computer. These may be tagged on a P&ID as AV—actuated valve—or less desirably tags such as FCV—flow control valve. They should not be tagged as MV—motorized valve—to avoid confusion with the last category.

Then there are the self-operating safety valves, including nonreturn valves, pressure-relief valves, and pressure-sustaining valves.

My final category is externally operated safety valves such as emergency shutdown valves.

The preceding list is of valve duties rather than valve types. In order to choose an appropriate type of valve for a duty we need to know the characteristics of the various types of valves commercially available. Table 11.5 gives this information to allow a choice to be made.

There is also a handy table in *Practical Process Engineering* (see Further Reading) which I reproduce in Table 11.6.

**Table 11.5** Valve selection

| | Relative price | Robustness | Sizes (mm NB) | Materials of construction | Fluids handled | Solids handling ability | Seal in–out | Seal up–downstream | Controllability | Actuator type | Pressure rating[a] | Manufacturer[b] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Isolating*** | | | | | | | | | | | | |
| Butterfly/disc | L | M | 50–500 | Plastics, cast iron | Cleaner fluids only | M | M | M | M/H | 1/4 turn cylinder, electric motor | M/H | Bray |
| Globe | L | M | 50–600 | Brass | Cleaner fluids only | M | L/M | M | M/H | Multiturn electric motor, linear cylinder | M | Vela |
| Ball | L | H | 5–1200 | Plastics | Clean and dirty fluids | M/H | M | H | M/H | | H | George Fischer |
| Diaphragm | H | H | 15–500 | Plastics, stainless steel, aluminum | Clean and dirty liquids, sludge, and slurries | H | H | H | L/M | | M | Saunders |
| Gate | M | M | 50–1250 | Cast iron | Clean and dirty fluids, sludge, and slurries | H | L/M | H | M/H | | H | GWC |
| ***Control*** | | | | | | | | | | | | |
| Needle | H | M | 6–25 | Stainless steel | Clean fluids only | L | M | H | H | | H | Hoke |
| Globe | L | M | 50–600 | Brass | Cleaner fluids only | M | L/M | M | M/H | | M | Velan |
| Plug | H | M | 15–1800 | Cast iron, ductile iron, bronze, aluminum, carbon steel, stainless steel, alloy 20, and Monel | Clean and dirty fluids, sludge, and slurries | H | M | M/H | H | Lever, hand wheel, chain wheel, cylinder, electric motor | M | De Zurik |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| V-Notch ball | L | H | 6–150 | Plastics, stainless steel | Cleaner fluids | M | M | H | M/H | | M/H | George Fischer |
| Eccentric disc | H | M | 50–1200 | | Clean gases | M | M | H | M/H | | M | Neles |
| ***Other*** | | | | | | | | | | | | |
| Emergency shutdown | H | H | 50–400 | | Cleaner fluids | M | M | H | H | | M/H | Becker |
| Pressure relief | H | M | 6–900 | Brass, cast iron, stainless steel | Clean fluids | L | L/M | L/M | NA | | M | Farris |
| Swing check | M | H | 50–900 | Cast iron | Clean and dirty fluids, sludge, and slurries | H | M | L/M | NA | | M | Velan |
| Spring check | M | M | 6–600 | Cast iron | Cleaner fluids | M | H | M | NA | | M | Flowserve |
| Pressure sustaining | H | M | 6–350 | Plastics | Clean fluids | L | M/H | – | M/H | | M | Bermad |
| 3-Way ball | M | M | 12.5–150 | Plastic, cast iron | Cleaner fluids | M/H | M | H | M/H | | M | George Fischer |
| 3-Way plug | M/H | H | 80–400 | Cast iron, Ni-resist, aluminum, carbon steel, 316 stainless steel | Clean and dirty fluids, sludge, and slurries | H | M | M/H | M/H | Lever, hand wheel, chain wheel, cylinder, electric motor | M/H | DeZurik |

[a]There are ISO/API classes of valve by pressure/temperature ratings.

[b]Not a recommendation, just a route to more information.

**Table 11.6** Primary usages for various common valve types

| | Liquid flows | | | | | | | | | Gaseous flows | | | | | | Solid flows | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Neutral (water, oil, etc.) | | Corrosive (alkaline, acid, etc.) | | Hygienic (beverages, foods, drugs) | | Slurry | | Fibrous suspensions | Neutral (air, steam, $N_2$, etc.) | | Corrosive (acid vapors, chloride, etc.) | | Vacuum | | Abrasive powder (silica, etc.) | Lubricating powder (graphite, talc, etc.) |
| **Type** | **On–off** | **Reg** | **On–off** | **Reg** | **On–off** | **Reg** | **On–off** | **Reg** | **On–off and Reg** | **On–off** | **Reg** | **On–off** | **Reg** | **On–off** | **Reg** | **On–off and Reg** | **On–off and Reg** |
| Gate | • | | • | | | | | • | • | • | • | | | • | | | • |
| Globe | | • | | • | | | | | | • | • | | • | • | • | | |
| Ball | • | | • | | | | • | | | • | | • | | • | | | |
| Plug | • | | • | | | | • | | | • | | • | | | | | |
| Butterfly | • | • | • | • | • | • | • | • | | | • | • | • | • | • | | |
| Diaphragm | • | • | • | • | • | • | • | • | • | • | • | • | • | | | | |
| Flush-bottom | | | | | | | • | • | • | | | | | | | | |
| Squeeze | | | | | | • | • | • | • | | | | | | | • | • |
| Pinch | | | | | | • | • | • | • | | | | | | | • | • |
| Needle | | • | | | | | | | | | • | | • | | | | |
| Slide gate | | | | | | | | | | | | | | | | • | |
| Spiral sock | | | | | | | | | | | | | | | | • | • |

Source: Reproduced from Sandler, H. J., & Luckiewicz, E. T. (1987). Practical process engineering: A working approach to plant design.

## Heat exchangers

All new graduate chemical engineers can perform a "shortcut design" for a heat exchanger, but few really know of more than one type, specifically the shell and tube variety which the shortcut method applies to.

Table 11.7 is intended to help the beginner to select a suitable heat exchanger type or types.

I will also add here an ultra-shortcut method, for those like me who don't find the shortcut method quite short enough.

### *Ultrashortcut heat exchanger design*

1. Establish the heat load based upon flowrate, temperatures and specific heat capacities (Eq. 11.1).

$$q = UA\Delta T_m$$

Where

Q = heat load

U = heat transfer coefficient

A = heat transfer area

$\Delta T_m$ = log mean temperature difference

**Equation 11.1** Heat load calculation.

2. Establish approximate physical properties of the process streams.
3. Allocate streams: tube side is for corrosive, fouling, scaling and high *P* fluid, or lowest d*P*, shell side for high viscosity, low flow, or condensing fluids.
4. Calculate *Ft* to help the selection of the configuration of the heat exchanger.
5. Calculate mean temperature difference.
6. Calculate the required surface area from basic equation with ¾″ OD tubes, triangular spacing, 16 ft long (1 ft f shell contains 100 $ft^2$).
7. Estimate heat transfer coefficients for reboiler = 200 BTU/h/$ft^2$/F; water-liquid and condensers = 150; L2L = 50; L2G and G2G = 5, or use the chart in Fig. 11.2.
8. Estimate headloss as follows: 1.5 psi for boiling/condensing, 3 psi for gases, 5 psi for low-viscosity liquids, 7–9 psi for high-viscosity liquids, 20 psi for process fluid passing through a furnace.

The kind of detailed design taught in universities is usually a matter for equipment suppliers rather than process plant designers. There are, however, quite a number of types of heat exchangers, and selection between them is part of the process plant designer's job. The important things for a process plant designer to consider include making sure that the use of a heat exchanger is practical in that situation,

**Table 11.7** Heat exchanger selection

| | Relative initial cost | Robustness | Sizes (kW) | Materials of construction | Fluids handled | Solids handling ability | Fouling resistance | Maintainability (cleaning) | Sealing | Max. design pressure | Max. design temperature | Hygienic operation? | Efficiency | Footprint | Required temperature of approach | Pressure drop |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Shell and tube | M | VH | H | Flexible, depends on corrosion study | Liquid, gas. or two phase | M; to select appropriate pitch and type | L | M; to select appropriate pitch and type depending on service | H | H | H | N | M | H | H | L |
| Spiral | | | | | | VH | | | | | | Y | | | | |
| Double pipe | L (for low duty) | VH | L | Flexible, depends on corrosion study | Liquid, gas, or two phase | H | L | H | H | H | H | Y | L | VH | H | L |
| Printed circuit heat exchanger | H | VH | H | Flexible, depends on corrosion study | Liquid, gas, or two phase | L; Depends on particle size and flow passage size; prior filtration may be required. Generally only for clean service | H | VL (chemical cleaning only; mechanical cleaning is not possible) | VH | VH | VH | N | VH | VL | VL | VH |
| Plate and shell | VL | H (plate failure) | H | Ensure fluid handled compatible with gasket | Normally liquid, rarely gas or two phase | L; prone to blockage | H | VH | M | M | H | Y | H | L | VL (as low as 1 °C) | H |
| Plate and frame | VL | L (plate failure, gasket failure) | H | Ensure fluid handled compatible with gasket | Normally liquid, rarely gas or two phase | L; prone to blockage | H | VH | L | L (up to 25 bar g) | L (design temperature limited by gasket material) | Y | H | L | VL (as low as 1°C) | H |

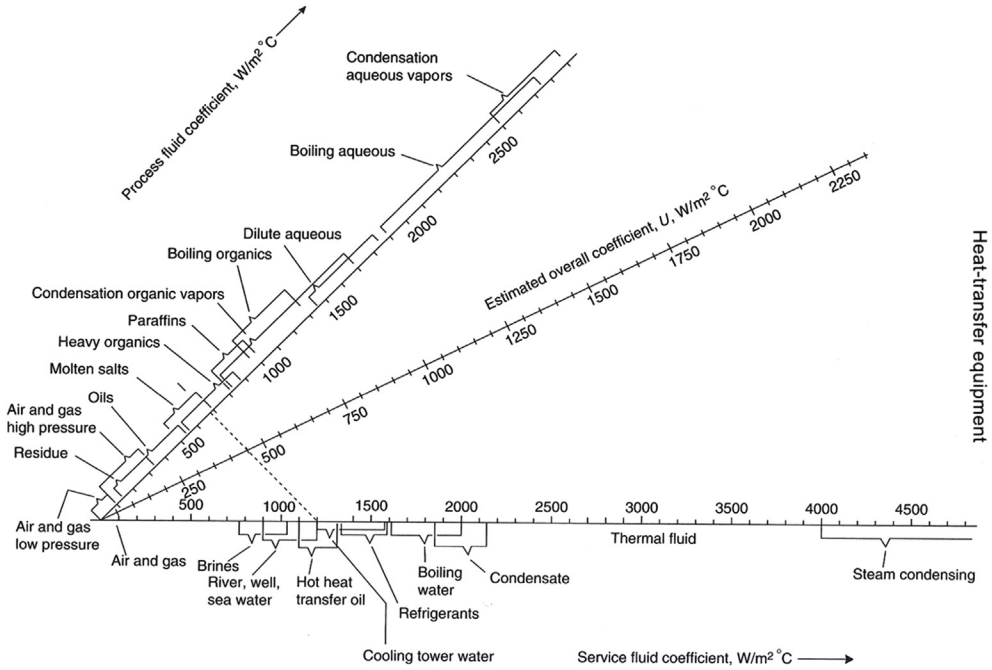


**Figure 11.2** Heat transfer coefficients. *Reproduced from Sinnott, R. K. (2005).* Coulson & Richardson's Chemical Engineering*, Vol. 6, 4th ed., p. 639, with permission of Elsevier.*

that there is sufficient $\Delta T$, and no temperature crosses exist, because heat (like water) only flows downhill.

## Electrical and control equipment

Chemical engineering students do not really think about power and control for the systems they "design," other than in the most abstract mathematical terms. An understanding of the needs of electrical and control engineers is, however, crucial to competent design.

The most important items of electrical and electronic control systems which a process plant designer must consider are described here.

### Motor control centers

When I first started designing plants, I did not know what a motor control center (MCC) was, why it was needed, and what it contained (this is a standard feature of chemical engineering degrees: we don't get taught about the most basic needs of the other disciplines we will be interacting with). This became a bit of a problem when I

almost won a job for my employer in which I hadn't thought it necessary to include an MCC. To save you the same embarrassment, allow me to explain.

Electrical motors or "drives" require maybe six times their running power to start them up. Rather than uprating all the power cabling and so on to this starting current, motor starters are used to send a pulse of power to get the drive spinning. They also contain overload protection and so on.

Direct on line (DOL) starters are very cheap, but they simply apply the full line current to the motor all at once in a way which usually limits their use to drives rated at less than 11 kW.

Star Delta starters are more expensive. They apply current to the motor in two configurations in a way that reduces starting torque by a factor of three. These are probably required above an 11-kW drive rating.

Soft starters are the most expensive type. They control voltage during drive start-up in a way which avoids the torque and current peaks associated with DOL and Star Delta starters and have some of the sophisticated control functions of the variable-speed drive (VSD).

Inverters or VSDs are perhaps a little more expensive than Star Delta starters, but they have a lot more flexibility. They allow very sophisticated patterns of power ramping to be applied to the drive on start-up, as well as allowing variable frequency to be supplied in a way which allows drive rotational speed to be controlled. They always have a microprocessor on-board nowadays so that multiple, quite sophisticated control loops and interlocks can be run directly through them.

These drives are usually collected in a big box called an MCC, which will usually contain internal subdivisions housing starters or groups of starters. There are some other common features, as shown in Fig. 11.3.

Fig. 11.3 shows a "Form 2" panel, with an intermediate degree of separation between controls for different aspects of a process. There are four forms of panel specified in IEC 60439-1: 1999, Annex D and BS EN 60439-1: 1999. There are lettered subtypes, but broadly:

*Form 1* has no separation and is often referred to as a wardrobe type. Failure of one component in a Form 1 panel can damage other components, and a single failure will take the whole process offline.

*Form 2* separates the bus bars (big copper conductors which carry common main power throughout the panel) from other components. Not much better than Form 1.

*Form 3* separates the bus bars from other components, and all components from each other. This is the minimum specification if you would like sections of the plant to be capable of running while one of them is offline.

*Form 4* is as Form 3, but also separates terminals for external conductors from each other.

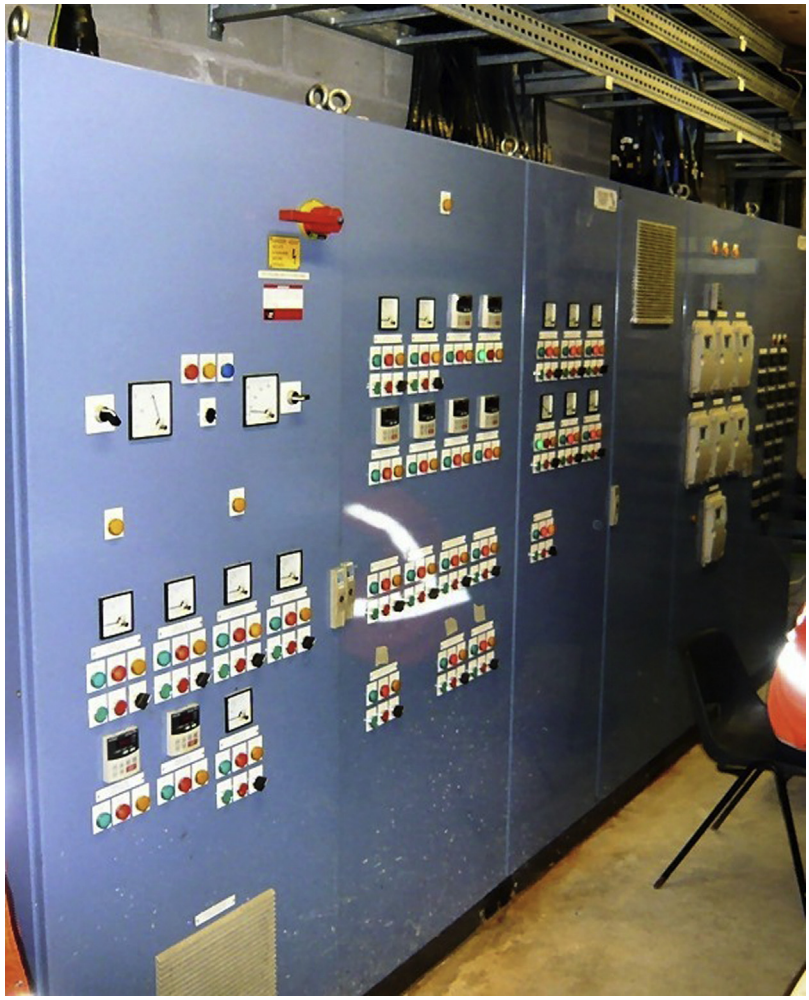

**Figure 11.3** MCC unit showing incomer, starters, marshalling cubicle, and PLC/UPS sections. *Courtesy: Process Engineering Group, SLR Consulting Ltd.*

There is a different system in the United States (described in standard UL 508A) which takes a different approach but addresses the same issues. In either case the process designer will be required to specify broadly which kind of panel they want, though clients may specify a minimum separation between control switchgear. The important thing to know about these types is that the higher the number, the greater the cost, safety, and robustness of the panel.

Panels will also have a specified degree of ingress protection (IP55 is usually the minimum standard).

Consideration will also need to be given to direction of cable entry, which can be from the top, bottom, or a combination of both. Bottom entry requires the panel to sit on a channel in the floor, so there are civil engineering implications.

There is a great deal more to this, but this is the minimum level of knowledge required of a process designer to integrate their MCC design.

## Cabling

Another thing which generally receives no attention in chemical engineering degrees is cabling. The absolute minimum information you need to know about cables is as follows.

Every instrument needs incoming power and outgoing signal cabling. Every electrical drive (motor) on the plant needs incoming power cabling. Every MCC needs incoming power cabling and outgoing power and signals cabling.

Power cable size is calculated by electrical engineers in a similar way to pipe size. The more current a cable carries, the thicker it has to be to avoid overheating. A complicating factor is that cables can have a variable number of wires or "cores" inside them. Thus, we can have a thick cable with a single set of large cores feeding a single large drive, or a similarly thick cable with multiple smaller cores feeding a number of drives.

Instrument cabling needs to be arranged so as to be unaffected by electromagnetic fields from the power cabling. This is usually achieved by some combination of physical separation and shielding. One meter of separation will usually do it, but your electrical engineer will advise.

The basic kind of power cable is the relatively inflexible SWA (steel wire armored) PVC-insulated type. There is also a more flexible, unarmored, and waterproof kind used to connect submersible pumps. Instrument cabling also comes in a number of types and is a lot smaller than power cabling as it is only carrying 5−240 V, and no real power.

Cables have a minimum bend radius. The thicker the cable, the bigger this is. There needs to be space in the design to accommodate this. It is approximately equal to the radius of a commercially available long radius bend in a pipe large enough to carry the cable.

All kinds of cable are carried underground through ducts, which are nowadays laid with commercially available plastic pipes. These pipes may be cast into concrete slabs, unlike pipes which carry fluids. We usually specify a few more of such ducts than we need in a design to allow for future expansion. Cables are carried overground on (usually elevated) cable trays. Power and signals cabling should ideally be in separate ducts and cable trays.

## Instrumentation

There are many specialized process instruments, but the four commonly measured parameters are pressure, flow, temperature, and level, and process designers need to be able to choose between the most common types of instrumentation used for measuring these things. Table 11.8 should help.

**Table 11.8** Instrumentation selection

| | Relative price | Robustness | Contact with process fluid? | Solids-handling ability |
|---|---|---|---|---|
| ***Pressure instruments*** | | | | |
| Bourdon | L | L | Y | M |
| Capacitance | M | H | Y | H |
| Resistance | L | M | Y | H |
| Piezoelectric | M | H | N | H |
| Optical | H | M | N | M |
| ***Flow instruments*** | | | | |
| Variable area | L | L | Y | L/M |
| Mechanical | L | L | Y | |
| Pressure | M | M | Y | L/M |
| Electronic | M/H | H | N | H |
| Radiation | H | H | N | H |
| Vortex | H | H | N | H |
| Doppler | M | H | N | VH |
| ***Temperature instruments*** | | | | |
| Thermocouple | L | H | Y | H |
| Bimetal | L | M | Y | M/H |
| Resistance | L | H | Y | H |
| ***Level*** | | | | |
| Sonar/radar | M | M | N | H |
| Float | L | M | Y | H |
| Pressure | M | M | Y | M/H |

*L*, Low; *M*, Medium; *H*, High; *Y*, Yes; *N*, No.

## Control systems

A number of control systems are used in process plant design. Selection between them for whole-system or local design may be as much a matter of client preference, industry familiarity, and designer preference as inherent characteristics of the system type.

### *Local controllers*

Once upon a time, control loops were operated by mechanical, electromechanical, pneumatic, or electrically operated boxes which were mounted locally to the thing being controlled.

By the time I was at university, these were most commonly solid-state electronic PID (proportional, integral, differential) controllers (Fig. 11.4).

We still use the odd dedicated field-mounted controller (for pH control, for example) but process plant designers never do the thing we were taught to do in university—writing algorithms for these boxes. Controllers are products, whose manufacturers have done this job for us. Their limited configurability also makes these controllers the most robust solution. Writing software is best left to experts.

The oil and gas industry still uses the modern equivalent of P&ID controllers, and a distributed control system (DCS) system to facilitate their aftermarket optimization and tuning of plants, but this is not much to do with greenfield process plant design as I define it here.

### *Programmable logic controllers*

In my industry, programmable logic controllers (PLCs) are commonly used for whole-system control. PLCs are a kind of computer which is custom built out of components to suit a particular duty.

**Figure 11.4** Wall-mounted PID controller. *Courtesy: Amot.*

A range of central processing units of increasing power is available, and rack-mounted cards are added to this to provide a suitable number of input and output channels.

Direct interface with a PLC is via a human–machine interface (HMI) or PC program. These can vary in appearance from the program's green-screen and ladder logic to the PC-based sophisticated simulation interfaces of supervisory control and data acquisition (SCADA) systems.

It should be noted that, while PLCs themselves cannot be directly infected with computer malware, the intelligence community produced a worm (Stuxnet) to attack PLCs via their SCADA-connected PCs (thought to have been written to target the Iranian nuclear program). Stuxnet was purely destructive, but a more recent virus called Duqu is a keystroke-logging spyware program.

Any systems which include a PC may be compromised, especially as PCs are almost always connected to the internet nowadays, and site communications and signals are increasingly connected via Wi-Fi rather than hard wired.

With the "Industrial Internet of Things" expanding into process plants, cybersecurity is an increasing concern. In August 2017, malware targeting safety controllers was used in cyberattacks on a number of Saudi petrochemical facilities, which only failed due to bad coding by the attackers.

### *Supervisory control and data acquisition*

SCADA systems run on a PC (usually a standard Windows-based desktop computer vulnerable to Windows viruses, connected to the internet). They can receive signals from one or more PLCs, or from remote telemetry outstations (RTUs) which convert 4–20 mA signals from field instruments into digital data.

Such signals may be carried by local or wide area networks using internet protocols, by telephone lines, or satellite signals.

The SCADA system has an HMI—usually in the form of simulation screens which look rather like animated PFDs, alarm-handling screens, "trends" screens which allow variation in parameters to be seen as a graph against time, and input screens which allow process parameters to be changed (ideally only by authorized users).

### *Distributed control system*

DCS used to differ more from SCADA than it does nowadays. Historically SCADA used dumb field instrumentation, and had a centralized system "brain," whereas DCS has a lot more control out in the field.

As it is becoming increasingly difficult to buy dumb instrumentation, or even dumb motor starters, the distinction is not as sharp as it was, but DCS is more likely to involve field-mounted controllers. These are less likely to be simple PID controllers but will be capable of more sophisticated control.

The oil and gas industry makes extensive use of DCS, which is well suited to their culture of radical post-purchase control system tuning.

### *Aftermarket systems: supervisory computer, etc.*

In the oil and gas industry, there is a tendency to install, postpurchase, a supervisory control system running advanced control software, such as MPC (multivariable predictive control) and RTO (real-time optimization). To quote Myke King:

> *MPC is installed on pretty much every oil refinery and petrochemical site, but it's not something that needs a lot of attention at the process design stage.*
>
> *It and RTO (if justified) would typically be engineered well after process commissioning—in some cases 30 years after commissioning! There would be other PCs connected to the DCS for process data collection—typically based on a real-time database (such as OSI's PI, Honeywell's PHD etc.). They would have links to other process management systems—such as LIMS (laboratory information management system).*

## Further reading

Branan, C. (2012). *Rules of thumb for chemical engineers*.. Oxford: Elsevier Press.
Couper, J. R., & Penney, W. (2012). *Chemical process equipment—Selection and design*.. Oxford: Elsevier Press.
Moran, S. (2018). *An applied guide to water and effluent treatment plant design*.. Oxford: Butterworth-Heinemann.

# CHAPTER 12

# How to design and select unit operations

## Introduction

Process plant designers are very rarely carry out detailed design of unit operations, as they do not offer the process guarantees for the units. Detailed design is a job for those guaranteeing the performance of the unit operation.

The plant designer's job is to get their design correct enough such that the design envelope for the unit operation is robust, as the process guarantee will limit its validity to that design envelope. We also frequently check that there are no misunderstandings in what vendors have offered or any design details incompatible with the broader design.

We will also usually make sure that the equipment weight, size, power, and other utilities requirements are in line with our expectations. If they are not, we may need to consider modifying the whole plant design to suit, or reject the item of equipment as it is less favored when these knock-on effects are considered.

## Matching design rigor with stage of design

We do not wish to spend any more time on design at each stage than is necessary to progress the overall design. Rule of thumb design is therefore the norm for process plant designers. We do, however, use more onerous but accurate heuristics as it grows increasingly likely that the plant will actually get built.

## Rule of thumb design

If you are working as a process designer, there will mostly (but not always) be a design manual which will give the relevant rules of thumb for the items you are being asked to design which encapsulates the company's experience in the area.

Failing that, there will be a more experienced engineer in your department or at least in your company who knows the rules of thumb. If there is neither a manual nor such a person, this could be a warning sign that you aren't going to learn much in this company.

If there is such a person, they may not be willing to share their knowledge. This isn't a great sign, but sooner or later the company will have to give you support if they want you to do a competent job.

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00013-6
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I personally have a compilation of methods from a variety of sources: books that sit collecting dust, publications that are not in circulation, individuals who are no longer with us. Every engineer's job is different and there is no single manual to help us get the job done. Rather, it is the responsibility of the engineers to identify what is relevant and what is not. As an early career engineer told me:

> *Some of the more experienced co-workers possess methods of design and rules of thumb that I never encountered in school. Shortcuts, if you will, that might not be 100% scientific but are sufficient to getting the job done and are backed up with the assurance of countless installations still being used to date. These co-workers were kind enough to lend me their handbooks from the days of a previous employer, companies that have not existed for 40+ years. Despite the age of the method (or the worn, malodorous, paper it was printed on) the design is in fact relevant, and readily modernized by a computer program for ease of use.*

A more experienced engineer is often the world's leading expert on the particular job you have to do, as they don't just know a way to design the plant, but they know how to design the plant so that your company can build it. So be nice to him or her, as they can teach you more than university ever did.

But what if you don't have a manual—or a Yoda? As well as my books, and Perry's Handbook, there are books which contain general rules of thumb; I list a couple of good ones in the Further Reading section at the end of the chapter. These are not going to be as good as direct access to the experienced engineer, but they may well be more useful than attempting to use some of the theoretical approaches you were probably taught at university.

There are some recent books offering "rules of thumb" generated by modeling and simulation programs. Don't use these. Proper rules of thumb come from experience with multiple full-scale real-world plants, not first principles computer programs. First principles design doesn't work.

For example, process designers size a knock out (KO) pot (an air–liquid separator used extensively in the CPI) using a method ultimately based on the Stokes equation, via the Souders–Brown equation, to allow the prediction of the theoretical velocity of a rising gas stream which will just suspend a spherical particle. Published data in the *Gas Processing Suppliers Association Engineering Data Book* gives values for the constant in the Souders–Brown equation, allowing a theoretical velocity to be calculated. That is as far as first principles can take us.

To finish the job of sizing, a practical recommended velocity is required, which is where rules of thumb come in. Either 15%, 50%, or over 75% of the allowable velocity are recommended for flash drums in which either no losses are tolerable (as with a valuable or hazardous liquid); some losses are tolerable; or devices to collect droplets such as a demister pad are used, respectively. An engineer will modify the dimensions of the vessel to find (usually in practice by using MS Excel's goal seek function) an acceptable velocity based on the rules of thumb above.

## Approaches to design of unit operations

### First principles design

As I state throughout this book, first principles design simply does not happen in normal professional process plant design practice. Even if you had enough data to allow you to design a unit operation from first principles, it would be at best a prototype, and your employer would be the one offering the process guarantee by making it part of the plant they were guaranteeing.

If you are designing unit operations for a living, you are an equipment designer, not a process plant designer, so I will not cover this issue in much detail in this book. You probably have colleagues who have the necessary know-how, or more likely still, a spreadsheet or program written by someone else which encapsulates the know-how.

If you are asked to author such a spreadsheet or program, make sure it reflects the experience held in the company, that it is debugged, and accurate across its range of operation by full-scale real-world experiments. It will have fewer bugs if you write it in MS Excel rather than compiled code.

### Design by simulation program

Despite all that I have said about the use of simulation at the whole-plant level, unit operations are less complex than whole plants, and some suppliers now offer simulation program blocks which they have verified and tuned to match their real equipment (though not validated for your specific application).

Companies which offer plants which are made of blocks of a limited number of unit operations running on basically invariant feedstocks (as when, for example, producing nitrogen from air) can produce model blocks which encapsulate much empirical data.

In this way the most normal of normal process design activity can become rather similar to building a Lego model. I am not, however, sure that we can call this activity process plant design. It seems to me more like equipment design, if a whole process plant may be specified as a collection of standard equipment.

### Design from manufacturers' literature

Since detailed design involves putting together unit operations you can actually buy, manufacturers' catalogs are a useful tool for selecting the unit operations which we put into our plant designs. Updated catalogs also frequently include new items of equipment we might not have considered if we had not read the catalog.

Back when I only designed plants for a living, reading through the pile of supplier catalogs which had accumulated while I was engrossed in designing and pricing the last plant was a very useful way to spend the time waiting to be allocated my next job.

Nowadays these catalogs are more likely to be found on websites rather than in hardcopy, and this is very handy in an academic setting, allowing us to bring realism to our students' designs without bothering manufacturers with enquiries from students who are not actually going to purchase anything.

One thing which we find hard to recreate in the academic setting is interactions with technical sales staff. Their detailed knowledge of their products and their capabilities and limitations can allow plant designers to see new ways to design ourselves ahead.

Civil engineers are, by the way, often convinced that picking "gubbins" from catalogs is all process engineers do for living. This is a point they may make to you when you tell them they can't have the data they need to proceed with their design for a couple of weeks. (The standard riposte to this is to tell them that whatever you say, they will in any case specify the concrete wall they are going to design to be 150 mm of concrete containing two sets of #10 M rebar).

## Sources of design data

For the professional designer, the strength of sources of design methodology information is generally as follows:

↓
Close to full-scale pilot-plant trial;
Thoroughly developed and validated tailored modeling program directly based on many full-scale installations of exactly the type and size of plant proposed;
Supplier information;
Robust rule of thumb direct from a chartered engineer with lots of relevant experience;
Rules of thumb from a book by a chartered engineer;
Direct from a chartered engineer with little relevant experience;
First principles;
Guessing by a beginner;
Less than thoroughly debugged and validated simulation and modeling program output.

As far as sources of data required for inputting to design methodologies is concerned, strengths are generally as follows for feedstock and product qualities and quantities:

↓
Statistically significant ranges of values for the exact type and scale of plant envisaged.
Statistically significant ranges of values for the type of plant envisaged.
Ranges of values for the exact type of plant envisaged, falling short of statistical significance.
Ranges of values for the broad type of plant envisaged, with or without statistical significance.
Guessing by a beginner.

As far as thermodynamic and other physical and chemical data are concerned, the test of validity should be whether the data are intended by those generating it to be valid over the range of physical conditions likely to be encountered under all reasonably foreseeable plant operating conditions.

## Scale-up and scale-out

*In theory, there is no difference between theory and practice. But in practice, there is.*

***Yogi Berra.***

Theoretical types and scientific researchers fondly imagine that if a reaction works in a conical flask, getting it to work in a 100-$m^3$ reactor is a pretty trivial thing. If this were true, there would be no chemical engineers. There is a lot more to chemical engineering than chemistry.

There are two basic approaches to making a bigger plant. We can have a lot of parallel streams of unit operations which we know to work at the given scale (scale-out), or we can have a smaller number of larger but at least slightly experimental unit operations (scale-up).

What we need to know as engineers to carry out a scale-up exercise is the critical variable or dimension. This variable is the thing we need to keep constant (or vary in a predictable way) in order to get the process to work at the larger scale.

We might need to maintain the length, area, or volume of a process stage, or it might be more complex, such as a number of theoretical plates for a distillation column.

It should be noted that the key variable might change at different stages of scale-up as the balance of effects varies. Scale-up by a factor of more than about 10 (some say five) from even a good pilot plant study should make us quite nervous as designers.

We might also need to ask the chemists to go back and make the reaction work with less hazardous reactants or solvents, or in some other way restrict their freedom to get them to offer a process which can be made to work in a safe and economically viable plant.

There is a lot to this subject, but the main thing to grasp is that something working in a 250-mL flask is no guarantee at all that it will be cost-effective, safe, or robust in a 25-L vessel, let alone at full scale.

## Further reading

Coulson, J. M., & Richardson, J. F. (1995). *Chemical engineering: Fluid flow, heat transfer and mass transfer.*. Oxford: Butterworth-Heinemann.

Green, D. W., & Perry, R. H. (2007). *Perry's chemical engineers' handbook*. New York, NY: McGraw-Hill.

Hall, S. (2012). *Rules of thumb for chemical engineers*.. Oxford: Elsevier Press.

Sinnot,, R., & Towler, R. K. (2005). *Chemical engineering design* (Vol. 6). Oxford: Butterworth-Heinemann.

Woods, D. R. (2007). *Rules of thumb in engineering practice*.. Weinheim: Wiley.

# CHAPTER 13

# How to cost a design

## Introduction

> *Engineering ... to define rudely but not inaptly, is the art of doing that well with one dollar, which any bungler can do with two after a fashion.*
>
> ***Arthur Mellen Wellington.***

Engineering is a commercial activity. Sufficient effort is put into pricing at each stage of design to allow a rational commercial decision to be made as to whether to proceed to the next stage, but ideally no more. Costing itself has costs.

## Matching design rigor with stage of design

Conceptual design is sufficient for what contractors would call a budget estimate of costs. If you get a real budget estimate from a contractor, it will probably be accurate to around $\pm 30\%$, as they have lots of data from equipment suppliers and genuine knowledge of just what it costs to engineer and build plants.

Beginners without this information and experience can produce estimates out by several hundred percent (almost always underestimates). They tend to leave out everything other than the very core of the production process, have unrealistic ideas of the cost of engineering and construction, no knowledge of the cost of engineering by other disciplines, and so on. Many of my students also seem to be willing to forgo profit, which is the whole point of engineering. They certainly used to frequently forget to add it to their estimates.

Beginners tend to use exactly the same techniques and make the same errors if asked for a more accurate costing. Professionals working in contracting companies do a very detailed design and price all the goods and services required to supply the plant, consider risks, margins, contingency, and so on (or, if they don't work in a contracting company, they ask a favor of someone who does).

Engineers have (of course!) quantified this into five classes of estimate as given in Table 13.1. These are used by public bodies in the United States and worldwide (see also the *AACE Practice Guide* in "Further Reading").

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00014-8
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**Table 13.1** 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% |

## The basics

The most basic point of all is this: if you aren't considering price, you aren't engineering. Engineers consider the cost, safety, and robustness implications of every choice we make at every stage of a project.

I have worked in a few places where technical and economic evaluation have been split, and all of these have provided salutary lessons in why they should not be. Decision-making processes were very poor, and too easily swayed by fashion (yes, there is such a thing in engineering!) or the whim of managers.

The degree of confidence you have in your technical design is the maximum degree of confidence you should place in your costing. More usually we have to price in all kinds of other risk factors to arrive at a robust pricing. So, it isn't just a question of what the kit costs, risk has a price as well.

There are process risks—the more novel the process, the greater the chance it will underperform, or fail to perform at all. If your plant fails its performance test, your company will probably be paying penalties every day until it passes the test at your company's expense. You can buy performance bonds which will insure the process risk, but they cost money, and the more novel you have been, the more they are likely to cost.

There are financial risks—overseas contracts can be subject to currency fluctuations, and even domestic contracts can see significant inflation. Currency fluctuation can be a risk irrespective of whether the project is local or abroad because many equipment suppliers manufacture products overseas, exposing almost all equipment to such risk. If you have made heavy use of some material subject to large price fluctuations (which need be no more exotic than stainless steel), things can cost a lot more than you expected.

There are political risks—countries can fall out with each other, industries can be nationalized without compensation, wars can break out and, closer to home, regulation can disallow certain approaches, or make aspects of the design—for example, waste disposal—far more expensive than you originally costed for.

There are geographical risks—the first time you design a plant in a new region can reveal numerous unexpected challenges such as how to deliver goods to a site, what terms and conditions to use, supply chain risks, and special engineering considerations associated with the local environment (seismic zones, weather, etc.).

Sensitivity analysis is the key to understanding these risks and deciding how to price them. You are unlikely to win a competitive tender if you price all of them into your offer at 100% probability. A guide to the kind of price which is reasonable would be probability of occurrence multiplied by cost of occurrence. Many of your competitors in a commercial situation will, however, undercut this value considerably.

In commercial practice you need to consider all of these factors and produce a price accurate to a few percent. I know that many who have not worked in contracting doubt that you can do this, but a $\pm 10\%$ costing is no use if your profit margin is smaller than that, as it usually will be.

This price will need to be based upon a design which is optimized to meet the client tender evaluation criteria: lowest price that meets the specification, lowest whole-life cost, best net present value (NPV), fastest payback period—all affect every aspect of competitive design.

In one way or another, all design is competitive. Even if you are doing an in-house design, it needs to be the best design it can be against the evaluation criteria, and you can rest assured that when it goes out to the engineering contractor, they will be redesigning it as much as they are allowed, to maximize their profit and minimize their risks.

## Academic costing practice

In order to decide if it is economic to proceed with a design we need a quick way to estimate capital and running costs. The main plant items (MPIs)/factorial method is almost always used in academia (though far less commonly in practice).

Douglas (see "Economic potential" section below) offers a more sophisticated process compatible with academic use which increases in resolution as the project progresses, namely economic potential (EP). This is, however, frequently misused in academia—the more rigorous stages he proposes are left out, with the result that costing is reduced to the vestigial stub of an almost meaningless comparison of feedstock and product costs.

## Capital cost estimation by MPI/factorial method

This is standard academic practice. Academics and students cannot obtain supplier quotations for all of their equipment and engineering services as a professional would, so they need a stand-alone costing methodology for use in the academic setting.

Chemical engineering departments worldwide seem to do more or less the same thing.

First, they estimate the cost of MPIs, usually from cost curves: Timmerhaus and Peters (see "Further Reading") contains many of these curves. They then add factors to account for things like operating pressure, special materials, and so on, to the base costs for the curves.

Having added up all the MPI costs, they calculate installation and other engineering and construction costs as a percentage of MPI costs, using Lang factors such as those to be found in Chapter 6, Neglected industries; and processes of Sinnott and Towler (see "Further Reading"). This allows them to estimate the capital cost (capex) of the plant.

As well as the practitioner's critique, an academic criticism can be made of this near-universal academic approach, enshrined in Sinnott and Towler, the bible of academic design practice. Lang factors date back to the 1930s, and other more accurate factors have since been devised to replace them.

## Operating cost estimation

In academia, operating costs (opex) are usually estimated as a percentage of capital costs, often a nominal 10%. It is actually possible to get a lot closer to professional practice than this (even in a university setting) but very few in academia try, as far as I know.

Professionals estimate how much power, chemicals, manpower, capital, and so on will be required to run the plant, and price these inputs at market rates. There is no reason why even the most inexperienced student cannot try this approach, though obviously they will not be as good as the professional. My experience in asking students to do this in the past suggests they are not as terrible at it is as you might think they would be.

## Economic potential

Economic potential, as it is explained in Douglas's conceptual design of chemical processes, does start with a simple comparison of feedstock and product prices, but rapidly advances to a far more sophisticated accounting of costs and benefits than the standard MPI/factorial approach.

The approach makes a number of assumptions which mean that it is only applicable to a subset of process plant types but is in its appropriate setting superior in my opinion to the MPI/factorial method.

The very sketchiest version of EP (intended only for use before any design has been undertaken at all) is frequently nowadays the sole costing consideration in academic "plant design" exercises.

### Payback period, NPV, etc.

A slightly more sophisticated financial analysis can be undertaken in an academic setting, as it commonly is in professional practice.

The payback period tells us how long it takes to get back our capex from revenues/profits. NPV discounts future revenues and expenditure to reflect the fact that we care less about our money in the future than we do about our money now, and also inflation/interest rates on money.

NPV can incidentally be criticized, as large expenditures far in the future are automatically thought fairly unimportant. This can be used to justify projects with very high future decommissioning costs (such as, e.g., oil rigs and nuclear power plants) in ways which green pressure groups disagree with. Accountancy is not value-free.

### Sensitivity analysis

Even though academic costing methodology is necessarily a bit flaky, we can firm things up (or at least quantify our flakiness) with an honest sensitivity analysis.

Sensitivity analysis varies the costs and revenues which might apply to a system and considers the shape of the curves obtained. If profitability falls off sharply around your assumed costs and revenues, your process economics are not very robust.

I am personally not so bothered about whether students or other beginners get a realistic price, as whether they know how good their price is—give me a range in which the professional price lies, and a realistic estimate of where it is most likely to lie.

## Professional costing practice

I spent most of the first five years of my career producing proposals for turnkey plants for design and build contractors in the (ultra-competitive) international water industry. I was pretty good at it by the end, and I used to win quite a lot of contracts for the plants I designed and bid.

This was sometimes based on price and sometimes on technical merit. It isn't always about getting the lowest price on the table—it does usually help a lot, though.

I have been keeping my hand in during the intervening years and little seems to have changed other than that we now make a lot more use of computers and external design consultants that we used to.

### Accurate capital cost estimation

Usually, competitive bids are invited from potential suppliers for the various goods and services used to construct a plant before a process contractor makes a firm offer to an ultimate client. Three is usually thought a good number of bids to have for any

item. A smaller number means that there might be a limited number of places where that item can be obtained, which is risky. Inviting a larger number may be thought unfair by bidders, considering the cost they almost always bear of producing the bid documents. The better potential bidders might decline to quote.

Bids are checked by the party inviting bids against the specification, to ensure that all which has been asked for has been included (this is frequently not the case), and that the requested payment terms and other contract conditions have been explicitly complied with (also frequently not the case). Once bids have been standardized, prices are compared, and a supplier is selected on an "or approved equal" basis.

These prices constitute firm offers by third parties to supply the item for a given sum. They are not at this point estimates, they are guarantees to offer the goods for the price quoted.

Enquiry documents need to be detailed enough to allow suppliers to understand completely what is required both technically and commercially. If they are not, suppliers may decline to quote, or may price in the uncertainty.

Care must also be taken not to overspecify. Very often an equipment vendor needs a little leeway within acceptable standards to apply their product knowledge. Overspecification can lead to suboptimal offers, or even elimination of the best product for the job.

Purchasing companies will have their own terms, ultimate client companies will have theirs, and equipment vendors will have their own. It is frequently the case that enquiry documents will ask for quotations based on a combination of client and contractor terms, and vendors will offer their own terms in their offers. This is not a trivial matter, and the differences in prices between alternative suppliers can be less than the price implications of variation in contract terms. This issue will need resolving to obtain a firm price basis.

If you work in a process contracting organization, you may well have access to many such firm prices for exactly the kind of equipment you are pricing from previous jobs. The basis of your estimates can be very accurate indeed.

## Bought-in mechanical items

Professional engineers price unit operations as one or more purchased items of equipment (known as "bought in items," i.e., physical plant bought as discrete items) by sending enquiry documents to relevant equipment suppliers.

These prices usually have to have sums added to address the items the various suppliers have left out of their bids, so that they can be evaluated on a like-for-like basis.

They will probably also have sums included to reflect risk. For example, the fewer potential suppliers you have, the greater the risk that prices will rise, or that your equipment will not be available in time or at all.

## Bought-in electrical items

Control panels, aka motor control centers (MCCs), can be bought as a discrete item or along with electrical installation and/or software supply.

It will usually require input from an electrical engineer, and probably an element of in-house design to be able to produce sufficiently detailed enquiry documents to obtain reasonably accurate quotations for MCCs.

PCs, PLCs, DCS systems, or supervisory computers may also be bought as discrete items or integrated with the MCC.

If anything, greater care needs to be taken to adjust bids, and to price risks associated with these bids, than it does with those for mechanical equipment.

## Mechanical installation

Mechanical installers will usually supply (in addition to the skilled labor required to fix and mechanically commission the mechanical bought in items) the pipework, bracketry, supports, and so on required to make a working plant. They may also do detailed design of pipework support systems, supply any nonspecialized valves, and so on.

These bids are at best only as good as the drawings and instructions the bidders have been issued with, though they are less prone to underestimation and price escalation than electrical installation bids.

## Electrical installation

One of the biggest risks in the cost of electrical installation is due to the lack of understanding between electrical, control, and IT interfaces. The interface between these different disciplines is very often not understood and can cause overestimation due to double specification or, worse yet, underestimation due to items being left out.

The supply and installation of cables, emergency motor stop buttons, site lighting and small power, and making connections from MCC to motors will normally be the responsibility of a specialist contractor.

This element is possibly the most prone to underestimation by beginners. It is important to issue sufficient information to installers to make sure that everything needed has been accounted for and, ideally, the offer should be checked by an in-house electrical engineer.

Special consideration shall be given to high-voltage ($>1000$ V) works which are only carried out by a few specialist companies and therefore can attract a premium price.

## Software and instrumentation installation

This may be provided in-house or by some combination of MCC supplier and installation contractor. A specialist may be used to install and commission instruments, program PLCs, and set up SCADA, DCS, remote telemetry, and other such systems.

Whoever is doing it, great care has to be taken in pricing this element, as it is a major source of cost overruns at the construction stage, especially due to underestimation of the number of inputs and outputs to the system.

## Civil and building works

*How much is a ton of pumps?*

*Anonymous Civil Engineer*

Civil engineering companies work on very tight margins and tend to interpret their communications very literally. They work from drawings, so you need to make sure that anything issued to them for pricing is very clearly marked with respect to those elements which you are willing to stand by later, and those which are indicative only.

Their pricing methodology is based on counting tons of stuff. Once they have completed a design, they "take off" from their drawings how many tons of concrete, steel, and so on are required. They are consequently usually in a hurry to get their longest lead time item (design) started and will pressure you for the required information.

Civil works are most often scheduled at the start of a construction project. Civil engineers argue that they need to get their designs out first, but very often they have to wait until last for information. For instance, the vessel design must be almost complete before the civil engineer can start designing the foundations. Yet, the foundations must be in place before the vessel can be installed.

It is however prudent to wait until you have a reasonable degree of certainty before issuing documents to civil engineers, if for no other reason than because civil engineering companies have a reputation for being rather more litigious than other disciplines.

Civil and building costs are relatively easy to control as long as you have nailed down the usual "weasel words" in civil engineering pricing documents ("unforeseen ground conditions" for starters) during the initial stages.

## Design consultants

Nowadays, companies are increasingly using the services of design houses to carry out design, particularly for specialist items. If you are going to do this, you will need to price it in, and allow for the strong possibility of requirements for additional design work later in the project.

This can come to a surprising amount of money. At the time of writing, the market rate in the United Kingdom for an experienced process design engineer is approximately £150 per hour.

## Project programming

Professional engineers produce a schedule or program of events setting out the timescales for the key elements of the design/construction/commissioning phase and allocating resources against each of the tasks required.

This allows pricing of those items whose costs are based entirely on their duration of use (such as hire of site cabins) as well as indicating how many hours will be required for each discipline, and whether the company has the resource to handle the project in-house or will need to buy in (usually more expensive) external resources.

## Man-hours estimation

The plant design engineer will have produced their estimate of how many hours of engineering time for each discipline it will require to do the job, but the discipline heads within a company will also want to give their estimate of how long it will take their people to do it.

Since they are the ones who have to deliver the project, and the plant designer is responsible for winning the work, estimates from discipline heads tend to be on the high side, and those from plant designers on the low side. There should be some negotiation.

## Pricing risk

Once you have prices for all the goods and services you need to make the plant, you need to make sure that you have included a contingency allowance against the chance that process, financial, legal, political, or other risks go against you.

As well as adding sums to individual prices as previously described, you might do this formally by buying a form of insurance known as a performance bond, which usually costs a fraction of a percent of the complete contract value. You might add an overall contingency, which is built into your price. Alternatively, you might declare the risk to the client, and include a prime cost (PC) sum which you would charge if the possible adverse event materializes.

Sometimes, a formal risk register is required to get a full understanding of the risks and their potential cost impact. Contingency may then be split into known risk- and unknown risk-based elements. The known risks are on the risk register and will have an estimate or true cost associated to them, while the unknown risks are accounted for as a percentage of capex.

## Margins

Margins vary greatly from industry to industry. Back when I was pricing water treatment plants for a living in a very competitive sector, we were happy to get paid 22% more than our bought-in costs.

Some very sharp practitioners were bidding contracts at less than cost, by (many of us thought deliberately) leaving things out which had to be included later (under what are called variation orders, VOs) at top dollar.

Generally, the less money there is swilling around in a sector, the tighter the margins will be, and the sharper the practitioners.

## Competitive design and pricing

This is the only kind of design I know, and this book is based throughout on the assumption that process plant designers are doing it for profit rather than fun (though it is fun when you get the hang of it).

You can cut your margins of safety as far as you dare, you can negotiate with suppliers, discipline heads, and financial directors at the pre-tender stage, but you can only get so far by reducing your bought in cost and margins through arm-twisting or charm.

The way to win better contracts more of the time is to design yourself ahead. Don't do what everyone else is doing, but a little less well, for a little less money—do something better. That's why process engineers get the big bucks.

You don't need to be too radical to find all sorts of little ways to be a little bit cleverer than the other guy, and if you find enough of them you can win work with decent margins.

Much of it is to do with seeing the system working together as a whole and seeing the full implications of making small changes. It's all about system-level design.

## Accurate operating cost estimation

With a well-developed design, the contractor knows how many operator man-hours are required, and has an idea of what each discipline costs an employer. They know estimated chemical use and can calculate expected effluent costs with the Mogden formula (see Chapter 15: How to lay out a process plant). They have accurate estimates of hours run for motors and can forecast the price of electricity. They have maintenance schedules and costed spares lists obtained from suppliers, and so on. The contractor should consequently be able to cost the expected running cost for the plant to a high degree of accuracy.

## Further reading

AACE International. (2005). Recommended Practice No. 18r-97: Cost estimate classification system—As applied in engineering, procurement, and construction for the process industries (Online). <http://web.aacei.org/docs/default-source/rps/18r-97.pdf>. Accessed 24.10.18.

BNP Paribas Warranty Direct. (2018). *Reliability index* (Online). <http://www.reliabilityindex.com/manufacturer>. Accessed 23.10.18.

Peters, M., Timmerhaus, K., & West, R. (2003). *Plant design and economics for chemical engineers.*. New York: McGraw-Hill.

Sinnott, R., & Towler, G. (2009). (5th ed.). *Chemical engineering: Chemical engineering design*, (Vol. 6). Oxford: Butterworth-Heinemann/Elsevier.

PART IV

# High Level Design

# CHAPTER 14

# How to design a process control system

## Introduction

As Myke King (see "Further Reading") has pointed out, much of what is taught in chemical engineering courses under the heading of process control is out of date, irrelevant, and impractical, with the result that most new process plant designers have little idea of how to design the process control aspects of their plant.

Plant designers need to be able to specify control loops based on instruments and control actions which make the plant approximate a steady state under all the conditions which are reasonably likely (i.e.,within the design envelope) namely within:

- Normal operating limits (i.e., alarm set points);
- Safe operating limits (trip);
- Safe design limits (PSV/design pressure).

In order to do this, standard control approaches for unit operations are an excellent starting point. Harvey Dearden's view is as follows:

> *The focus of the process engineer is typically on maintaining a steady state around nominated operating points and, in that respect, they are prompted to place feedback loops around all the key variables—this is fair enough, but collaboration with a competent process control engineer will likely identify opportunities for enhanced regulatory control designs that will help the plant reject disturbances and migrate smoothly from one operating point to another. They will also allow effective co-ordination of series and parallel unit operation, for example, automatically transferring load to other boilers if a particular boiler should trip. Feedforward schemes are useful in anticipating the effect of disturbances and not simply waiting for the feedback loop to correct the error as it develops. There is a world of possibilities here—the main challenge for the process engineer is finding a competent process control engineer who has a proper appreciation of the process and its dynamics—many will simply slavishly provide what they were asked for. Much is made of sophisticated advanced process control technology, but a great deal can be achieved with intelligent use of enhanced regulatory control techniques that are immediately 'doable' with the toolset provided with modern control systems. Although advanced controllers may be 'sexy', what is often forgotten is that they typically operate by manipulating the set points of the basic regulatory control loops (flow, pressure, temperature etc.). If these are not effectively implemented, the advanced control capability will be severely compromised, and it often does not work as well in practice as expected.*

Another fellow engineer commented:

> *It is extremely common in oil and gas that we specify multiple complex feedback loops that run away, resulting in competing loops that compromise the system.*

Myke King advocates having sufficient consideration of process control issues to build controllability into the design, an approach developed more fully by Luyben (see "Further Reading"), albeit in quite a narrow field.

I see the rationale for Myke's version of this but I am not sure that Luyben's formal and simplified approach is as useful. Like so many elements of process design, academic approaches laboriously solve problems which can be better solved by simpler intuitive means.

I can see the need for integrating process design and control, but I would go further than Luyben does in a different direction, including under this heading things which might not be thought of as process control elements, such as hardware selection, hydraulic design for passive flow equalization, integrated consideration of process control and safety elements, and the interaction both of operating and maintenance manuals/operators, and functional design specifications/software. I give an example from my own experience of how this works in practice at Appendix 1, Integrated design example.

At the start of your professional career, the feedback you will hopefully receive from commissioning and control engineers or from attendance at HAZOPs should eliminate the features which can lead to poor controllability, but I would like to give you more of a head start than is presently on offer.

Integration of process control and design by professionals is far more intuitive and qualitative than mathematical. To quote Myke King:

> *It's a difficult subject. I've learnt how to design control strategies instinctively. I've been asked on many occasions to document a methodology. I've got as far as "Work in the industry for 40 years and you get the hang of it."*

Difficult it may be, but beginners definitely seem, in my experience, to need to be given a place to start. Interactions with more experienced engineers will refine their understanding, but what I think is needed in the first instance is a way, as an absolute minimum, to put the basics on the piping and instrumentation diagram (P&ID). That is what this chapter aims to provide.

## Matching design rigor with stage of design

At the conceptual design stage, very little or no consideration needs to be given to process control issues, unless the plant has some novel or very hazardous components, technologies, or process fluids, or a climate so extreme as to be likely to present entirely new or very high-risk process control problems.

At the detailed stage of design, a fully thought-out and instrumented P&ID needs to be produced, and ideally, precise models of instruments specified. As a minimum, realistic instrument choices and specifications should be produced. Instruments can be expensive and vary between manufacturers in their requirements and capabilities. The process engineer should know the relevant properties of the streams in the process (abrasiveness of a slurry, cloud point of a solidifying liquid, tendency to interfere with the optical clarity an instrument may need, etc.) and bring that knowledge to the control engineer in order to allow them to select the right instrument for the job.

Perhaps more importantly, the number of inputs and outputs to the control system cannot be determined unless the instrumentation has been thought through to this degree.

Modern instrumentation tends to be smart, with considerable onboard processing power. We need to decide how we are going to use this. Are we going to have smart instrumentation with dumb control, or dumbed-down instrumentation with smart control which might be important to minimize personnel exposure and/or optimize plant uptime.

And then there is the question of whether we are going to have a smart plant with dumb operators or a dumb plant with smart operators? Plants tend to be smart nowadays, but I was once asked to design a fully manual plant to be run by postdoctoral researchers. (Although postdoctoral researchers are not necessarily guaranteed to be smart operators!)

The software for a dumb plant is defined in the operation and maintenance manual, and for smart plants in the functional design specification (FDS). As most plants have some smarts nowadays, a combination of the two documents will be required to specify how the designer thinks the plant will be controlled.

## Operation and maintenance manuals

Operation and maintenance (O + M) manuals are written for (almost) every process plant, describing how it is to be operated and maintained, and how to troubleshoot any problems which occur. They certainly should be written (and they should also be read!).

They are to me largely a type of process control software since, on a fully manual plant, they describe in detail the control actions which people will undertake to achieve the things which a programmable logic controller (PLC) would do on a fully automatic plant.

Most plants are, however, not fully automatic. There are automatic control actions, and there are manual interventions. Some of these manual interventions are required by law. For example, in certain circumstances (such as motor overheating), the UK

IET regulations require motors to be stopped in such a way that they require manual intervention in order to be restarted. Other countries have analogous requirements.

Thus, some conditions are considered trivial enough to allow the system to automatically restart itself via remote command. Others, however, are thought dangerous enough that the system will force someone physically to go to the site and press a button before restart is possible; and the O + M manual will tell them that they must go and look at the kit before they press the button.

So, decisions have to be made about safe operation of the plant; and how software and operating procedures will work together to ensure safety.

Control philosophies always, to my mind, make implicit assumptions about how the plant will be operated. It is better to set out these assumptions in the document, as another reader may make different assumptions if they are not made explicit.

## Specification of operators

The level of education and training of operators and their availability has to be specified to determine the degree of automation which a plant requires.

In choosing whether to have a highly automated plant, one needs to consider the advantage of operators over instrumentation—operators can detect not just specified conditions, but unspecified and unexpected conditions.

The more we expect our operators to do about the things they monitor, the higher their required level of operator skill and understanding needs to be.

A fully manual plant will need a high availability of highly experienced staff. A fully automatic plant may need no permanent staff on-site at all, especially now that we can access plant telemetry and system control and data acquisition (SCADA) systems remotely via IP technology.

## Automatic control

We don't build fully manual plants in the developed world nowadays. Computers are too cheap and reliable, and operators too expensive (and human!), for routine operation activities to be best done by people alone.

Control is mostly done using a combination of PLCs, PCs, and high-level control system [distributed control system (DCS) or SCADA], though a few field-mounted controllers may also be specified for a number of reasons.

In the limited scenarios where field-mounted PID controllers are employed, they will have their own built-in control algorithms. Process plant designers do not write the software for these controllers. Commissioning or control engineers might undertake some tuning of the control loops, but even this would normally be achieved by by plugging in a laptop and pressing the "optimize" button on the manufacturer's

dedicated software. Commissioning (while very important) is not the subject of this book. Process plant designers need to know how to specify instrumentation and control hardware, populate their P&IDs with these items, and write FDSs so that software engineers can design and price their software.

Process plant designers need to have an idea of what neighboring disciplines do, and what they need to do their jobs. We don't, however, need to be able to do their jobs; we have to be broad-brush people. We don't sweat the details.

## Specification of instrumentation

Instrument engineers/technicians (aka "tiffies"—from the military term "artificer") have their specialisms, but we don't need to be one of them to specify instruments well enough to design a process plant. Table 11.8 should help you with this.

We should be willing to be corrected by a tiffy at more detailed design stages on details of instrument choice, as we should by other specialists.

It is, however, unlikely that a selection made by an experienced designer would not have worked at all. The specialist's choice might, however, work a little better (as long as they fully understand what we want the instrument to do).

## Precision

Precision in mathematics is (confusingly to engineering students) to do with what engineers call resolution. When I used to tell my students off for "spurious precision," this is the sense in which I was using it.

For example, in the filter pretreatment example in Appendix 1, Integrated design example, I say that we need control of pH to within 0.1 pH units. This is not the same as saying that we need control to within 0.10 pH units, which implies 10 times the (mathematician's) precision.

Precision in engineering is different and is to do with repeatability and reproducibility. It is not to do with how close the measured value is to the true value (accuracy) or the smallest change in the measured value which the instrument can detect (resolution). It is to do with whether the instrument will give me the same reading against the same true value the next time I test it.

We might further split engineering precision into reproducibility and repeatability, the first encompassing variability over time, and the second being precision under tightly controlled conditions over a short time period.

(I received a few comments from my correspondents about these definitions, and offers of alternatives, so it is fair to say that there is a problem with precision in the language of precision. These are the definitions I choose to use for the purpose of this book. To quote Humpty Dumpty: "When I use a word, it means just what I choose it to mean—neither more nor less".)

In my specific example, pH probes require regular recalibration against standards to maintain precision and accuracy. Over the period between calibrations, the accuracy (measured value for a given true value) varies. Eventually it is not possible to calibrate the instrument to give accurate readings against the standards, and a new probe has to be substituted. There are gradual decreases in accuracy, precision, and response time during the periods between new probe installations.

### Accuracy

Accuracy is to do with the gap between the true value and the value indicated by the instrument. In the filter feedwater treatment example mentioned above, I need pH to be controlled within the range around the set point $\pm 0.05$ pH units, therefore my measurement accuracy needs to be reliably at least this good.

### Cost and robustness

Instrument precision and accuracy both tend to cost money. Very precise and accurate (basically lab grade) instrumentation also tends to be less robust as well. Lab instruments tend not to be suited to field mounting. We therefore tend not to specify any more accuracy or precision than we strictly need, and we may take manufacturers' lab test values for an instrument with a pinch of salt.

All instrumentation needs to have a purpose to justify its cost. It may be true that "you can't manage what you don't measure" but it's also best not to measure things you don't need to manage.

### Safety

Safety-critical instrumentation requires a higher standard of evaluation than that which only affects operability, or less important still, process monitoring without associated control actions.

We might, for example, specify for a process or for a safety-critical reading the use of redundant cross-validated instruments (in which the reading most likely to be correct is determined by a voting system).

## Specification of control systems

The P&ID shows graphically, whilst the FDS describes in words, what the process designer would like the software to do. The job of the software engineer is to turn these deliverables into code.

PLCs are the basis of many modern process plant control systems, with DCS or SCADA supporting the control interface or HMI. The petrochemical industry uses PLCs only for low-level distributed control functions (often as part of vendor

packages) and prefers to use a combination of DCS and a supervisory computer for overall plant control. This allows for their more sophisticated control functions, which are at least as often retrofitted by control engineers as designed into the original system.

The true nature of the control system should be reflected on P&IDs and in FDSs. We should not expect to see a local control loop and field-mounted controller on a P&ID representing a loop which actually works via signals going out and back via PLC. There are appropriate symbols in the British Standard to show this correctly.

## Standard control and instrumentation strategies

In this section I will break down process control systems into some commonly used blocks, which should allow you to populate your P&ID and control philosophy with the standard features which appear on almost every plant.

I will assume that you know what feedback, feedforward, and cascade control are, but that the rest of your university module on process control focused more on mathematical software engineering stuff about transforms and algorithms. In 21st century process control, signal processing is built into the box, and algorithm writing is done by the software engineer, though they may well need input from the process engineer to do with outcomes of control functions.

Commissioning and control engineers who straddle the divide between process engineers and software engineers need a deeper understanding, but their jobs are very little to do with process plant design. Process plant designers do, however, need to understand what software and control engineers are going to need from them, so that they can design in controllability.

## Alarms, inhibits, stops, interlocks, and emergency stops

Process plant designers will need the assistance of electrical engineers to ensure compliance with the IET or equivalent regulations and the various European or other regional directives which apply to this area.

However, I have included this section because beginners usually do not understand that all electrical equipment needs to be easy to switch off in an emergency, and very frequently comes with safety features that switch it off automatically in a number of potentially hazardous situations. These might include such things as motor winding overtemperature, motor overtorque, fluid ingress, and so on.

It is frequently the case (and it may be a legal requirement) that the more hazardous of these cases will be set by the electrical/software engineers such that they require an operator to attend site to reset the "trip."

Less potentially serious conditions may stop motor operation only while the state is current or, if less serious still, may only prevent the motor from starting. Both of these conditions might be called inhibition.

All of these conditions will usually be set to generate local alarms in software. More serious ones may generate off-site alarms or activate an alarm beacon on site.

A design which has an excessive number of alarms should be avoided. If there are too many alarms, operators will be subject to alarm flooding, and develop what is known in health care as alarm fatigue and either ignore them or find ways to disable them. So, how many is too many? The Engineering Equipment & Materials Users' Association (EEMUA) suggests the following criteria (see Table 14.1).

Interlocks prevent operation during maintenance and other hazardous conditions, such as open equipment covers.

It should be noted that commissioning engineers frequently temporarily disable alarms and interlocks during the early stages of commissioning, but this should be a planned and highly controlled aspect of a commissioning procedure, and suitable substitute safety plans should be made. A good practice when closing a commissioning phase is to perform a "Start Up Safety Review": this consists of a check that all alarms and interlocks function as designed, and any added by commissioning staff are removed or approved in the presence of the process, software, and safety engineers.

Many of these signals, alarms, and interlocks will have to be handled by the control system, and leaving them out of the control system specification, if that is the case, is a classic beginner's mistake leading to cost overruns down the line.

Many are, however, wired directly into the motor starter, which eliminates a potential weak link in the chain. Hardwiring is standard for safety critical interlocks. For example, a thermal switch is commonly implemented as a hardwired interlock on centrifugal pumps, causing them to stop before damage. In some cases, the same strategy is used for high discharge pressure or discharge valve anomaly (valve closed on discharge line).

**Table 14.1** EEMUA criteria for acceptability of alarm rate in steady-state operation

| Long-term average alarm rate in steady operation | Acceptability |
|---|---|
| More than one per minute | Very likely to be unacceptable |
| One per 2 min | Likely to be overdemanding |
| One per 5 min | Manageable |
| Less than one per 10 min | Very likely to be acceptable |

Source: Courtesy: EEMUA Publication No. 191.

European (and other) standards also require the provision of emergency motor stop buttons immediately adjacent to motors. Resetting the emergency stop locally cannot incidentally allow the drive to restart, but there has to be a trip to reset on the motor control center (MCC) as well.

## Chemical dosing

There can be many nuances to design of dosing pump systems dealing with liquids which release gases on suction, leak detection, overpressure, cavitation, and so on, but I will deal here with the most common issues.

### *Pump speed control*

There are now digital dosing pumps like the one illustrated in Fig. 14.1 with integrated speed and stroke control on board, working from digital inputs originating in a flowmeter and pH probe.

However, it is still common to control a piston diaphragm pump's motor speed with a 4–20 mA signal from a flowmeter in the stream to be dosed. This is known as

**Figure 14.1** Memdos Smart LP: stepper motor-controlled dosing pumps offering smoother, almost continuous, dosing. *Courtesy: Lutz-Jesco.*

flow pacing, and when used in conjunction with stroke length control as described in the next section, it can give very accurate ( ± 0.1 pH units) pH control.

On the other hand, some engineers use simple speed control proportional to the difference between measured pH and set point. This is okay, but not as precise as flow-paced stroke control unless the flow into which we are dosing is always constant.

A more old-fashioned way to do this simple type of control is to send pulses to the pump at a frequency corresponding to the desired stroke frequency. Commonly available pumps and pH controllers can usually handle both pulsed or 4–20 mA control signals.

### *Pump stroke length control*

A 4–20 mA signal from a dedicated pH controller can be input to a suitable flow-paced dosing pump to control stroke length, giving a robust two-variable control of chemical dose (Fig. 14.2).

**Figure 14.2** Memdos E ATE: mechanically actuated diaphragm dosing pump with inverter controlled motor and actuator/servomotor for automatic stroke length adjustment. *Courtesy: Lutz-Jesco.*

### *Actuated valve control*

Some plants are still built using an actuated valve to add chemicals by gravity into a mixed tank but, to put it very politely, this is a bit old hat nowadays. Control loop time is long, chemical flow control is pretty rough, and the homogeneity at the point of pH measurement is questionable.

## Compressors/blowers/fans

### *Positive displacement*

Positive-displacement blowers need similar control systems to positive-displacement pumps (see later), though the compressible nature of gases makes these systems a little more forgiving than their liquid equivalents.

### *Centrifugal*

Centrifugal compressors (Fig. 14.3) are more efficient at large sizes than positive displacement blowers, but they are more difficult to control. They are therefore quite often favored where there are high fixed flows.

They are, however, capable of variable output. Back when I started as an engineer, we used to do this on single-stage compressors with variable position inlet guide vanes, and on multistage compressors with inlet throttling valves, but nowadays inverter control is usually favored, especially on larger units. I recently bought two different-sized compressors from the same company (Siemens). I challenged them to give me the most economic control arrangement for both. From a purely economic point of view, the guide vanes were more economical on the smaller compressor and the variable-speed drive (VSD) more economical on the larger compressor.

Surge conditions—in which too low a flow causes a sudden powerful reversal of flow—have to be avoided, and this is usually achieved via an "antisurge" control valve in a bypass back to the compressor suction. (In some cases, surge may result in catastrophic failure of the compressor.) There may be one of these valves for each

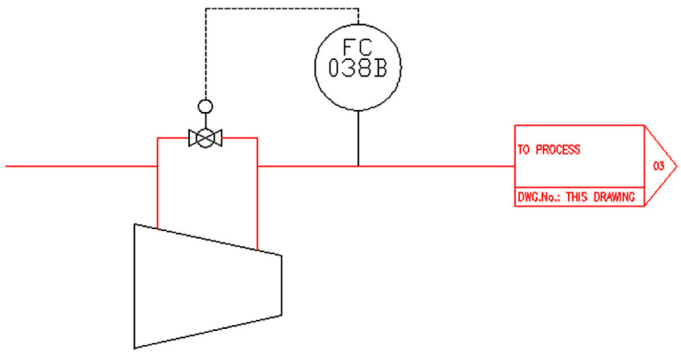


**Figure 14.3** CAD representation of centrifugal compressor control.

compression stage, going back to the inlet of that stage. (For some machines, a very fast and specialized control scheme may be required.)

Such valves may also be used to control flow through the compressor if inverters are considered too expensive. As inverters become relatively cheaper all the time, I would predict that this will eventually become an obsolete approach although the need for antisurge valves may remain in the oil and gas sector because of the potentially destructive aspects.

## Distillation

There are many processes and measured variables which we might consider—which of the 120 possible permutations will we pair to which? There is a lot to this area, and for more detail I recommend Myke King's book, a chapter of which is dedicated to what he considers a broad outline of the subject. I have illustrated in Fig. 14.4 his basic suggestion, which is essentially pressure controlled.

## Filters

### *Backwash control*

The standard methodology for differential head control of particulate water filters is that accumulated dirt is removed by reversing flow through the unit, known as backwashing (Fig. 14.5). This is done periodically on the basis of a number of criteria:

- Differential pressure (almost always);
- Time since last backwash (almost always);
- Queueing/hierarchy of wash initiation (very frequently if there are filters in parallel);
- Outgoing turbidity (fairly rarely);
- Outgoing particle size analysis (very rarely).

Each filter will therefore need measurement of incoming and outgoing pressure, via separate instruments or a differential pressure instrument. There will usually also be a timer in PLC software (or less frequently nowadays in MCC hardware). Queuing, if required, will be handled in PLC software.

Solids removal efficiency can be measured online via turbidity or particle size analysis. Turbidity measurement is reasonably cheap and robust, though it adds complexity which is usually redundant. Particle size analyzers are very expensive and fragile kit, and best avoided if at all possible.

There will need to be a backwash pump, whose output flowrate is crucial to effective backwashing. An associated flowmeter is therefore required. The backwash flow needs to be high enough to effect dirt removal, though not so high that the filter is damaged, but the acceptable range of flows is usually fairly broad.

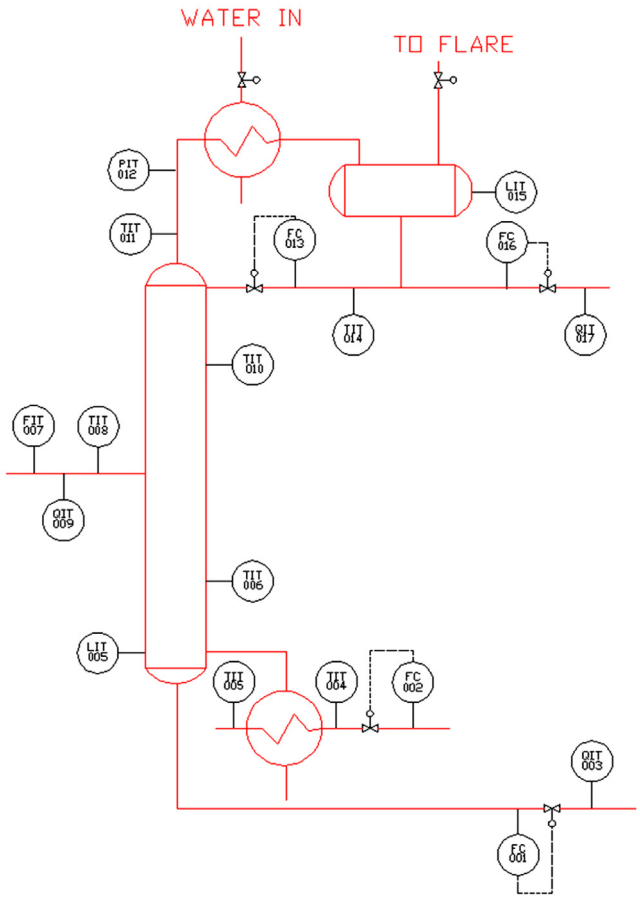


**Figure 14.4** CAD representation of distillation column control.

It is therefore usually the case that the commissioning engineer sets this flow by throttling a manual valve or setting a range of inverter outputs, and thereafter it is just monitored and returned to commissioning values by maintenance staff if required. We may, however, sometimes specify a more sophisticated system with temperature-dependent flow control of the backwash pump to ensure a constant mass rather than volumetric flowrate during backwashing.

## Chemical cleaning control

Membrane filters often require a chemically enhanced backwash (CEB) in addition to simple backwashing (Fig. 14.6). While the control of this is quite sophisticated, based on analysis of trends in differential pressure across the membranes compared with the original condition and the condition after the last backwash, the instrumentation and

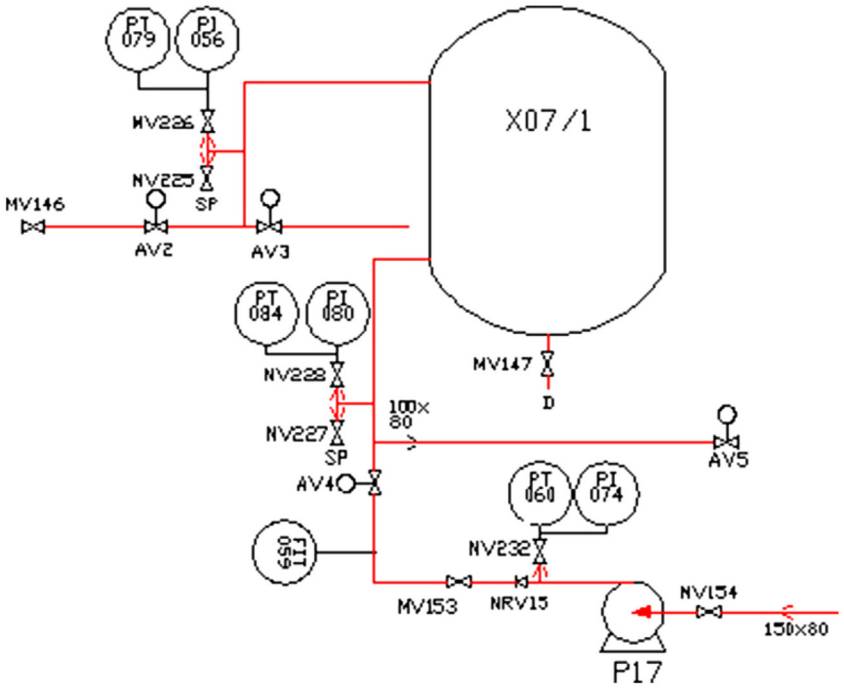


**Figure 14.5** CAD representation of backwash control.

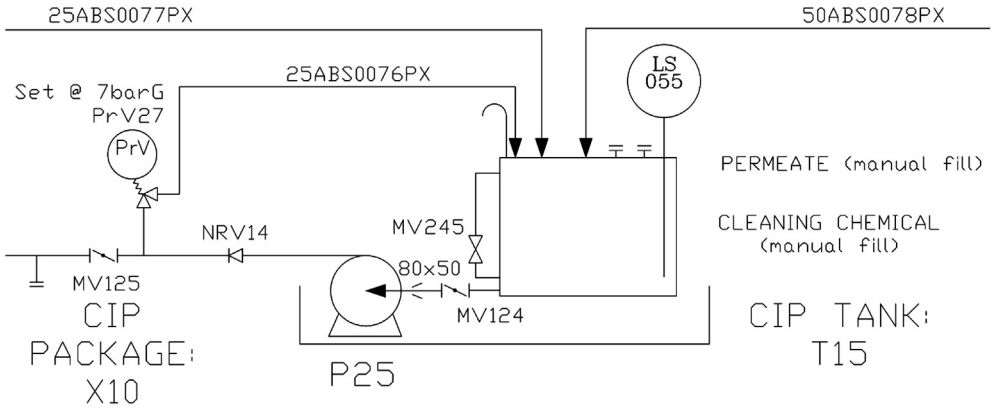


**Figure 14.6** CAD representation of chemical cleaning control.

available control actions are basically the same as for simple backwashing. The modifications to backwash frequency, cleaning chemical type and strength, and so on, which are instituted in response to declining membrane performance, are usually manually initiated.

The CEB system's tanks, dosing and centrifugal pumps, flow control, and so on are controlled as described in their respective sections of this chapter. If a heated

backwash is used, there is a control loop which modulates the output of a process heater in response to a temperature measurement. This loop may well be critical—such systems (most notably the very expensive membranes themselves) are often made of polymers which can be damaged by even quite moderate excessive temperatures.

## Fired heaters/boilers

Fired process heaters have to account for variation in composition of feed, and variation in pressure in the case of gaseous fuels. It may also be the case that the heater feed flow cannot be controlled, as its feed is the product of another process and cannot be economically stored.

One way around this is the dual-firing option shown in Fig. 14.7. The heater duty is set above that of the greatest expected yield of uncontrolled feed gas, and a second fuel is added as required to top up the heater output to the duty required based on the temperature of the fluid being heated.

This is a very complex area, which Myke King discusses in some detail in his book Process Control: A Practical Approach from which Fig. 14.7 is adapted.

As he explains there, boiler control is essentially the same as fired heater control except that the control is via steam header pressure rather than based on heated fluid temperature. He also draws attention to the difference in control requirements for fixed-duty (baseload) boilers and the assist (swing) units which are used to control the steam pressure.

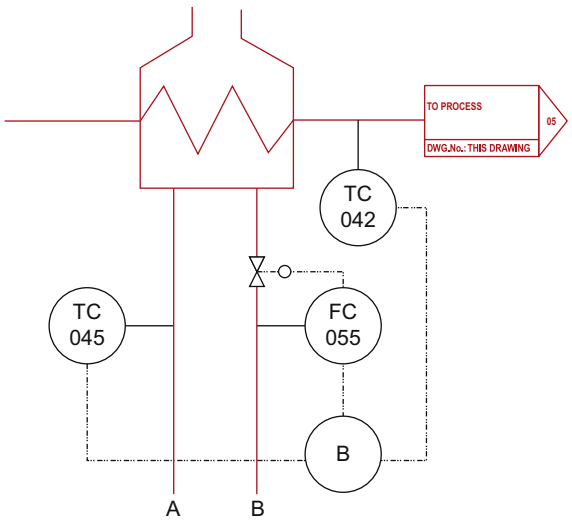


**Figure 14.7** CAD representation of fired heater/boiler control.

## Heat exchangers

Heat exchangers (Fig. 14.8) are usually designed to have temperature sensors in both process and service streams going in and coming out. It is possible to vary the service flowrate to control process stream temperature. Tighter control is, however, given by bypassing the process side with a control diverter valve in the bypass, thus modulating throughput whilst maintain overall flow. When this valve is operated, the temperature changes almost immediately. Care must be taken if this approach is followed to prevent excessive fouling or scaling due to lowering flow rates through the equipment.

## Pumps: general

### *Dry running protection*

Many pump types are damaged if they run without liquid for any length of time, so control loops are used to prevent this and are a standard feature of pump configuration (Fig. 14.9). The most common variant is an interlock between pump running or starting and the level in a tank feeding the pump, such that low level in the feed tank inhibits pump running and/or starting.

Ultrasonic, radar, hydrostatic, or float-type level sensors are most commonly used to provide the level signal. Float switches are very cheap, ultrasonics are good for noncontact measurements of aggressive liquids and powders, and hydrostatic or radar types are good if there is likely to be significant foaming. An interlock can be wired directly into the motor starter from the sensor, or control can go via PLC.

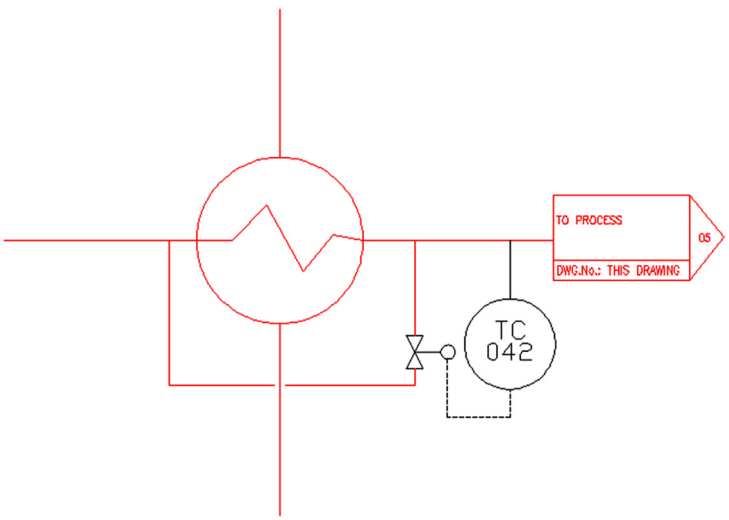


**Figure 14.8** CAD representation of heat exchanger control.

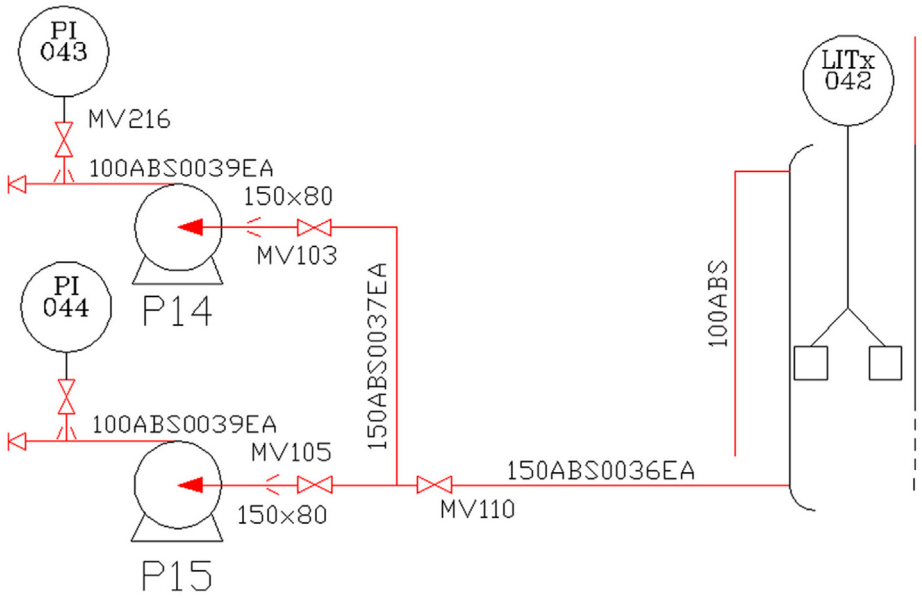


**Figure 14.9** CAD representation of dry running protection (of P14/15 by LITx0420).

### *No-flow protection*

Many modern flowmeters can detect empty pipe conditions, and this can be used as a secondary measure to prevent dry running (Fig. 14.10). Alternatively, flow switches can be used for this duty. This is sometimes hardwired into the starter. Going via the control system is, however, probably best so that a timer can be placed in the loop to help commissioning engineers to prevent nuisance trips from transient conditions, especially in the case of flow switches. "Tuning fork" switch sensors are commonly used to detect the level rising/falling below a specific point or to detect the presence/absence of liquid at a given point in a line. They are commonly used for dry-run protection on pumps.

### *Overtemperature protection*

Most electric motors come with thermistors incorporated in the windings, so that drives can be stopped automatically if they are getting too hot. This safety-critical interlock is usually hardwired into the starter.

## Pumps: centrifugal

Centrifugal pumps (Fig. 14.11) are not immediately damaged by being operated against a closed valve (though they can overheat in fairly short order and even water pumps have been known to suffer steam explosion) but throttling their suction can cause immediate cavitation.

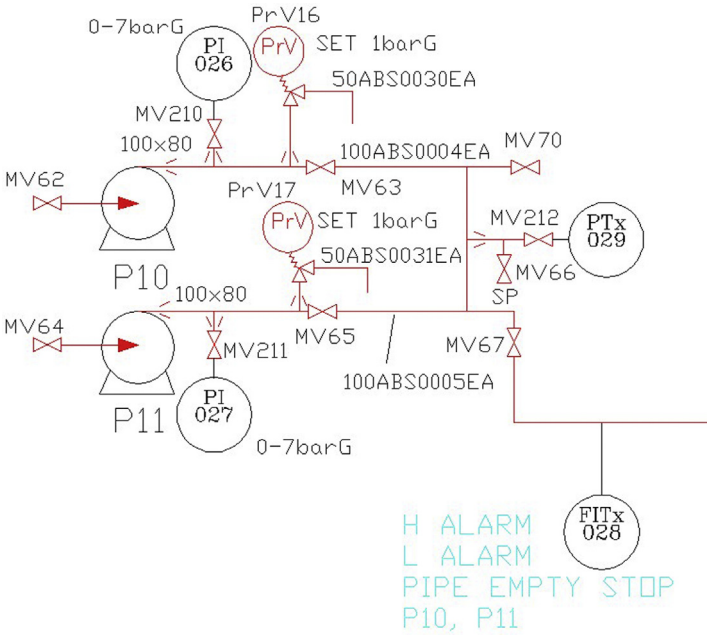


**Figure 14.10** CAD representation of no-flow protection (by FITX028).

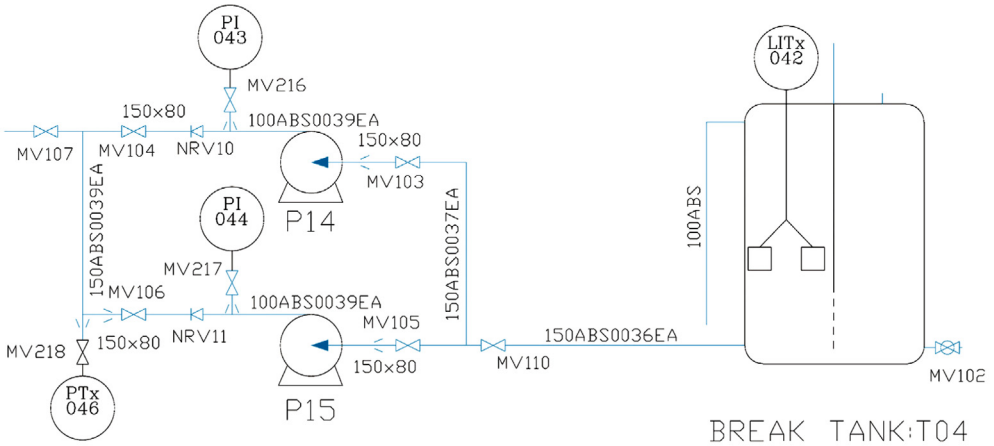


**Figure 14.11** CAD representation of centrifugal pump control.

Their output can be controlled by running them against a control valve in the delivery line, or by a bypass valve returning output to pump suction, though I personally prefer to use the more efficient inverter control. Others favor mechanical

minimum flow valves, on the grounds that they are extremely reliable and often cheaper than the control system alternative. This approach however prioritizes capex over opex and sets aside the greater energy efficiency of the inverter.

Flow delivered by a rotodynamic pump is inversely proportional to system pressure (though $Q/H$ curve shapes differ), but a flowmeter on the delivery side can be used to control the degree of actuated control valve opening or inverter frequency to accurately deliver the desired flowrate against variable delivery pressure.

Centrifugal pumps offer no resistance to reverse flow (and can generate unwanted electricity if run backwards), and protection is sometimes put in to address this, though nonreturn valves are usually thought sufficient protection if their (approximately 10%) backflow prevention failure rate is acceptable.

## Pumps: positive displacement

Positive-displacement pumps (Fig. 14.12) are quickly damaged by being run against a closed valve on the delivery side, and are not usefully controllable by throttling on either side. You can control them to some extent with a valve on a bypass to suction, but very accurate control can be given using an inverter drive.

I would still recommend the use of a flowmeter to modulate the bypass valve position or inverter frequency. While delivered flow is largely independent on backpressure, wearing parts in these pumps may cause delivery volumes to drop during the intervals between servicing.

These pumps are normally protected from damage caused by downstream valve closing or other line blockage with a pressure-relief valve, placed between the pump and the first valve downstream.

## Pumps: dosing

The most modern digital dosing pumps have on-board integrated stroke speed controls, driven directly by digital signals. Fig. 14.13 shows the pressure-relief valve (PrV2) which protects against pump damage in the event of line blockage, as well as the pressure-sustaining valve and pulsation damper which remove flow pulsations.

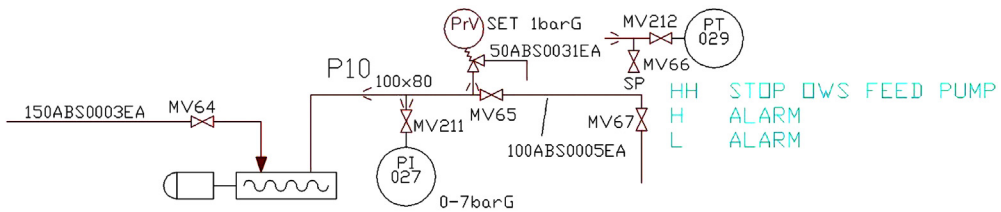


**Figure 14.12** CAD representation of positive-displacement pump control.

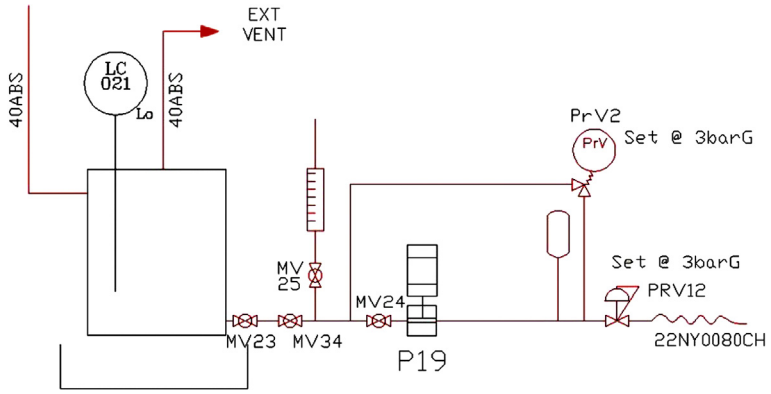


**Figure 14.13** CAD representation of a positive dosing pump control.

High High High HHH Alarm, Stop P12 and P13
High High HH Start Assist pump
High H Start Duty Pump
Low L Stop Assist Pump
Low Low LL Stop Duty Pump
LOE (X2) Alarm, Stop P12, P13, (P18 AND P19,
P20, P22

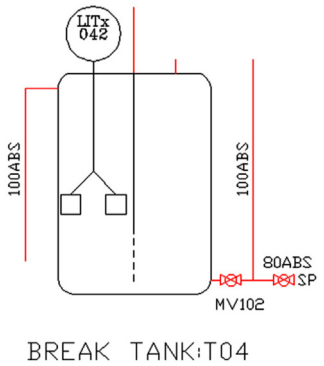


**Figure 14.14** CAD representation of break tank filling and emptying control.

Piston diaphragm pumps commonly come with two 4–20 mA inputs for control. One controls motor speed, the other stroke length. Solenoid pumps are far simpler (and cheaper); their solenoid produces a stroke for every pulse of power sent to it.

There is more detail on dosing pumps in the "Chemical dosing" section of this chapter.

## Tanks

Whilst they are not favored by those who like elegant solutions (and are ideally made as small as possible), buffer tanks (Fig. 14.14) make for a flexible and robust plant design and allow smoothing of disturbances in feed rates to downstream units.

Breaking the plant into sections ending/starting with a buffer or break tank is a solution favored by most commissioning engineers, as it makes it easy to commission the plant in sections.

Pumped flows can be ramped up and down, based on levels in the feed and/or delivery tanks, in such a way as to maintain either a fairly constant tank level, or a fairly constant flow. Note that tight level control will mean upstream disturbances are immediately propagated into the downstream (turning a buffer vessel into an expensive piece of pipe!). For smoothing purposes, we want the level to vary to absorb fluctuations in flow. Specific control approaches can be employed for this purpose. In either case, rapid changes in flowrate and on/off control of pumps should be avoided. Smoother operation is normally better operation.

Tanks and other holding vessels generally require a working level range in which the level of the tank can fluctuate freely without affecting the rest of the plant. Finding the most suitable device for measuring levels in vessels can be very tricky, depending on the liquid to be measured. The ultrasonic and hydrostatic types of level sensor—which measure level continuously, rather than trip at a threshold level—are therefore preferred.

Ultrasonic or radar level indicator controllers can typically handle this control function well using their on-board electronics. Foaming can however cause problems for them, in which case the hydrostatic type is better.

## Valves

Fig. 14.15 shows how an on/off actuated valve can be used to control the level in a tank. There are some details of the nature of control valves which are not commonly explained in university courses and which I will cover in the sections which follow.

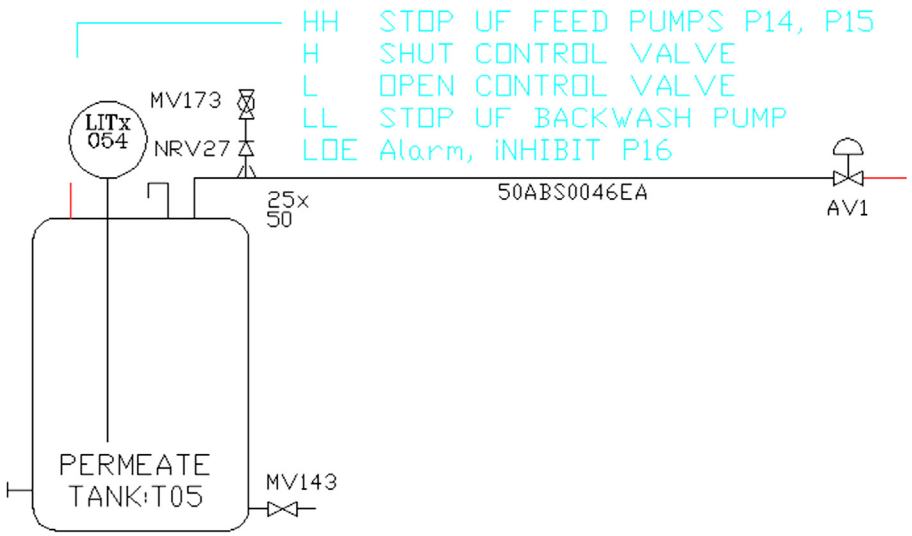


**Figure 14.15** CAD representation of an actuated valve control.

**Figure 14.16** Rotary actuator. *Courtesy: AUMA.*

### *Rotary actuators—modulating duties*

Globe valves used in a modulating duty require multiple controlled turns to go from open to closed, and consequently require multiturn rotary actuators, which are most frequently electrically driven (Fig. 14.16).

Butterfly and ball rotary valves go from open to closed in 90° of shaft rotation, and "quarter-turn" actuators are used to operate them. Such actuators may be electrically or pneumatically driven. They are typically actuated with a linear piston or diaphragm actuator acting through a linkage mechanism, but some rotary action actuators are also available.

### *Linear actuators—open/closed duties*

There are linear actuators which are used in a vertical orientation with globe and other rising spindle-type valves, usually in on/off applications (Fig. 14.17). This type is typically actuated by pneumatic piston or diaphragm linear actuators. Electrical actuators suitable for modulating control are also now available.

### *Valve positioner/limit switch*

Valve positioners are self-contained controllers using stem position feedback that drives the valve to the commanded position. They are useful in overcoming the effects of

**Figure 14.17** Linear actuators (*painted red*). *Courtesy: Ascendant.*

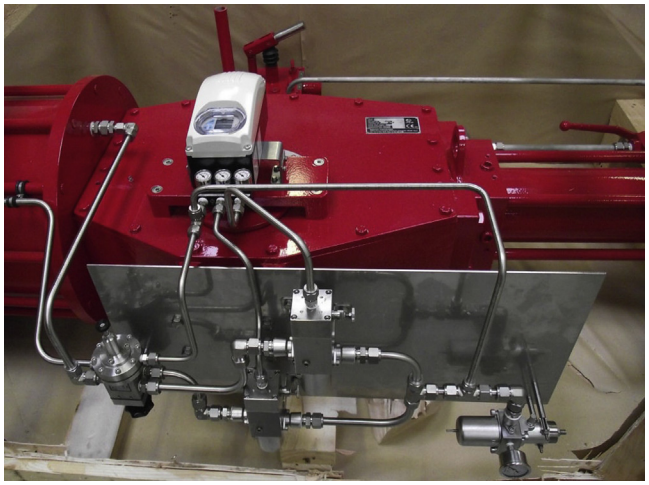

**Figure 14.18** Valve positioner/limit switch. *Courtesy: Ascendant.*

line pressure forces and stem/seat friction which might otherwise introduce poor positioning accuracy. Limit switches tell the system when the valve has reached a certain position, so that it can be reliably driven to a certain degree of opening (Fig. 14.18). This gives a positive indication that the valve has in fact reached the desired position. This is not a guarantee of a given valve headloss or throughput, but it does increase the accuracy of operation considerably.

## Further reading

Ali, R. (2013). Keep it down. *The Chemical Engineer*, November 2013.
British Standards Institute/Institute of Engineering & Technology. (2018). *Requirements for electrical installations, IET wiring regulations* (18th ed.). BS 7671:2018.
Dearden, H. T. (2018). *Functional safety in practice* (2nd ed). CreateSpace Independent Publishing.
King, M. (2010). *Process control: A practical approach*.. Chichester: Wiley.
Luyben, W. L. (2011). *Principles and case studies of simultaneous design*.. Chichester: Wiley.

# CHAPTER 15

# How to lay out a process plant

## Introduction

This chapter is based on the IChemE book *Process Plant Layout*, of which I produced an updated second edition in 2016. Its first edition, published in 1985, was written by a small committee, mostly of senior practitioners, led by an academic researcher, Dr. John Mecklenburgh. Although I spent a few years in an academic role (at the same institution where Mecklenburgh worked before his premature death), I am a practitioner rather than a scholar and have personally designed and laid out many process plants. Nonetheless, I tried at first to follow the lead of the first edition in offering academic references wherever possible to support the text.

However, I soon discovered that this was not going to be possible in the vast majority of cases, because there has been almost no professionally relevant research in this area since the first edition was published. Indeed, plant layout has all but disappeared entirely from universities, both as a taught subject and a research area.

The update was therefore based on my own professional experience and personal research into how modern practicing engineers lay out process plants. Despite all of the scientific references cited by Mecklenburgh, professional experience was in fact the true source of its most useful and enduringly correct content. Layout design is—and always has been—a practical, rather than a theoretical business.

There has more generally been a loss of drawing and visual/spatial skills from chemical engineering courses. Many universities (to the extent that they use drawings at all) accept Google Sketch or MS Visio sketches which bear no resemblance to engineering drawings. They restrict even these drawings to block flow diagrams or weak approximations of piping and instrumentation diagrams (P&IDs).

Good plant layout is however still just as important as ever. A study by Kidam and Hurme (see "Further Reading") showed that 79% of process plant accidents involved a design error, and the most common type of design error leading to accidents was poor layout.

In this chapter I have attempted to summarize current best practices in layout design, which is based in codes and standards; and in design experience, modified to suit individual circumstances by multidisciplinary design review.

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00016-1
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Layout design practice nowadays is practiced by process engineers, piping designers/engineers, and process/technical architects. However, there are differences in approach between these disciplines and between industry sectors which mean that there are now a number of species of plant design, with very limited interactions, or even awareness of each other (and don't even get me started on the attempts by mathematicians in academia to treat plant layout as if it were a mathematical problem).

For example, how layout is done in the oil and gas industry (where piping engineers are key to plant layout) now differs greatly from how it is done in the pharmaceutical industry, where process architects are taking a lead far more often. How it is done (and who does it) on small plant designs differs radically from how it is done on larger ones.

Even the language used to describe key documents and parts of the plant differs in complex ways. The meanings of "plot," "site," "plot plan," and "general arrangement drawing" not only differ between designers, but they differ in ways which are not simple substitutions of terminology.

## What is layout design?

The discipline of layout design is concerned with the spatial arrangement of process equipment and its interconnections, such as piping.

Good layout practice achieves a balance between the requirements of safety, economics, the protection of the public and the environment, construction, maintenance, operation, space for future expansion, and process needs. It will also consider weather conditions, country-specific legislation and regulations, as well as esthetics and public perception.

There are three main approaches to layout design. These are the chemical engineer's approach, the piping engineer's approach, and the process architect's approach. Table 15.1 illustrates where such approaches are likely to be followed, and the characteristics of the approaches.

Each of these disciplines may lead the layout design process, or provide the primary model used for the process. Other disciplines will be involved, but one of these three disciplines will tend to set the approach to layout design.

Chemical or process engineers will always be involved in layout, as they are required in all cases to size the unit operations (process equipment) and, to some extent, to set out their mutual interrelationships in space. They may do little more than this, they may lead the process, or they may do all of it themselves on smaller plants in certain sectors.

Piping engineers are often used where there is a lot of complicated and expensive pipework, for example in the traditional bulk chemical or oil and gas industries.

**Table 15.1** Discipline-based approaches to plant layout

| Discipline | Industries | Primary focus | Approach | Strengths/weaknesses |
|---|---|---|---|---|
| Chemical engineers | All process industries | Unit operations | Highly mathematically modeled engineer/scientist | Strong on process knowledge and mathematics/science but may lack intuition/creativity/practicality |
| Piping engineers | Traditional oil and gas, heavy chemical, nuclear | Pipework/steelwork | Intuitive/artisanal mechanical design draftsman/engineer | Strong on effective traditional approaches, spatial intelligence but may lack knowledge of why things work, lack of process knowledge |
| Process architects | Indoor plant such as fine chemical, pharmaceutical, nuclear | Buildings | Philosophically inclined technical artist/design draftsman | Strong on esthetics, spatial intelligence, may lack process knowledge, mathematics/science. May underemphasize commercial factors. |

Architects are often used where there are significant numbers of buildings, or where the plant must be integrated within a building. In recent years, architects have become increasingly responsible for the layout of indoor process plants as part of the building design.

## Terminology

The term "plant layout" in my book's original title was used generically, as it still often is, to mean all aspects of process production facility layout. However, even this usage is incompatible with the present legally defined meaning of the term "plant." So, at the outset, we need to distinguish between the layout of the various plots within a site, the arrangement of plots within a plant, and, finally, the detailed arrangements of both equipment and piping within a plot.

Layout designers disagree about what constitutes plant, site, and plot layout, what the various layout drawings are called, and even what people responsible for layout design are called. This disagreement occurs less *within* disciplines and within industries than it does *between* disciplines and industries, but even within a discipline in a single industry sector there can be a surprising lack of consistency. I have used definitions of

the terminology consistently, in order to clarify the text, but I make no claim that these are the "correct" definitions, only that these are the ones I am using, and that they are perhaps the most commonly used ones.

By standardizing definitions in this way, we can see that there is a common core approach to laying out plants which represents the heart of universal best practice. In addition, there are a number of variants that represent sector- or discipline-specific best practice.

Fig. 15.1 illustrates, in simplified form, a process production facility or "site" which can be defined, in summary, as "...bounded land within which a process plant sits." A site may contain a number of process plants, as well as nonprocess plant and buildings. In Fig. 15.1 the site is in gray.

A "process plant" (or more simply "plant") is "a complete set of process units and direct supporting infrastructure required to provide a total operational function to produce a product or products...".

Plants may be arranged across a number of plots: "An area of a site most commonly defined as being bounded by the road system..."—which is bounded, as implied by the definition, by plot roads. Plots are shown in aqua in Fig. 15.1.

The term "plant" is sometimes (but never in my books) used by practitioners synonymously with "plot," reflecting the reasonably common occurrence where a plant occupies a single plot.

Within the discipline of layout design, a distinction is commonly made between piping layout (defined here as "the layout of piping and associated support systems...") and equipment layout ("layout at the level of a single process unit and associated ancillaries"). Either of these disciplines may also be known colloquially (but never in my books) as plant layout.

Initially, plot layout is mostly equipment layout, and piping layout only comes in at the detailed design stage.

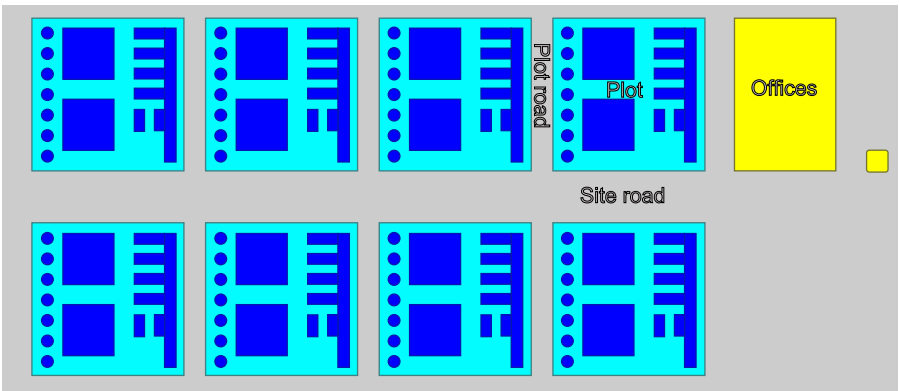


**Figure 15.1** A process production facility and its constituent parts.

## General principles

We need to consider layout in sufficient detail from the very start of the design process. Even at the earliest stages of design, attempting to lay plant out will throw up practical difficulties.

Layout is not just a question of making the plant look pretty from the air (or more usefully from public vantage points). The relative positions of items and access routes are crucial for plant operability and maintainability, and there are more detailed site-specific considerations.

The three key elements which have to be balanced in plant layout are cost, safety, and robustness. Thus wide plant spacings for safety increase cost and may interfere with process robustness. Minor process changes may have major layout or cost consequences. Cost restrictions may compromise safety and good layout.

The layout must enable the process to function well [e.g., gravity flow, multiphase flow, net positive suction head (NPSH)]. Equipment locations should not allow a hazard in one area to impinge on others, and all equipment must be safely accessible for operations and maintenance.

As far as is practical, high cost structures should be minimized, high cost connections kept short, and all connection routing planned to reduce all connection lengths.

Layout issues at all design stages are always related to the allocation of space between conflicting requirements. In general, the object most important to process function must have first claim on the space. Other objects must fit in the remaining free space, again with the next most important object being allocated first claim on the remaining space. The constraints always conflict, and the art of layout lies in balancing the constraints to achieve an operable, safe, and economic layout.

Layout most obviously affects capital cost, since the land and civil works can account for 70% of the capital cost. Operating costs are also affected, most obviously through the influence of pumping or material transfer cost and heat losses, but more subtly in increased operator workload caused by poor layout.

The layout must optimize the consequences of a process accident and must also ensure safe access is provided for operation and maintenance. Things further apart are less likely to allow domino effects from explosion, fire, or toxic hazards, but it is likely that lack of space means that complete mitigation of fire, explosion, and toxic risk will not be achievable by separation alone.

Layout starts by considering the process design issue of how the equipment items function as a unit and how individual items relate to each other.

For example, the individual items in a pumped reflux distillation unit should be close together for effective fluid flow and minimal heat loss. The condensers and

drums should be near ground level to reduce the cost of associated structures, but the drums must be elevated to provide NPSH for the pumps. Such relationships may sometimes be identified by a study of the process flow diagram or P&ID, but not all will be as obvious as this example. This is where a general arrangement (GA) drawing, experience, and judgment become vital to find and balance the physical relationships in the layout.

There are many other factors to consider. Equipment needs to be separated in such a way that it can be safely accessed for maintenance, for other safety reasons such as zoning potentially explosive areas, and to avoid unhelpful interactions.

Exposure of staff to process materials needs to be minimized. Access to areas handling corrosive or toxic fluids may need to be restricted. This may require the use of remotely operated valves and instruments located outside the restricted area.

In a real-world scenario we will have a site or sites to fit our plant on to. Different technologies will have a different "footprint." They will have a required range of workable heights and overall area. They may lend themselves better to long thin layouts or more compact plants.

There may be a choice to be made between, for example, permanently installed lifting beams, davits, and so on, more temporary provision, or leaving the eventual owner to make their own arrangements.

There are no right answers to these questions, but professional designers will need to have given these issues sufficient consideration to be able to argue that they have exercised and documented due diligence. In the United Kingdom, the minimum extent of this due diligence is specified in the Construction Design and Management (CDM) regulations. More generally, more or less all countries have a regulatory framework which governs "due diligence."

Layout does not require complex chemical engineering calculations but it does require an intuitive understanding of what makes a plant work, commonly known as professional judgment. If it were more common, we might call it "engineering common sense."

These qualities cannot be taught formally but must be acquired through practice. It is, however, possible to start the learning process in an academic setting by design practice, though judgment will mostly be developed in professional practice.

Mastery comes only from learning from experienced practitioners and by testing one's own ideas rigorously. The best way to do this is by listening to those who build, operate, and maintain the plants you design for 15 years or so, and adopting their good ideas (no matter how embarrassing the learning process might be during layout reviews).

Generally speaking, the most economical (and easiest to understand/explain to operators) way to lay out a plant is for the process train to proceed on the ground as it proceeds on the P&ID, with feedstock coming in on one side, and product out of the far side of the site or plot. There may, however, be arguments for grouping certain

unit operations together in a way which does not correspond with the P&ID order if the site is on multiple plots with any degree of separation.

Land is cheap in some places and expensive in others. Tall plants are generally more favored away from human habitation, but some municipalities will tolerate big ugly plants if they create jobs. Such places might also be happy to have quite dangerous processes close to human habitation, as we were before we could afford to be as fussy as we are now.

## Factors affecting layout

Layout is, in short, the task of fitting the plant into the minimum practical or available space so that each plant item is positioned so as to balance the following competing demands.

### Cost

- The capital and operating costs must be affordable (e.g., placing heavy equipment on good loadbearing ground).
- The plant must be capable of producing product to specification with the practical minimum levels of operation, control, and management.
- Regular maintenance operations should be capable of being performed as quickly and easily as is practical. Units should be capable of being dismantled in situ and/or removed for repair.
- The plant must be arranged so as to promote reasonably rapid, safe, and economical construction, taking into consideration staging of construction/length of delivery period.

### Health/safety/environment

- Ensure that safe and sufficient outgoing access for operators, and incoming access close to units for firefighters are designed in.
- Operating the plant must not impose unacceptable risk to the plant, its operators, the plant's surroundings, or the general population.
- Operating the plant must not impose excessive physical or mental demands on the operators. Manual valves and instruments, for example, need to be easily accessible to operators.
- Design out any knock-on effects from fire, explosion, or toxic release.
- Avoid off-site impact of noise, odor, or visual intrusion, mainly by moving such plant away from the boundary and communities and presenting nice offices and landscaping to public view.
- The plant, whether enclosed in buildings or outdoors, should not be ugly through uncaring design but should blend with its surroundings.

## Robustness

The plant and its subcomponents must be so arranged as to operate and make its product(s) as specified:

- Process requirements must be met (e.g., arranging plant to give gravity flow).
- The plant must be designed to operate at the planned availability and should not be subject to unforeseen stoppages through equipment failure or malfunction.
- Consider how the plant might be expanded in future, allowing space and connections to do so easily.
- Consider access to commissioning resources in layout.

## Site selection

The site layout must provide a safe, stable platform for production over a period which might be measured in decades. It is essential to define, early in the design process, if the site is to be used by the designer or others for a single plant or if several plants are to be installed either now or in the future.

If future plants are planned, some assessment of future development is needed. It might be that space needs to be reserved, road networks planned, and major utility distribution expanded to serve the new plants. When a site specification is drawn up, the site layout aims to make the best use of all features of the site and its environs, for example:

- site topography;
- ground characteristics;
- natural watercourses and drainage;
- climate;
- external facilities;
- water, gas, electricity supplies;
- effluent disposal services; and
- transport of people and goods.

Due care and attention also needs to be given to the effects of the plant on the site surroundings, especially:

- housing;
- hospitals, schools, leisure centers;
- other plants;
- forests, vegetation;
- wildlife;
- rivers and groundwater; and
- air quality.

If we have a number of candidate sites which we need to choose between, the following factors should be considered at a minimum:

- desired layout of the proposed complex;
- cost, shape, size, and contours of land/degree of leveling and filling needed;

- loadbearing and chemical properties of soil;
- drainage: natural drainage, natural water table, and flooding history;
- wind: direction of prevailing winds and aspect, maximum wind velocity history;
- seismic activity;
- legacies of industrial activity such as mine workings, chemical dumps, and in-ground services;
- ease of obtaining planning permission; and
- interactions with both present and planned future nature of adjacent land and activities.

Many of these are environmental factors. We can split them into three categories: natural, manmade, and legislative.

## Natural environment

Weather varies greatly from place to place. Singapore has lightning on average 186 days a year. Cherrapunji in India had 2.5 m of rain over 2 days in 1995. Death Valley has air temperatures of up to 57°C, and Antarctica down to −89°C. A gusting wind speed of 300 mph was once recorded in Oklahoma City. There may also be sandstorms, earthquakes, tsunamis, floods, snow, hail, fog, and so on to consider.

Could our pipes freeze, or could they be softened by foreseeable ambient temperatures? How much rainwater might we need to handle? What earthquake and wind loadings do we need to specify? All need to be considered from the start.

Well-designed plants are site-specific: process plant designs cannot be cut and pasted from one location to another, as a *TCE* article (see "Further Reading") suggests is occurring in Southeast Asia.

## Manmade environment

At the detailed design stage, we will need to consider the possibility of effects on and interaction with surrounding plants, installations, and commercial and residential properties.

In the United Kingdom, this is likely to involve interaction with regulators such as UK Department for Environment, Food & Rural Affairs, the Environment Agency (EA), and planning authorities.

## Regulatory environment

The likely effluents, emissions, and nuisances (gaseous, solid, and liquid, as well as noise and odor) and any abatement measures need to be considered at the earliest stage.

It should not be assumed that regulatory authorities will allow any release to environment, or sewage undertakers allow any discharge to sewer without discussion with them.

As well as the question of simple permission, there will be the question of emission quality, which will set the size and cost of on-site treatment, or the ongoing bill for third-party treatment. Not all effluents can be economically treated on site, and third-party costs can be very significant, so this needs to be considered at the earliest stages of design.

In the United Kingdom, third-party costs can be predicted using the Mogden formula (Eq. (15.1)).

$$C = R + M + Vm + V + Bv + \frac{OtB}{Os} + \frac{StS}{Ss}$$

where

*R* is Reception charge
*V* is Primary treatment charge (also referred to as *P*)
*M* is Treatment charge where effluent goes to a sea outfall
*Bv* is Biological treatment charge (also referred to as *B*1 and *Vb*)
*Vm* is Preliminary treatment charge for discharge to outfalls
*B* is Biological oxidation charge (also referred to as *B*2)
*S* is Sludge treatment charge
*Os* is Chemical oxygen demand of settled sewage
*Ss* is Suspended solids concentration in crude sewage

**Equation 15.1** Mogden formula.

Mogden formula calculators are also widely available online.

It should be borne in mind that the regulations which cover releases to environment always become more stringent over time. Future-proofing might be considered. If you are not going to include additional plant, you need to at least allow space for potential growth and expansion.

## Plant layout and safety

### General principles

The IChemE book *Process Plant Design and Operation* (see "Further Reading") contains the following suggestions about the safety implications of plant layout:

> *Incompatible systems should be separated from each other; humans from toxic fluids; corrosive chemicals from low grade pipework and equipment; large volumes of flammable fluids from each other and from sources of ignition; utilities should be separated from process units; pumps and other potential sources of liquid leakage should where possible not be located below other equipment to minimize the chance of a pool fire. (This is particularly important with fin-fan coolers where air movement may fan the flames).*

The Health and Safety Executive (HSE) states that the most important aspects of plant layout affecting safety are for our designs to:

> *. . .prevent, limit and/or mitigate escalation of adjacent events (domino); Ensure safety within on-site occupied buildings; Control access of unauthorized personnel and Facilitate access for emergency services.*

So, the advice is fairly consistent. A well-run hazard and operability (HAZOP) should pick up any issues in this area, but designers should not go in to a HAZOP with ill-considered layouts which will require extensive modification. HAZOP is not supposed to involve redesign. Safety studies should be carried out as part of the design exercise, as described in Chapter 16, How to make sure your design is reasonably safe and sustainable.

As well as these guiding principles, there are many detailed considerations, such as siting dangerous materials as far as practical from populations and control rooms, considering plan operability and maintainability, safe access and loading/unloading of deliveries and collections, and so on.

Regulatory authorities including DEFRA, the EA, and planning authorities (or such equivalents as may exist in other countries) may want to place restrictions on the design with respect to siting, distance of certain structures from people, height of certain structures, size of inventory of specified substances, releases to environment, and so on. These issues need to be considered as soon as possible in the design process. Certain types of plants, especially those likely to be covered in Europe by Control of Major Accident Hazards (COMAH) legislation will need special attention.

There are various codes of practice and guidance notes which address plant layout issues, as well as many specific codes for specifics such as installations handling liquid chlorine. A good place to start with these, especially for UK readers, is the HSE website (see "Further Reading"). The Dow/Mond indices are also explained there—these can be used at an early design stage as rules of thumb to give outline guidance on equipment spacing. I include further international references in Chapter 16, How to make sure your design is reasonably safe and sustainable, which is specifically on safety. However, the general principles designers most need to bear in mind are those of inherent safety and risk assessment.

## Separation principles

The following principles should be followed for separation of source and target:

- Large concentrations of people both on- and off-site must be separated from hazardous plants.
- Ignition sources must be separated from sources of leakage of flammable materials.

- Firebreaks should be included and are often best provided by a grid-iron site layout.
- Tall equipment should not be capable of falling on other plant or buildings.
- Drains should not spread hazards.
- Large storage areas should be separated from process plant.
- Central and emergency services should be in safe areas with emergency access to and from outside the facility.

Further data on recommended separation distances are set out in Appendix 3, Plant separation tables. These are of course for guidance only and should be subject to the application of engineering judgment.

## Plant layout and cost

As far as capital cost is concerned, the further apart things are, the more piping and cable will be required to connect them. In addition, placing things further apart also requires more steelwork and concrete, land, and buildings to support and contain them. Smaller plant often costs more than less space-intensive plant, but land costs money too.

With respect to operating costs, things which are further apart have higher fluid transfer head losses, higher cable power losses, and higher heat losses from hot and cold services. It also takes more time to go from one part of a larger plant to the next.

There will be a balance to be struck between capital and operating costs, as designers need to think of how every item of equipment will be maintained, how motors and other replaceable items will be removed and brought back, and how vehicles required by operational and maintenance activities will access the plant during commissioning and maintenance activities as well as during normal operation.

A few cost-saving guidelines are as follows:

- Buildings should be as few in number and as small as practical.
- Gravity flow is preferred and, failing that, pump NPSH should be minimized.
- The number and size of pipes and connections should be the minimum practical.
- Save space and structures wherever possible (consider safety!).
- Group equipment where practical and safe.
- Make multiple uses of structures, buildings, and foundations.
- Make full use of the height available.
- Consider column locations when laying out equipment in a building/choosing building type.
- Don't bury services under buildings.
- Storage tanks can be made of welded steel, bolted glass on steel panels, site-cast concrete, preformed concrete, plastics, and composite materials. All should be considered and have implications for layout with respect to construction access.
- Ground conditions can affect the economics of concrete tankage—it might most economically be fully in-ground, fully out, or intermediate depending on the water table and how hard it is to dig, etc.

- Ground conditions can also affect civil costs of locating heavy structures on a site. Put them where the ground is good.
- Structure loading can interact with ground conditions—heavy structures can have a low loading by being shorter and wider. This can be in tension with the process design if a tall thin structure is required.

Having considered the most practical issues, we need to remember that we may need to make our plant acceptable to the public (and their proxies, the planning authorities) if it is to be built. It matters what it looks like.

## Plant layout and esthetics

Esthetics can be very important to engineering designers, but it is more or less absent from engineering curricula. Esthetics falls within the province of philosophy, or maybe psychology, which is bad news for any hope of coming up with any definitive answers. Philosophers have yet to find a definitive answer to any of the questions which they have been pondering for a couple of thousand years now.

Personally, I like the look of process plants, and I think that great big flames coming out of the tops of flare stacks look very cool. However, this is a minority opinion (though it is one shared by Ridley Scott, who incorporated the appearance of the Wilton chemical plant near his boyhood home into his film Bladerunner). Most people don't like the appearance of process plants. Neither do they like how they sound and smell, the associated vehicle movements, or the effect on their house prices.

Architects can help us with esthetics, though this may come at a price. Fig. 15.2 shows a sewage pumping station designed by an architect for the London 2012 Olympics.

This will usually be another issue settled by negotiation. Generally speaking, we would like our buildings to be unadorned big metal sheds, and planners (and the general public) may ideally like them to be ancient oasthouses saved from demolition by being lovingly rebuilt on our site to contain our process plant.

This seemingly strawman example actually comes from my past experience—I recall one job where, after negotiation, we ended up with a row of token cowls of the sort seen on oasthouses on a big tin shed, more than a hundred miles from the nearest real oasthouse.

All of this aside, we will need to care about esthetics, because the planning authorities do (and some would say that good engineering is rarely ugly). The cost implications of building something to the standards required where we will attract NIMBY ("not in my backyard!") resistance might make it more economical to build it where people care more about jobs.

Architects will know the rules under which planners have to work, and the ones who know how big a brick is are our best source of information on how to satisfy the planners at least cost. The artist/philosopher type of architect will be far less helpful to

**Figure 15.2** London 2012 Olympic park pumping station. *Courtesy: Olympic Delivery Authority.*

us than the other kind. It might be an idea to ask any architect you are considering using how big a brick is [215 mm ($L$) × 102.5 mm ($W$) × 65 mm ($H$) is the right answer] and save yourself a lot of heartache.

Practical architects may also help us to produce a plant which is a more pleasant and efficient place of work. Staff morale is important—some even think it improves performance.

## Matching design rigor with stage of design

### Conceptual layout

Conceptual design aims to do enough work on layout to ensure that the proposed process can fit on the site available, and to identify any layout problems which need to be addressed in more detailed designs.

From a regulatory point of view, you need to establish whether enhanced regulatory environments like COMAH or Integrated Pollution Prevention and Control (IPPC) are going to apply to the plant and design your layout to suit.

There are a number of issues which might be neglected at early-stage design by beginners.

#### *In which direction is the prevailing wind?*

Upwind/downwind positions can matter, for example, pressure vessels should not be downwind of vessels of flammable fluids, toxics should not be upwind of offices/

personnel/significant community population, and cooling towers need to be as far away as possible from anything which would interfere with airflow, and so arranged as not to interfere with each other.

### *Indoor or outdoor?*

You also need to decide on whether you want indoor or outdoor plant. Good lighting, ventilation and air conditioning, protection from excessive noise, glare, dust, odor, and heat help staff to do their work well, so indoor is often the most comfortable for operators. Indoor is more secret, easier to keep clean, and indoor equipment usually has a lower IP rating, making it cheaper to buy. Outdoor plant is, however, usually best for toxic and flammable vapor dispersal, and buildings cost a lot of money.

## Construction, commissioning, and maintenance

Designers need to consider all stages of the plant's life, and specifically vehicle access and space for removal and laydown of plant and subcomponents like heat exchanger tubesheets.

There may also be a requirement for tankers and temporary services for maintenance, commissioning, and turnaround activities. This should be identified and accommodated early in design.

Maintenance activities also need to be covered—instruments and plant requiring regular attendance and maintenance should be reachable by short, simple routes from the control room and mounted at a location that can be reasonably accessed without scaffolding and/or ladders (transmitters, for example, may be between 3 and 5 feet off the ground). This is also particularly important with batch processes, which often require a lot of operator intervention.

Where equipment is to be maintained in situ, space needs to be left for people and tools to reach equipment for inspection and repair, the lifting gear required, and laydown for parts, and the design needs to consider accessing different levels in the plant via ladder or staircase, and how to get tools to the working level.

Where it is to be maintained in the workshop, space should be allowed for people and tools to reach equipment for inspection, disconnection, and reconnection, the lifting gear required for removal and replacement, and loading/unloading onto transport to workshop or off-site.

In either case, the working area should be designed to be safe with respect to access, lifting, confined space entry, electrical and process isolation, draining, washing, and so on.

Items requiring regular access for operation, maintenance, or inspection should not be in confined spaces or otherwise inaccessible.

### Materials storage and transport

The size of on-site materials storage and transport facilities will be determined in the first instance by practical issues of import and export from site of feedstocks, products, and waste material. It should be noted that there may be a choice of road, rail, and water transport to be made. Larger volumes of transport may be best handled by rail or water transport, if practical.

The process's requirement for storage and transport facilities will need to be moderated by statutory and commercial standards and codes of practice, as well as planning authority requirements.

There is commercial software that allows the designer to overlay a vehicle turning circle over a road layout to check that the roads are suitable for the proposed use, but I offer guidance in the following section on suitable road and turning circle sizes which can be used in the absence of such software.

Materials storage and transport considerations will form part of the layout safety review and will probably need to be at least justified and possibly reconsidered as part of planning and permitting applications.

The provision of utilities such as steam, compressed air, cooling, and process water and effluent treatment facilities needs to be considered at the earliest stage, as their design needs to be well integrated with that of the whole plant.

### Emergency provision

I give relevant dimensions for fire appliances to allow designs of suitable roads, hardstanding, etc. to ensure suitability of access provision for emergency use in my *Process Plant Layout* book. To summarize, roads need to be at least 4 m wide, suitable for 20-ton vehicles, with turning circles of at least 21 m. About 5 m of hardstanding needs to be provided 5–10 m from buildings and items which might require firefighting.

### Security

As soon as equipment is on-site, we will need a site fence to protect company and staff property from theft and prevent unauthorized access for safety reasons. We may want, in some cases, to design out any features which could shelter protestors at the site entrance or make plant buildings amenable to occupation.

### Central services

Admin, welfare facilities, labs, workshops, stores, and emergency services need to be well-sited, and should be featured on designs from an early stage.

### Earthworks

Earthworks may be required to shield tanks of dangerous materials or controls from the site fence. If we are close to communities, we might also want to consider bored

teenagers with air rifles. I once had a site where we had to put bulletproof shields on all emergency shutdown switches visible from the fence, to protect them from target practice, and another where we had to erect sight screens during commissioning to stop them shooting at anyone in hi-viz.

## Conceptual layout methodology

Different layout designers and companies may have their own specific methodologies (as discussed in Appendix D of my *Process Plant Layout* book), but my simplified version of Mecklenburgh's method for initial layout, outlined in Table 15.2, is my base case.

**Table 15.2** Summary of conceptual/FEED layout methodology

| Step | Description |
|---|---|
| 1 | Generate initial design, sizing, and giving desired elevations of major equipment |
| 2 | Carry out initial layout safety review or apply MOND index; consider all relevant codes and standards |
| 3 | Produce plan view GA of plant based on these data and the suggested spacings in Appendix C (it may help to cut out paper shapes to scale and arrange them on a large sheet of graph paper before proceeding with CAD) |
| 4 | Question elevation assumptions, consider and cost alternative layouts |
| 5 | Produce simple plan and elevation GAs of alternatives without structures and floor levels |
| 6 | Produce more detailed plan GAs based on decision for last stage |
| 7 | Use this drawing to consider operation, maintenance, construction, drainage, safety, etc. Consider and price potentially viable alternative options |
| 8 | Consider requirement for buildings critically. Minimize where possible |
| 9 | Produce more detailed GAs in plan and elevation based on deliberations to date |
| 10 | Carry out informal design review with civil engineering input based on this drawing |
| 11 | Revise design based on this review |
| 12 | Hazard assess the product of the design review. Determine safe separation distances for fire and toxic hazards, zoning, control room locations, etc. Consider off-site effects of releases |
| 13 | Revise design based on layout safety review |
| 14 | Confirm all pipe and cable routes. Informal design review with electrical engineer would be helpful |
| 15 | Multidisciplinary design review considering ease and safety of operation, maintenance, construction, commissioning, emergency scenarios, environmental impact, and future expansion |
| 16 | Reconcile outputs of design review and layout safety review, taking cost into consideration |
| 17 | If they will not reconcile, iterate as far back in these steps as required to reach reconciliation |

## Detailed layout methodology

Detailed design broadly replicates the stages outlined above in more detail.

The detailed design stage for plants of any significance should include a number of formal safety studies, as well as less formal design reviews. These should address layout issues as well as the process control issues which may form the core of such studies. Details of recommended formal safety studies can be found in Chapter 8 of my *Process Plant Layout* book.

If it is identified that the site will comprise a number of plots, interactions between these plots and with any existing ones on the site and those on surrounding sites need to be considered at the detailed design stage.

A detailed design procedure bringing together plot designs into a site-wide design for multiplot sites is summarized in Table 15.3.

Reviews at this stage may be undertaken in a 3D model in the "richer" industries, such as oil and gas, but many industries will still proceed with 2D hardcopy drawings.

**Table 15.3** Summary of detailed design layout methodology

| Step | Description |
|---|---|
| 1 | Compile the materials and utilities flowsheets for piping and conveyors as well as vehicle and pedestrian capacities and movements on and off-site |
| 2 | Lay out whole site, including areas for the various plots, buildings, utilities, etc. |
| 3 | Use the flowsheets to place plots and processes relative to each other, bearing in mind recommended minimum separation distances, sizes, and areas |
| 4 | Add in services where most convenient and safe from disasters |
| 5 | Place central services to minimize travel distance (but considering safety) |
| 6 | Consider detailed design of roads, rail, etc., keeping traffic types segregated, and maintaining emergency access from two directions to all parts of the site |
| 7 | Identify and record positional relationships between parts of the plant/site which need to be maintained during design development |
| 8 | Hazard assess site layout, with special attention to the possibility of knock-on effects |
| 9 | Single discipline design review (chemical; electrical; civil; mechanical): representatives from design and construction functions should critically review the design from the point of view of their discipline |
| 10 | Multidisciplinary design review: the various disciplines should critically examine the design with respect to hazard containment, safety of employees and public; emergencies; transport and piping systems; access for construction and maintenance; environmental impact, including air and water pollution and future expansion |
| 11 | If there is still more than one possible site location at this point, the candidate sites can be considered in the light of the detailed design, and one selected as favorite |

## "For construction" layout methodology

After site purchase, a detailed design to optimize the site to its chosen location can be undertaken.

It is usual for there to be considerable pressure on resources at the design for construction stage. This, taken with the common requirement to run design and procurement together, works against the idea of any further detailed design review as a practical solution. In any case, the great cost of changing layout at this stage means that any design errors which are less than catastrophic may best be left as they are. It may be best not to expend resource in order to discover minor errors which will not be corrected in practice.

## Further reading

Bausbacher, E., & Hunt, R. (1993). *Process plant layout and piping design*. Upper Saddle River, NJ: Prentice-Hall.

Eades, J. (2012). It couldn't happen here. *The Chemical Engineer*, *857*, 26–28.

England & Wales, Health and Safety Executive. *Technical measures document: Plant layout* (Online). (n.d.). <http://www.hse.gov.uk/comah/sragtech/techmeasplantlay.htm> Accessed 25.10.18.

Moran, S. (2016). *Process plant layout* (2nd ed.). Oxford: Butterworth-Heinemann.

Scott, D., & Crawley, F. (1992). *Process plant design and operation: Guidance to safe practice*. Rugby: Institution of Chemical Engineers.

Smith, P., Beale, R., & Bowers, P. (2017). *The planning guide to piping design (process piping design handbook)* (2nd ed.). Houston, TX: Gulf Professional Publishing.

# CHAPTER 16

# How to make sure your design is reasonably safe and sustainable?

## Introduction

Why is Health, Safety, and Environment (HSE) our number one concern? Process engineering (especially water process engineering) saves far more lives than the best medical practitioners ever will, but we can do harm on an industrial scale as well.

Back when I applied to be a chartered engineer, the only aspect of professional practice in which experience had to be demonstrated by all applicants was "safety aspects of process plant design and operation." I consider the subsequent removal of this requirement to be a mistake, as you can become a chartered chemical engineer now without having experience in this area. You cannot, however, become a good engineer without this experience.

Consider, for example, the worst doctor who ever lived. He might have killed a few hundred people over a long period of time. Bad engineering, on the other hand, could kill tens of thousands of people in a day.

The most pressing argument for the prime importance of safety issues is the more or less universal ethical one that people should not die or be injured so that we can make money. The argument for avoidance of environmental degradation is weaker. Many societies are willing to tolerate a degree of environmental degradation in order to industrialize and develop, just as the industrialized West once did. The IChemE sustainability metrics reflect the engineer's views on this, which are a fair bit more rational than the views of some environmental pressure groups and anticapitalist protesters.

## Why only reasonably?

Engineers make decisions on the basis of more or less formal cost–benefit analyses. We know that as we try to move toward perfect safety and sustainability, each incremental improvement becomes progressively more expensive. If the appetite for risk was zero and everything had to be inherently safe we would never do anything.

This fact is accommodated by United Kingdom and European law by the terms "as low as reasonably practicable" and the even uglier acronym SFAIRP (so far as is reasonably practicable), which define the required standards of safety. These terms set

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00017-3
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a limit on how far we have to go. We are not required to make plants any safer if the cost of an incremental increase in safety is grossly disproportionate to the benefit gained.

So, society tells us at least how safe it would like our plants to be through legislation. There may, however, be conceivable situations in which our interpretation of our moral obligations as professional engineers requires us to set a higher standard. There is also often a marked difference between the attitudes of different branches of the profession to safety. Safety specialists may well challenge strongly the idea that there should be any amount of money which was too much to save a single life. This sounds noble but process engineers may view this as unrealistic and may be even lazy. A more pragmatic approach, suggested by a fellow engineer, might employ the following distinctions:

*Acceptable Residual Risk:*

*As no change, implementation or HAZOP completion results in the elimination of all risk, there will always be a residual risk that must be managed either through procedures or just accepting it. It is critical that we understand that while we are always looking to eliminate where we can (creative design can do that) the reality is that doing anything will initiate a risk. The key is to ensure it is known and acceptable.*

*Worst case scenario:*

*A somewhat useless term in Process Safety because you can always imagine an incredibly unlikely scenario that will kill someone, or many someones. In practical cases this does not help you. We do not concern ourselves with alien invasions or 'sharknadoes'.*

*Worst imaginable scenario:*

*Through simulations you can model lots of cool things. On a facility [someone] simulated a scenario where 50 one-tonne drums of chlorine failed simultaneously and formed a cloud which was blown into the adjacent city largely undiluted. He also created a scenario where all the hydrocarbon in the facility was released simultaneously, mixed with air to form a combustible mixture and then found an ignition source. In both cases lots of people would be killed, but the situation, whilst imaginable is not realistic. A realistic scenario is informed by industry history and actual failure information. Chlorine tonners, for example, have an outstanding reliability record. The real data available for credible failure frequency should be used.*

*Worst credible scenario:*

*This is the worst real event that could happen based on real data and realistic calculations for the facility you are actually operating, considered in the light of real-world history, even local history. To take the chlorine example, what hazardous events involving a chlorine tonner or control system have actually occurred? Calculations would compare several competing events (releases, explosions, fires etc.) to see which might be the worst credible.*

*Worst tolerable scenario:*

*This is a manager's financial comparison, sad to say. Specifically, can your organization suffer an identified worst credible scenario and survive? (Consider Union Carbide and Bhopal) If the worst tolerable scenario is less than the worst credible scenario then your design or your organization needs to change to ensure survival.*

In the United Kingdom, and Europe in general, we have legislation which requires higher levels of scrutiny of health, safety, and environmental aspects of a design under specified circumstances. For UK designers, the Environment Agency's "netregs" website and the HSE's are very good places to start looking at the requirements in more detail. The most important aspects for European process plant designers are as follows.

Control of Major Accident Hazards (COMAH) legislation requires that businesses holding more than threshold quantities of named dangerous substances "*Take all necessary measures to prevent major accidents involving dangerous substances … Limit the consequences to people and the environment of any major accidents which do occur.*" There are tiers within the legislation which impose higher duties on companies holding greater quantities of these materials. Plant designers need to consider whether their proposed plant will be covered by this legislation at the earliest stages.

Control of Substances Hazardous to Health legislation requires risk assessment and control of hazards associated with all chemicals used in a business which have potentially hazardous properties. Consideration of the properties of chemicals used as feedstock, intermediates, and products is a basic part of plant design. Inherently safe design requires us to consider these issues at the earliest stage.

There is a lot of similar legislation worldwide, and I would recommend the US Center for Chemical Process Safety's publications intended to assist process plant designers in addressing safety issues (see "Further Reading").

Plants which are more safe or sustainable than society requires are unlikely to be built in the normal run of things. I have seen a few cases where this has been done for marketing purposes by companies with enough spare cash not to worry too much about the costs, but mostly plants are built to make stuff in a cost-effective, safe, and robust manner.

## Matching design rigor with stage of design

We should consider inherent safety (designing out risks) at the very earliest stages of design. Chemists are notorious among chemical engineers for devising process chemistry optimized for their batch/bench-scale processes, and for often having a slightly gung-ho attitude to safety issues.

Their greater tolerance of hazardous chemicals is understandable, as they work with far lower quantities than process plants contain. Their bench-scale chemistry is, however, rarely optimal for full-scale production.

Here is an example of the gung-ho attitude I refer to—I once found in a Hazard and Operability (HAZOP) that chemists were routinely taking 100 kg batches of highly unstable explosive organic peroxides from one floor of a pilot plant to another in a passenger lift.

## Conceptual design stage

It would be unusual to go out of our way to design in sustainability, but we always design in safety from the very start. This tends in earlier design stages to be informal and instinctive and progresses to more formal studies later in the project.

## Formal safety studies

We aren't going to be able to do a formal HAZOP at the conceptual design stage due to lack of project definition and documentation, but we can and should carry out less formal Hazard Identification (HAZID) and Hazard Analysis (HAZAN) studies as well as other industry-specific types of formal study appropriate for this job.

It is very important to determine as soon as possible whether the plant is going to come under enhanced regulatory regimes such as IPPC and COMAH. These will have a major impact on plant design development construction and operation costs and may rule out certain locations and approaches entirely.

## Inherent Safety

Rather than controlling hazards, we should design them out of our process from the very start. Inherent safety is a way of looking at our processes in order to achieve this. There are four main keywords:

### *Minimize*

Reduce stocks of hazardous chemicals (Trevor Kletz called this intensification, which others later used, confusingly, to mean something else entirely).

### *Substitute*

Replace hazardous chemicals with less hazardous ones.

### *Moderate*

Reduce the energy of the system—lower pressures and temperatures generally make for lower hazards.

### *Simplify*

*KISS! (Keep it simple stupid)*

***Kelly Johnson.***

Don't design plants you don't understand, and especially don't pile safety features one on top of another [unless forced to by a safety integrity level (SIL) requirement] instead of solving the root problem. Doing this in the early stages of a project is likely to lead to common cause failure and independence conflicts in control systems. A fellow engineer recommends:

> *If a SIL must be added, strive to find the mechanically simplest one available. Think about how well that safety device will stand up to wear and tear. Try to achieve 'second-level' thinking — what degradation happens over time or when more than one SIL fails? The one near-explosion I was involved with resulted from a failure of two safety devices (a plug screw and hexane detector) resulting in the transmission of flammables into an area with ignition sources. We later installed a simple vent which was more effective than the other two devices combined and much, much more robust.*

Note that the principles of inherent safety are applied at the conceptual design stage to the proposed process chemistry.

In the situation where we are being given the process chemistry by a product development team, we need to consider whether they have considered the constraints of full-scale operation. Are the selected reactants, solvents, or process conditions the most inherently safe ones? If they are not, and we are in a position to influence the process chemistry, can we get the chemists to rethink the chemistry?

In the more common scenario where the technology/process chemistry is bought in from a third party, can we choose another bought-in process which is more inherently safe?

It is very important to understand and challenge stacked unrealistic conservatism, especially if this conservatism is driving an overly complicated safety system or novel design that hasn't been proven elsewhere. As the same engineer reports:

> *I worked on a project where the reservoir engineers specified a requirement for a high-pressure system (requiring a design pressure of just over 1000 Bar(g)), which limited qualified suppliers for the subsea production tree. The stacked conservatisms from the reservoir were completely ludicrous but went unchallenged, as a result on startup it turned out that a 690 Bar(g) production tree would have been sufficient. These are readily available and are used extensively through the industry, but excessive conservatism led to the specification of higher design pressures which on paper appear safer but did not consider the cost and robustness consequences of driving the design into uncharted territory and qualification of novel equipment.*

## Human factors

Some of the worst accidents ever were caused by what might be called human error, or more correctly by plants which were not designed with real operators and managers in mind. The IChemE is very keen on this issue, and in their last discussion document on the future of chemical engineering it is stated that "The crucial role of human factors in process safety will also shape the institution's approach to process safety."

There are lots of interesting books on the subject of how people interact with process plants—Trevor Kletz's are very readable.

I personally learned a lot by commissioning plant, watching, and training operators. In summary:

- Think about the limits of human attention;
- Think about the limits of human physical capabilities;
- Think about alarm overload;
- Specify minimum competence of operators required;
- Design your plant so that it is easy to do the right thing and hard to do the wrong thing;
- Design your plant so that even if the wrong thing is done, disaster does not ensue;
- Design your plant so that it is physically impossible to do truly disastrous things;
- Design in controlled operation of your plant with a combination of operating procedures and control philosophy;
- Consider carefully limits on access to operating software.

Ideally, we should, as a profession, build a knowledge-base of how difficult plant situations were handled successfully in the past—being good is more than just not being bad! When I ask my students if they have heard of Flixborough or Seveso (see Chapter 17: Success through failure), very few have. The IChemE used to keep an accident database, but no longer.

## User-friendly design

Trevor Kletz identified a related concept to inherent safety, which addresses human factors he called user-friendly design. There are a number of additional principles and suggestions which are mostly amplifications of the four principles of inherent safety.

## Tolerate errors

There will always be errors in plant operation. If such errors readily lead to disaster, your design is neither inherently safe nor robust. Design your plant to handle these events, ideally passively.

## Limit effects/avoid knock-on effects

If there is a chance of hazardous events in plant operation, their effects on people and the environment must be minimized by designed features. It is especially important to minimize secondary effects caused by damage precipitated by the initial event. Note that this applies only to hazards which it has not been possible to design out—it does not contradict the four main keywords. For example, if tanks containing flammable liquids have a weak seam around the roof, the lid may blow off, but the tank will not rupture spilling the contents.

### Make incorrect assembly impossible

Because what can happen will happen, if the effect of incorrect assembly is significant hazard, it needs to be designed out.

### Making status clear

Obvious visual clues as to the status of plant help prevent accidents. To borrow Trevor Kletz's example, commissioning engineers use blanking plates to shut off process lines—a variety of such plates known as a spectacle plate (aka "spec blinds") makes it clear from a distance the status of a line.

### Ease of control

Controllability is a desirable feature of process plant designs in its own right, though the safety case is perhaps the strongest justification.

## Detailed design stage

There will be formal safety reviews during detailed design, such as HAZOP, electrical equipment zoning, and other industry-specific analyses.

Note that formal does not necessarily mean quantitative. Qualitative judgments by professional engineers will very likely be the best way to pick up all significant risks until the design for construction stage. Quantitative methods applied before those late stages are both overkill and a waste of resources.

These formal methods are the subject of the next part of the chapter.

## Formal methods: safety

Formal risk assessment, as the Engineering Council Guidance says, "should be used as an aid to professional judgement and not as a substitute for it." In increasing order of rigor we have HAZID, HAZAN, and HAZOP. We also have what Mecklenburgh calls "hazard assessment," a design review/risk assessment exercise focusing on safety aspects of layout, which falls somewhere between HAZAN and HAZOP, and is arguably a precursor to layer of protection analysis (LOPA). I'm going to call this a "layout safety review."

### HAZID

The first step in management of risk and hazards is to identify potential hazards. This is the purpose of HAZID studies.

### *Personal/personnel safety*

Broadly there are five classes of personal safety hazards:

1. Physical/mechanical: Slips, trips, and falls; confined spaces; noise; burns, cuts, and strikes; heat/cold stress/dehydration;
2. Biological: Release of hazardous organisms;
3. Chemical: Release of hazardous chemicals;
4. Electrical: Including static electricity;
5. Psychosocial: Poor plant design and management can cause physical and mental health problems for workers. Many of these are potentially lethal to individuals, so consideration of them should not be beneath a process plant designer's notice.

Large organizations often have their own alternative classifications, but they are very similar. For example, BP's 'golden rules' cover permits to work, ground disturbance, confined space, working at height, energy isolation, lifting operations, driving and hot work, which more or less match the list above.

### *Risk matrix*

A common approach to risk assessment and HAZAN is the risk matrix. The underlying idea is that acceptability of risk is a product of how likely a thing is to happen, and how bad it would be if it did (Tables 16.1 and 16.2). It should always be borne in mind that these are indicative models only and not to be taken as in any way definitive.

These are combined to produce a risk matrix as in Table 16.3. They are likely to follow a company-specific format, especially where commercial impacts are to be considered. Risk matrices should be calibrated to give one fatality outcome at $10^{-3}$/year as "unacceptable."

## HAZAN

HAZAN is an initial screening technique which has a number of variants. The general principle is that a table is drawn up for the various hazardous events which might conceivably happen on a plant, with likelihood of occurrence on one axis and severity of outcome on the other, and the product of likelihood and severity is called risk. Dow and Mond indexes are commonly used to rank hazards.

**Table 16.1** Risk matrix: categorization of likelihood

| Category | Definition | Range (events per year) |
|---|---|---|
| Probable | Few times in system lifetime | $10^{-1}$–$10^{-2}$ |
| Occasional | May be once in system lifetime | $10^{-2}$–$10^{-3}$ |
| Remote | Unlikely in system lifetime | $10^{-4}$–$10^{-5}$ |
| Improbable | Very unlikely to occur | $10^{-6}$–$10^{-7}$ |
| Inconceivable | Cannot believe that it could occur | $<10^{-7}$ |

**Table 16.2** Risk matrix: categorization of severity of consequences

| Category | Definition |
|---|---|
| Catastrophic | Multiple loss of life |
| Critical | Loss of a single life |
| Marginal | Major injuries to one or more persons |
| Negligible | Minor injuries to one or more persons |

**Table 16.3** Risk matrix

| | Consequence | | | |
|---|---|---|---|---|
| **Likelihood** | Catastrophic | Critical | Marginal | Negligible |
| Certain | | | | |
| Probable | | | | |
| Occasional | | | | |
| Remote | | | | |
| Improbable | | | | |
| Inconceivable | | | | |

Key:
- Red: Class I—Unacceptable
- Orange: Class II—Undesirable
- Yellow: Class III—Tolerable
- Lime: Class IV—Acceptable

As with HAZID, this is done in accordance with the principles of process safety: major hazards are considered as a priority.

## Layer of protection analysis

LOPA is a HAZAN tool very commonly used in certain industries, which works to quantify key risks associated with hazards identified in a HAZOP exercise in a more sophisticated way than the risk matrix.

"Layers of safety" are utilized to compensate for less than desired equipment spacing and to implement additional aspects of inherently safer design. This use of layers of safety or layers of protection is a traditional risk management approach. These layers may include the inherently safer strategies of preventing the incident, minimizing escalation, and minimizing impact. They may also include using a less hazardous process, separation distances, operator supervision, control systems, alarms, interlocks, physical protection devices, and emergency response systems.

A typical outline LOPA methodology considers layers from inside to outside, following inherently safer concepts:

- Process design;
- Separation distance;
- Safety and process devices, instruments, alarms, and controls;
- Administrative processes and controls.

Note that LOPA should only address risks above a given threshold, to avoid "LOPA-ing" every last safeguard. If we use a safeguard to credit risk reduction we have to maintain and test appropriately. We should, as part of a HAZOP, assign likelihoods/severity to determine a risk ranking which will identify, in turn, what needs to be LOPA-ed.

## Functional safety standards

Functional safety standards nonexhaustively include provisions for:

- SIL determination;
- Project management;
- Architecture/redundancy;
- Probability of failure on demand;
- Equipment selection;
- Software;
- Proof testing;
- Verification and validation;
- Audits;
- Assessments;
- Management of change;
- Competency.

They are performance-based rather than prescriptive; it is essentially a matter of demonstrating fitness-for-purpose throughout the life of the installation. Although a variety of certificates are offered (with varying degrees of credibility) by various parties for different aspects of compliance, there is no requirement within the standards for certification of anything. Neither is there any legal requirement in the United Kingdom to follow functional safety standards. "As far as is reasonably practicable" is what the law requires.

A key point to bear in mind is that the "SIL" is nominated for each individual function, that is, the required effects to suppress the hazard associated with a given cause. A high pressure or high temperature may cause the same valve(s) or drives(s) to trip; these would typically constitute two separate functions: one temperature, one pressure. The trips may cause a variety of additional actions but only those necessary to suppress the hazard constitute the safety "function."

Protection functions are also typically required to be implemented independently of the control systems, the failure of which may create a demand on the protection function.

## Safety Integrity Level

SIL is founded in standards covering the specification of the required functional safety standards for electrical/electronic/programmable electronic safety-related systems. The functional safety standard IEC 61508, and its process sector-specific derivative IEC 61511, detail the approach to be employed throughout the design, implementation, operation, and maintenance of such systems.

Compliance with these standards is not mandatory, but they are considered to represent good practice (as opposed to best practice, as Harvey Dearden points out in Functional Safety in Practice). The performance requirements of the functions are tied to the risk reduction factor (RRF) target identified for them and are allocated to one of four "SILs":

- SIL 1 RRF $>10-\leq 100$;
- SIL 2 RRF $>100-\leq 1000$;
- SIL 3 RRF $>1{,}000-\leq 10{,}000$;
- SIL 4 RRF $>10{,}000-\leq 100{,}000$.

In practice, SIL 1 and 2 are relatively straightforward to meet and will be substantially achieved through the application of historical good practice for such functions.

SIL 3 is distinctly more challenging and will almost certainly require some redundancy in the system provision, for example, one out of two, two out of three voting.

SIL 4 is next to impossible to comply with. If a SIL 4 requirement is identified the likelihood is that (1) your process design is seriously flawed and you need to enhance inherent safety and/or (2) your approach for identifying the risk reduction requirements ("SIL determination") is wrong.

Trips and interlocks are known as instrumented protection functions (IPFs) and these can be used to help reduce the risk associated with process hazards. Many IPFs have a risk reduction requirement of less than a factor 10 and therefore are not SIL rated.

An SIL 1 requirement is routine; perhaps 10%–20% of trip functions. SIL 3 used to be quite exceptional; less than 1% of trip functions. However, following incidents such as the 2010 Macondo blowout and explosion (which resulted in the deaths of 11 workers and caused a massive ongoing oil spill into the Gulf of Mexico), it is apparently becoming more common.

SIL determination may be undertaken by a variety of approaches, such as by risk graph, risk matrix, LOPA, or fault tree. Each of these provides more or less rigor in

the assessment of risk, the risk reduction contribution from other provisions (e.g., relief valves), and the acceptable (tolerable) level of risk associated with the hazard to be protected against.

While achieving practical compliance with the SIL target is largely a matter for instrumentation specialists, identification of the SIL target is very much a whole-process concern. There will typically be a range of instrument system design options and effective management of these issues requires a dialogue between the instrument and process disciplines.

This is potentially fraught territory: provisions within the standards are often cited out of context or without due consideration of the particular circumstances. It is all too easy for an "expert" to weave a plausible but wrongheaded argument. A bad application of SIL can result in a bad design, as it is to some extent in opposition to the *KISS* principle. Absolute compliance is something that we approach asymptotically; there typically comes a point where the marginal gain in integrity does not warrant the additional expenditure in resources.

Harvey Dearden has a lot more practical experience-based advice on the interpretation and application of these standards, and their interaction with other safety methodologies such as LOPA in his book (see "Further Reading").

## HAZOP

### *Outline HAZOP procedure*

Process plants are complex, and even the most experienced engineer cannot tell at a glance all the ways in which the parts might interact. HAZOP is a formal technique which allows us to consider how the plant we have designed operates under a number of sets of operating conditions.

This is especially useful for beginners to design. Steady-state conditions will have been overemphasized in their education, but there is no steady state in the real world, and to the extent that we approximate it, it is a product of good process control.

Consideration of the construction, commissioning, decommissioning, start-up, maintenance, and shutdown phases should be incorporated into the HAZOP. Commissioning may involve the use of chemicals not used during normal operation (e.g., for pipe pickling), the production of noise, dust, odor, and fumes, heavy traffic loads with knock-on effects like mud and dust transfer offsite, as well as a requirement for temporary storage, office, welfare, and sanitary facilities. During start-up and shutdown, commissioning, and maintenance activities, the systems responsible for safe operation may be absent. We therefore need to see if our plant is safe, not just under our expected operating conditions, but under the reasonably foreseeable conditions at all stages of its life.

HAZOP (and other similar tools) allow us to systematically evaluate this question. In a university we can only approximate professional practice, but I always flag up those important areas where we have to lose an important aspect of the real-world procedure in order to teach it in an undergraduate chemical engineering course.

So, in summary, we take a set of engineering drawings and supporting documentation and apply a basic HAZOP methodology to identify possible safety and operability issues. The documents we consider will be a P&ID, general arrangement (GA) drawing, functional design specification, and a set of datasheets.

In professional practice, we have a larger set of documents available to us, and we have a multidisciplinary HAZOP team. The inclusion of electrical, software, control, instrumentation, piping, corrosion, and mechanical engineers, as well as operating and commissioning specialists maximizes the chance that all impacts are considered (though you can have too many attendees as well as too few). If possible, it is valuable to have an independent process engineer in attendance (this is compulsory in BP and a number of other companies).

The difficult thing for beginners to HAZOP is not grasping the methodology; it is being able to imagine the consequences of failure states, work effectively as part of the HAZOP team, and stay on task (and awake!) throughout the procedure. As a fellow engineer commented to me:

> *Some HAZOPs go on for weeks. The SD2 initial subsea HAZOP lasts 12 weeks! The actions in the first week were far more coherent than the actions in the final week. It's very repetitive and this is a real risk when revisiting the HAZOP actions in several years' time when something has happened.*

New engineers usually undergo some form of training before attending a HAZOP—typically a 1-day course for simple attendance at a HAZOP, which would normally offer a fair amount of practice at participating in mock HAZOPs. There are also longer courses for HAZOP chairs, and experienced chairs are often brought in from outside to lead company HAZOPs.

The basic HAZOP method is to inspect the P&ID one node at a time, and to permutate parameters (flow, pressure, composition, temperature, etc.) with guide words (more, less, no, reverse, other) in order to identify hazard (to health and safety) and operability issues (which might impact on profitability or the environment). Nodes are usually selected as sections of the P&ID surrounding and including a unit operation, encompassing those process lines which are most likely to be affected by the unit operation, or to affect it.

There are a number of roles in a real HAZOP team which require specialist training, but I used to simplify this in academia to just two fixed jobs: a chair to keep things on track, and a scribe to note down the findings. I sometimes do this in small simple real world HAZOPs too.

### Full professional HAZOP procedure

1. The core team should consist of a chair, scribe, process engineer, and control engineer; plus other engineering disciplines and specialists in operation, commissioning, etc.
2. Consider as a minimum four scenarios: start-up, steady-state operation, shutdown, and maintenance (and any special situations relevant to your industry, such as steam or air purge or clean-in-place).
3. Go through the P&ID one node at a time using guide words (e.g., NONE; MORE OF; LESS OF; PART OF; MORE THAN; OTHER) for each parameter (flow; pressure; temperature; component/impurity; phase; viscosity, etc.) to generate "deviations" to consider. For example: "MORE OF" + "flow" = more flow.
4. Make no assumptions. The chair should be asking "How do we know that?," etc., to break all assumptions.
5. Record all deviations identified/considered.
6. Identify changes to plant or methods which make deviation less likely or protect against the consequences.
7. Decide if the cost of changes is justified.
8. Agree the justified changes, and agree who is responsible for them.
9. Produce an action list with responsibilities.
10. Follow up to ensure actions have been taken.

### Reporting

The conditions leading to these potential problems and the issues themselves are listed, alongside the actions proposed to mitigate them, on an action report similar to that used in a professional context (Fig. 16.1).

In an academic exercise, the column identifying who is responsible for making sure the corrective action is done is omitted. In the real world, this is very important. Things which are everyone's responsibility are no one's.

Real-world HAZOP actions should be managed in an auditable controlled format which cannot be tampered with and which requires approval signatures. This is especially important in longer projects where the design evolves following the closure of HAZOP actions. Also, if a document is used to close a HAZOP action, we may need to add a warning triangle around the relevant section with reference to the action, to ensure it is not changed without considering the action. Any HAZOP actions that have the closure changed need reopening and resubmitting.

Professional HAZOP is a lengthy and expensive procedure. It is not to be undertaken lightly because of the unavoidable cost of the rigor which gives its results their value. It requires a significant number of senior engineers, with prior training and experience in the technique. Computer-aided design tools are, however, becoming available to emulate the procedure, which might offer real assistance to the HAZOP team.

HAZOP REPORT SHEET

| Name | Title | Role | Sign | Project Title | |
|---|---|---|---|---|---|
| | | | | | |
| | | | | Project No. | |
| | | | | ELD No. | |
| | | | | Sheet | |
| | | | | Date | |
| | | | | | |

| No. | Guideword/ Parameter | Possible Cause | Consequence | Action | Person Responsible | Date to be completed | Completion Signature |
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**Figure 16.1** HAZOP action report sheet.

If you would like to explore HAZOP in greater detail, I would recommend the late Trevor Kletz's books on the subject (see "Further Reading"), which are as readable and entertaining as they are informative.

### *Layout safety review*

In addition to P&IDs, the GA is an important tool to help put the cause/consequence scenarios identified by the HAZOP team into a plant context and visualize possible hazard locations. When a consequence is identified, the P&ID does not show which other items are in the vicinity and might be affected. The GA thus allows the team to make a rapid judgment of the potential for knock-on effects. Similarly, if a quantitative hazard analysis is required, the hazard contours can be drawn on the layout to show where unacceptable hazard levels are imposed on equipment and access areas.

A layout safety review is best done in collaboration with a number of engineering disciplines. Mecklenburgh developed the following methodology:

- Define the process design with drawings [piping and instrumentation diagram (P&ID), GA, equipment datasheets, etc.].
- Identify sources of failure and vulnerable targets and try to design out hazard by removing failure mode or, failing that, path to target.
- Identify parts of plant containing dangerous materials which would be hazardous to release even if no failure mode is identified.
- Estimate the frequency of release and potential rates and amount of leakage.

- Evaluate the potential consequences of release on targets.
- Adjust layout and/or design and repeat assessment until consequences of loss are acceptable.
- Make emergency response plans based on the residual risk, and revise layout accordingly.

Further detail on this methodology is given in Process Plant Layout (see "Further Reading").

## Formal methods: sustainability

Sustainability is a highly politicized word, but chemical engineers know exactly what sustainability means, because the IChemE has helpfully told us not just what it is, but how to quantify it, in their sustainability metrics (the AICheE also have their own sustainability index). As engineers, we understand that if a company goes bust, our business plan was not sustainable, so there are metrics in the IChemE document which measure the economic aspect of sustainability, as well as some of the "fluffier" ones.

### IChemE metrics

To quote the sustainability metrics document (see Further Reading):

> *The metrics are presented in three groups:*
>
> - *Environmental indicators;*
> - *Economic indicators;*
> - *Social indicators.*
>
> *which reflect the three components of sustainable development.*
>
> *Not all the metrics we suggest will be applicable to every operating unit. For some units, other metrics will be more relevant and respondents should be prepared to devise and report their own tailored metrics. Choosing relevant metrics is a task for the respondent. Nevertheless, to give a balanced view of sustainability performance, there must be key indicators in each of the three areas (environmental, economic, social).*
>
> *Most products with which the process industries are concerned will pass through many hands in the chain Resource extraction—transport—manufacture—distribution—sale—utilization—disposal—recycling—final disposal.*
>
> *Suppliers, customers and contractors all contribute to this chain, so in reporting the metrics it is important that the respondent makes it clear where the boundaries have been drawn.*
>
> *As with all benchmarking exercises, a company will receive most benefit from these data if they are collected for a number of operating units, over a number of years, on a consistent basis. This will give an indication of trends, and the effect of implementing policies.*

*A note on ratio indicators*

*Most of the progress metrics are calculated in the form of appropriate ratios. Ratio indicators can be chosen to provide a measure of impact independent of the scale of operation, or to weigh cost against benefit, and in some cases, they can allow comparison between different operations. For example, in the environmental area, the unit of environmental impact per unit of product or service value is a good measure of eco-efficiency. The preferred unit of product or service value is the value added. . ., and this is the scaling factor generally used in this report. However, the value added can sometimes be difficult to estimate accurately, so surrogate measures such as net sales, profit, or even mass of product may be used. Alternatively, a measure of value might be the worth of the service provided, such as the value of personal mobility, the value of improved hygiene, health or comfort. But a well-founded and consistent method of estimating these 'values' must be presented*

*The metrics are calculated under the following headings:*

*Resource usage—Energy; Material (excluding fuel and water); Water; Land.*

*Emissions, effluents and waste—Atmospheric impacts; Aquatic impacts.*

*Economic indicators—Profit, value and tax; Investments.*

*Social Indicators—Workplace; Society.*

Therefore the engineer's approach is (as ever) one of quantifying as best we can and then balancing costs and benefits. We do not set the value of all environmental goods to infinity, and the value of a company staying in business to zero. The majority (or a vocal minority) of the community may however feel differently. As a fellow practitioner comments:

*In Australia, you usually have to participate in some sort of community input gathering phase before major project approval is granted. Then after the plant is built there is often a community complaint hotline for odors etc. This hotline often results in the plant manager or whoever is on call heading to the complainant's house to investigate. Lots of fun. . .*

## Life cycle analysis

A more radical approach to ensuring sustainability is carrying out life cycle analysis (LCA), as set out in ISO 14040, amongst other places. The main problem with LCA is that it does not normally take into consideration either negative or positive societal impacts. There are technical difficulties as well. There is usually a lack of availability of the data required to put into the analysis, and a problem with how to weight different factors (for example greenhouse gases vs low-level ozone released, vs energy use vs water use, etc.). The numbers produced may look firm, but they are based ultimately on estimates, and analyzed using weightings based upon value judgments. This makes

LCA vulnerable to bias, which is perhaps why it is favored by businesses looking to highlight their environmental performance.

LCA is however required by law in certain jurisdictions for certain processes. It may not be the best tool, but if it is the one specified, we have to use it and take its outputs seriously. This may well require a very significant expenditure on research to firm up the input numbers, and make sure our comparisons are as objectively justifiable as possible.

## Specification of equipment with safety implications in mind

### Introduction

There is an excellent and concise treatment of the principles of safety in design in *Process Plant Design and Operation* (see "Further Reading"), which I do not propose to replicate in full here, but there is a useful introductory statement and a few overarching principles:

> *The design should ensure a secure containment system. It must be robust and capable of handling both over and under-pressure condition plus temperature excursions where appropriate.*
>
> *The design should avoid one event setting off a larger event. . .. If the process handles flammable materials, the sources of ignition must be kept to a minimum. It should be tolerant of small fires and designed to minimize the frequency of large fires and/or explosions. In the case of corrosive fluids, the design should be tolerant of corrosion both inside and outside the containment.*

### Principles

#### *Personal and process safety*

Much public discussion of health and safety issues (and many daytime TV adverts) focus on personnel/personal safety issues like slips, trips, falls, etc. In many cases, there is legislation which guides us on how to design out these personal hazards, though many (including former IChemE President and HSE Chair, Judith Hackitt) have argued that this kind of health and safety legislation is being commonly misused by ambulance-chasing lawyers and lazy public officials in a way which is bringing it into disrepute.

"Process safety," however, tends to focus on the small subset of these risks which have the potential for very serious incidents in industries handling large quantities of hazardous materials.

Release of large quantities of toxic substances, major fires, and explosions are very serious issues with the potential for multiple fatalities. These are the ones which are usually the primary focus of process plant design safety exercises.

### *Access*

A common fault of beginners' designs is a lack of provision of safe permanent access to equipment. This is normally done via platforms and walkways made of open mesh decking, and vertical and inclined ("ship's") ladders, all usually made of galvanized mild steel.

These items are also available in glass-reinforced plastic for chemical resistance, as well as aluminum for expensive shininess (but on the one occasion when my client specified aluminum instead of galvanized mild steel, it was all stolen the night after delivery). Stainless steel is popular in the food and pharma industries because of frequent cleaning with corrosive chemicals (and because it is extra shiny).

#### General

- Manways should be 0.5 m in diameter minimum and placed facing gangways. Provision should be made for winching a man out.
- Doors should be 0.6 m wide minimum.
- There should always be two escape routes for operators, especially at the top of tall columns. (I have met people who were forced to watch colleagues burn to death when a fire started below them on a column, blocking their only way out.)

#### Horizontal access

- Platforms should come with toeboards and 1 m high handrails. Platforms, walkways, and stairways should not be obstructed by pipes or equipment up to a height of 2.25 m. (But be careful how you measure that height where stairs cross underneath obstacles. If a stair tread is not exactly where you think it is the headroom can be reduced by the height of one step.)
- Design loads on decking are specified in BS45492 as follows:

| | |
|---|---|
| Light duty (one person) | 3.0 kN/m$^2$ |
| General (regular two-way pedestrian traffic) | 5.0 kN/m$^2$ |
| Heavy duty (high-density pedestrian traffic) | 7.5 kN/m$^2$ |

#### Vertical access

- The minimum height between floors should generally be at least 3 m, and minimum headroom under piperacks, cable tray, and so on not less than 2.25 m.
- Intermediate steps are required for elevation changes over 400 mm.
- Stairs are preferred over ladders for main vertical access. Ladders should be hooped over 1.5 m, and ship's ladders (Fig. 16.2) should usually be avoided. (Note that this order of preference is, as is so often the case, in descending cost order.)

**Figure 16.2** Ship's ladders.

- The maximum ladder height without a landing is 7.5 m.
- Ladders should be arranged so that users face into equipment, not out into space, and they should not be attached to the supports for hot pipes, to avoid distortion by expansion forces.
- A clear 1 $m^2$ should be allowed on the plan layout for a ladder.

## *Flammable, toxic, and asphyxiant atmospheres*

### Explosive atmospheres: Dangerous Substances and Explosive Atmospheres Regulations

The Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) require risk assessment and, ideally, elimination of hazards associated with flammable and explosive substances. The most important aspect of this legislation for the plant designer is to do with classification of areas where explosive atmospheres may occur.

This classification has a major impact on both equipment specification and plant layout.

DSEAR and other directives and standards require that plant areas which may feasibly contain explosive atmospheres as a result of gases, vapors, mists, or dusts be "zoned" based on the probability of occurrence of an explosive atmosphere.

The probability is usually assessed qualitatively, but for those who really like numbers, HSE gives approximate figures for zoning gas/vapor/mist hazards as follows:

- Zone 0: Explosive atmosphere for more than 1000 h/year;
- Zone 1: Explosive atmosphere for more than 10, but less than 1000 h/year;
- Zone 2: Explosive atmosphere for less than 10 h/year, but still sufficiently likely as to require controls over ignition sources.

  (The corresponding dust classifications are Zones 20, 21, and 22, respectively.)

Ignition sources have to be controlled within these zones. This may require the exclusion of certain types of equipment, or the use of special "ATEX-rated" drives and so on. (ATEX ratings code 1, 2, and 3 correspond to Zones 0, 1, and 2, respectively.) Note that this requirement applies to both electrical AND mechanical equipment that could be a potential source of ignition.

If there is residual risk of explosion, consideration needs to be given to provision of blast walls, safe paths for discharge of relief vents, explosion-hardened plant and control buildings, and design of tanks and other equipment to withstand explosion.

We tend, when designing plant, to need numbers to work with in order to quantify risks. In the case of flammable and toxic hazards, we have the upper and lower flammable/explosive limits for a material (and its flash point) and a range of workplace exposure limits for acute and chronic exposure to toxic substances defined as follows:

### Flammability hazards

- Lower explosive limit, LEL/LFL—The minimum concentration of vapor in air below which the propagation of flame will not occur in the presence of an ignition source. Also referred to as the lower flammable limit or the lower explosion limit.
- Upper explosive limit, UEL/UFL—The maximum concentration of vapor in air above which the propagation of flame will not occur in the presence of an ignition source. Also referred to as the upper flammable limit or the upper explosion limit.
- Flash point: The minimum temperature at which a liquid, under specific test conditions, gives off sufficient flammable vapor to ignite momentarily on the application of an ignition source.

  Flammable liquids are classed based on flash point as:
- Extremely flammable—Liquids which have a flash point lower than 0°C and a boiling point (or, in the case of a boiling range, the initial boiling point) lower than or equal to 35°C.

- Highly flammable—Liquids which have a flash point below 21°C but which are not extremely flammable.
- Flammable—Liquids which have a flash point equal to or greater than 21°C and less than or equal to 55°C and which support combustion when tested in the prescribed manner at 55°C.
- Inflammable—confusingly for nonnative speakers, the word "inflammable" is used to mean the same thing as "flammable" (or perhaps even extremely flammable). Its use should, therefore, be avoided.

The higher up this list a substance is, the more we should seek to substitute it with something less flammable (or failing that the more precautions we would have to take).

### Toxic hazards

- The long-term exposure limit is the time-weighted average concentration of a substance over an 8-hour period thought not to be injurious to health.
- The short-term exposure limit is the time-weighted average concentration of a substance over a 15-minute period thought not to be injurious to health.

For UK readers, the HSE publication *EH40* gives exposure limits for a wide range of chemicals (see "Further Reading"). The United States uses a similar system: OSHA is the main governing body (see Further Reading), while the US National Institute for Occupational Safety and Health (NIOSH) is a key source of exposure limits, alongside some other organizations which also set limits. The term "immediately dangerous to life or health" is defined by the NIOSH as exposure to airborne contaminants that is "likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment."

If we identify a risk of excessive exposure to toxic chemicals in our design, we should first consider substituting the materials which produce toxic hazards under the principle of inherent safety. Failing that, we can use engineering controls such as ventilation, avoidance of enclosure, controlling access to contaminated areas, and so on.

Note that there are many substances which are both toxic and flammable, and both hazards should be considered simultaneously as well as separately.

There may be some substantially enclosed areas containing flammable, toxic, or asphyxiating atmospheres which we cannot design out. These are classified as confined spaces, and access to them has to be tightly controlled. Note that it is the confinement rather than the potentially noxious atmosphere that gives rise to the classification.

### Confined space entry

According to the HSE, "A confined space is a place which is substantially enclosed (though not always entirely), and where serious injury can occur from hazardous substances or conditions within the space or nearby (e.g., lack of oxygen)."

It is most often the case that the relevant hazard is the possibility of presence of asphyxiating, flammable, or toxic gases, or the absence of oxygen, so there is some overlap with explosive area zoning.

Entering such spaces (even quite shallow trenches can qualify, as an operator can bend down and place his head in the hazardous atmosphere) has the potential for multiple fatalities, and formal risk assessment is required by law before any entry. This will often require any operators entering such a space to have special training and equipment. Entering confined spaces (even if supposedly only for a moment) is a big deal. It is a bad idea to have any equipment requiring operator access in a confined space.

If this cannot be designed out, the safest kind of confined space is one with a direct drop straight from the surface to the working area. Having to navigate turns and level changes in a confined space is a very risky operation—few except mine rescue teams have the necessary skills and equipment.

Lockable covers on confined spaces are a sensible idea, and it might be best not to have an internal access ladder. Fig. 16.3 illustrates an example of an undesirable layout I came across, complete with hanging cables and a nonrecommended access ladder.

In the arrangement in Fig. 16.3, properly trained staff could have been winched in, and the absence of a ladder would dissuade untrained staff from just popping down to look at something in a way which has led to many deaths in the past. Multiple fatalities have occurred on many occasions in which untrained operators have gone to the rescue of others who went before them and are overcome by the same conditions. In Qatar, in 2012, seven expatriate operators were killed in a single incident of this nature on the first day I worked there, and there have since been similar multiple fatality

**Figure 16.3** Example of poor confined space layout.

incidents in the United Kingdom and worldwide. Similar scenarios are very common where inerting has occurred. Nitrogen is one of the biggest killers in the oil and gas industry due to its potential for rapid asphyxiation, with people attempting to rescue the initial casualty also being overcome.

#### Wet/dusty atmospheres: ingress protection ratings

Equipment needs to be specified so that it is suitable for its environment with respect to particle and water ingress. The most commonly used standard is the IPXX standard, where the first X represents a solid particle ingress standard, and the second X a water tightness standard. 0 is no protection, and 5 is dust-tight in the case of the solids standard, 8 is water-tight (immersion below 1 m) in the case of the water standard.

Submersible equipment needs to be rated at IP68 or better, and control panels at IP55 or more. Indoor equipment may be rated as low as IP22 (the standard for domestic power sockets), protected only from probing fingers and water drips over a short period.

By minimizing the amount of electrical equipment located in the field (as opposed to inside an MCC) and using simple techniques such as bottom entry of cables to boxes and devices, we can add extra robustness for little extra cost. Cooling of enclosed electrical equipment should also be considered.

## Specification of safety devices

No safety device is 100% reliable, so (SIL notwithstanding) the use of safety devices is only indicated where it has not been possible to design out hazards, which is always the preferable option.

## Overpressure protection

Inexperienced engineers tend to do one of two things: either they put pressure-relief valves (PRVs) everywhere or (much worse) do not include them where they are needed. The first error adds significant cost to both capex and opex and possibly produces a net decrease in safety through increased complexity. The second error can be a disaster waiting to happen.

I do not intend to go into the detail of relief valve sizing, about which a whole book could be written; instead I will cover some of the basic scenarios in which a PRV could be required.

The real skill of sizing relief valves is not in grinding through the standard sizing calculations, it is the application of engineering judgment to identify the scenarios in which overpressurization could occur and determining the reasonable worst-case relief load in such an event.

This section is written with reference to *API520* and *API521*, the oil and gas industry standards for PRV sizing (see "Further Reading"). In the United Kingdom/Europe, the Pressure Equipment Directive will need to be complied with in all industries, but the API standards contain some useful rules of thumb for PRV application which have no equivalent in United Kingdom or European standards. *API521* discusses some common scenarios in which an overpressure (and therefore a "relief case") may occur. The most common of these are as follows.

### *Closed outlets (on vessels)*

In the event that all the outlets from a vessel are closed off (perhaps due to manual valves being closed through an operator error or automatic valves failing), system overpressure may occur. While this is quite unlikely, as engineers we have to assume that all the outlets to a particular vessel might be closed if it is physically possible.

The key issue is to determine if the highest achievable pressure in the vessel is above the design pressure. In many cases this may mean comparing the maximum rated delivery pressure of upstream pumps or supply vessels to the vessel in question. Inherently safe design implies that design pressures throughout the entire system which might be overpressurized by such an event must be consistent.

### *Burst tube case*

Heat exchangers will almost always contain fluid at higher pressure on one side of the tubes than the other, so a burst tube will result in the high-pressure fluid leaking into the low-pressure side (including, in some cases, flashing of the fluid) which might ultimately cause a catastrophic failure.

In this instance it must be noted that we are not protecting against cross-contamination but protecting the exchanger/pipework against catastrophic failure and consequent loss of containment.

We can "dismiss" this safety/relief case (i.e., create an inherently safe design) if the test pressure on the low-pressure side is higher than the design pressure on the high-pressure side.

### *Cooling water/medium failure*

Cooling can be used deliberately to create a pressure drop within a system. In these cases, a loss of the cooling medium may lead to increased pressure (a similar scenario can occur through loss of reflux cooling).

An inherently safe design will design vessels for the maximum pressure achievable in the event cooling is lost.

### Blocked in (hydraulic expansion)

This scenario often occurs with liquids in heat exchangers in two situations:

1. A cold liquid side of a heat exchanger becomes blocked in while the hot side continues to flow. Depending on the temperature difference, increased heating may cause expansion or vaporization, leading to overpressure.
2. Liquid in a line may be blocked in (e.g., by an operator closing a valve in error). If the liquid is normally below ambient temperature (or it has trace heating) it may expand on heating and cause overpressure. While the expansion may be small, in the case of incompressible fluids the pressure can quickly increase and cause a problem.

### Exterior fire case

In the event that a fire occurs immediately outside a vessel, the contents will be heated and can overpressurize the vessel. This is a very difficult case to dismiss, however it can be dismissed if the vessel is at least 7.6 m above the base of the fire, if the vessel is protected by fire-resistant insulation, or in some other way.

### Pressure-relief valves

Pressure-relief valves (PRVs) (Fig. 16.4) are spring-loaded valves which open automatically at a set pressure, releasing the contents of a pipe or vessel to atmosphere or to a vessel depending on design detail. While in theory they should not, in practice PRVs tend to leak increasingly over time so they are not the best choice where complete containment is crucial.

### Bursting discs

Bursting discs (Fig. 16.5) are an engineered metal or graphite plate fitted across a pipe designed to burst at a specified pressure, allowing the pipe contents to pass to atmosphere or vessel. They are a better choice than PRVs where containment is crucial but, once burst, they need to be replaced. They are quite often specified as protection upstream of a PRV to prevent fugitive emissions, or when a larger vent area is required. If you are using bursting discs as overpressure protection on vacuum vessels, it is worth thinking about what happens if air is then sucked back into the vessel once the overpressure event is over. In this scenario a PRV is a good complement to a bursting disc to prevent air ingress which would cause a fire (e.g., for vegetable oil deodorizers which operate at temperatures above the flash point of the oil).

### Blowout panels, etc.

Typical gas/air or dust/air explosion overpressures are of the order of 10 bar. It may not be practical to design vessels to withstand the overpressure (Fig. 16.6).

**Figure 16.4** Pressure-relief valves.

**Figure 16.5** Bursting disc. *Courtesy: Elfab.*

**Figure 16.6** Blowout panel. *Courtesy: Elfab.*

Instead, in a similar manner to bursting discs, the roof or wall of a building or vessel can be engineered to fail first, diverting a blast in a safe direction, and minimizing damage within the protected space.

It is common practice for the roof of fixed-roof atmospheric storage tanks to have deliberately weak seams for this purpose.

## Underpressure Protection

### *Vacuum-relief valve*

The lids of large tanks such as those used for storage of products and intermediates on oil and gas facilities may only be designed to withstand pressure but may be readily imploded by surprisingly small degrees of vacuum. They are therefore usually protected by vacuum-relief valves (or combined "vent/vac" or "relief/vac" valves) (Fig. 16.7).

Vacuum relief is especially pertinent in the oil and gas industry, since subsea-flexible/nonrigid cores can collapse and an oil well annulus can rupture if designers do not consider the forces associated with vacuum.

## Static protection

Nonconducting fluids such as hydrocarbons flowing rapidly through pipes or strongly agitated in vessels can produce sufficient static electricity to self-ignite by spark discharge. Contrary to popular belief, metal pipes are actually more likely to exhibit such charging behaviors than nonconductive materials (Fig. 16.8). While the risk may be reduced by reducing liquid velocities, such an approach is unlikely to be reliable or cost-effective enough for the complete elimination of risk. Such systems need to be

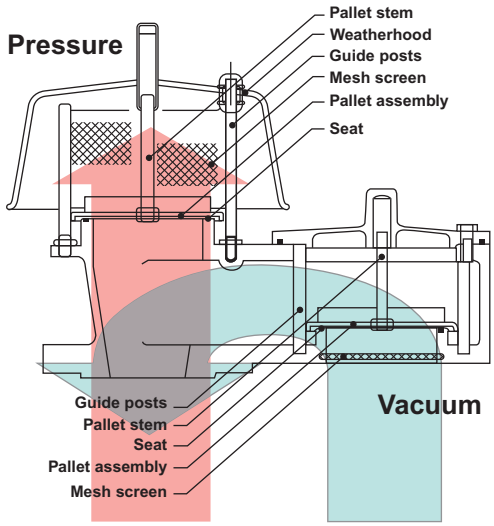


**Figure 16.7** Vacuum-relief valve.[1] *Courtesy: Kodiyath.*

safely earthed to prevent fires caused in this way. Note that earthing a vessel will not prevent charge building up within the nonconducting fluid/powder itself; earthing does not eliminate the hazard potential. Other methods which may be used include bottom entry instead of top entry piping to tanks and procedures to ensure the UFL is exceeded inside the vessel headspace.

## Gas detectors

Where toxic or flammable gases may be present, permanent gas detection and alarm systems may be required to promote personnel and plant safety (Fig. 16.9). Where used to monitor enclosed areas (e.g., inside conveyors), procedures need to be in place to make sure connecting tubes are checked regularly in case of blockage.

## Emergency shutdown valves

Where it is desired to cut off flow quickly in a potentially hazardous circumstance, valves may be installed which reliably shut off flow in that condition (Fig. 16.10). These are known as shutdown valves (SDVs) or emergency shutdown valves (ESVs, or ESDVs in oil and gas, also commonly referred to informally as XXVs). They are common features in the oil and gas industry and other safety-critical industries.

ESVs are actuated valves, which introduce a number of risks to reliability. The hazardous condition has to be detected, a signal has to pass to the valve, and the valve actuator has to work. All of these things may need to happen very

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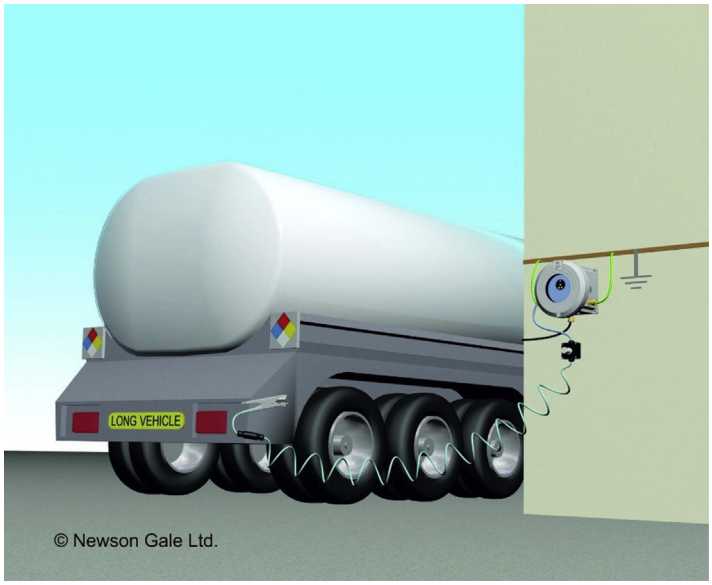


**Figure 16.8** Static protection measure. *Courtesy: Newson Gale.*

**Figure 16.9** Gas detector heads. *Courtesy: Crowcon.*

reliably in a condition where the plant is on fire, and the main plant power is offline.

For this reason, ESV actuators are normally of the spring return type or actuated by fail-safe fluid power systems, and any signals wiring is fireproofed, as it is in riser areas. When in flammable areas, passive fire protection is a requirement as it is in the

**Figure 16.10** Emergency shutdown valve. *Courtesy: Ascendant.*

presence of fire and gas detectors. To provide a higher degree of reliability, redundancy could be introduced, such as "high-integrity pressure protection systems", safety instrumented systems which shut off the source of pressure via software controls.

## Flare stacks

When PRVs are lifted by overpressure on a gas processing facility, it is undesirable to vent large quantities of flammable gas to the atmosphere. Burning the gas in a flare stack makes it safer (Fig. 16.11).

Flare stacks are also used to handle gas produced during maintenance and repair activities, plant bypasses, and so on, as well as gas which is considered economically nonviable to recover.

## Scrubbers

An alternative way of removing dangerous (usually toxic, nonflammable) substances from a vented stream is through the use of emergency scrubbers (Fig. 16.12). For systems where noncondensibles are continuously vented from a vacuum system (e.g., the oilseed industry), scrubbers form part of the normal operating process.

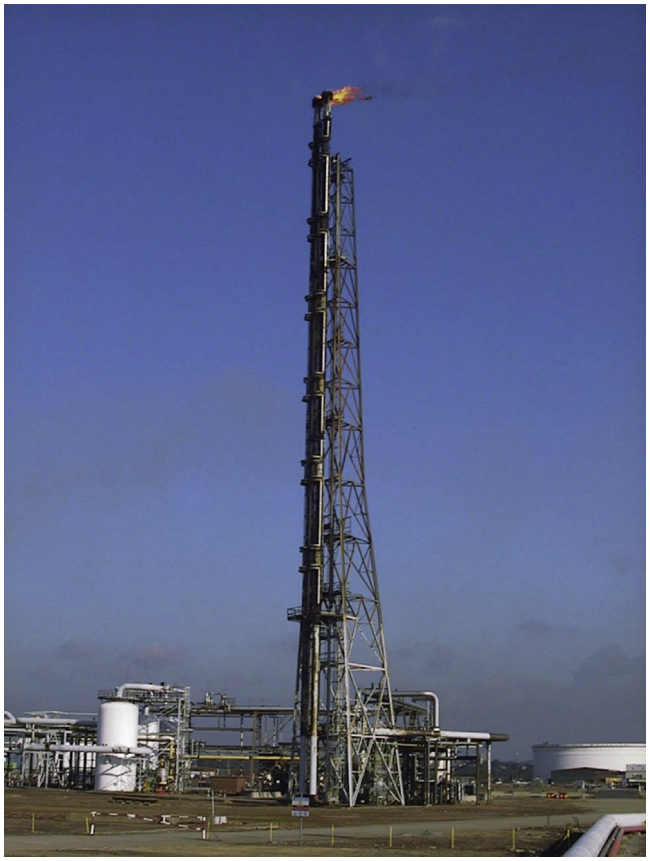

**Figure 16.11** Flare stack at the former Shell Haven Refinery, UK.[2] *Courtesy: Terryjoyce.*

## Water sprays

Fixed water spray cooling systems are commonly provided on the tanks used to store flammable hydrocarbons in petrochemical facilities (Fig. 16.13). There is a commonly used standard, "NFPA 15: Standard for Water Spray Fixed Systems for Fire Protection," but the design of such safety-critical systems is best left to specialists.

## Quench tanks

We can arrange for the contents of a vessel containing a reaction which might run away to be dumped quickly to a tank whose physical or chemical conditions stop the reaction very quickly.

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**Figure 16.12** Scrubber.[3] *Courtesy: Murr Rhame.*

## Snuff steam

Steam pipes with on/off valves located in a safe area which allow steam to be fed to the interior of vessels to extinguish fires are used on solvent extraction plants in the oilseed industry, and in some fired heaters.

## Inerting

This can be done either through the use of inert gases (nitrogen being the cheapest option) or by increasing the temperature of flammable liquids in order to use vapor to

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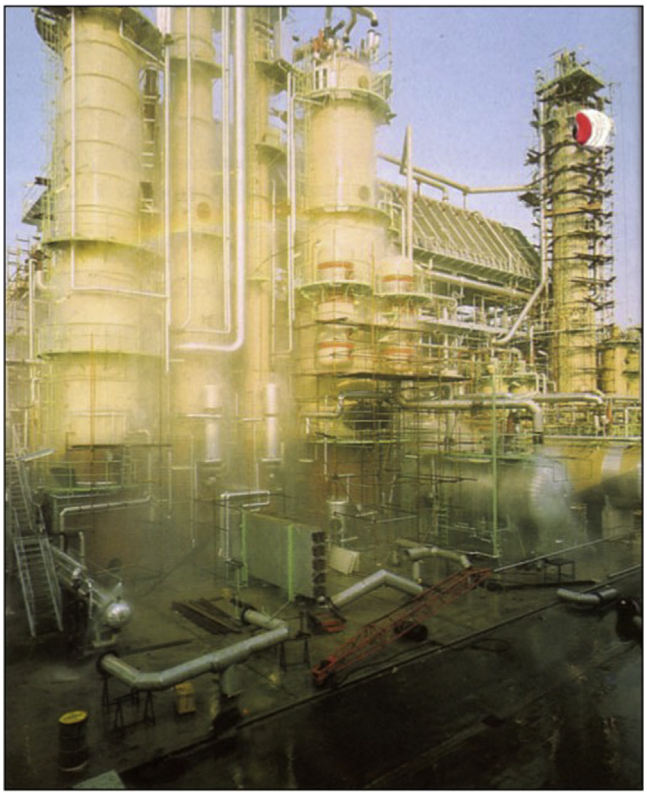

**Figure 16.13** Water spray system in operation. *Courtesy: Lechler.*

push oxygen from the headspace of tanks connected to a vacuum system to condense the vapor.

Another area to consider is the confinement of flammables where nonflammable streams are entering and leaving a plant. This issue has been responsible for disasters in the oilseed industry, most notably the Memphis City disaster (caused by hexane in effluent leaving the plant), and a barge explosion in Nantong, China (caused by hexane in "desolventized" meal). Plastics recycling plants and to some extent the oil and gas industry have similar scenarios.

## Further reading

AIChE, Center for Chemical Process Safety. (2008). *Guidelines for hazard evaluation procedures* (3rd ed.). Weinheim: Wiley.

AIChE, Center for Chemical Process Safety. (2009). *Inherently safer chemical processes: A life cycle approach* (2nd ed.). Weinheim: Wiley.

AIChE, Center for Chemical Process Safety. (2012). *Guidelines for engineering design for process safety* (2nd ed.). Weinheim: Wiley.

American Petroleum Institute. (2014). *API STD 520-1 sizing, selection, and installation of pressure-relieving devices in refineries: part I—sizing and selection* (9th ed.). Washington D.C.: American Petroleum Institute.

American Petroleum Institute. (2014). *API STD 521 pressure-relieving and depressuring systems* (6th ed.). Washington D.C.: American Petroleum Institute.

Azapagic, A. (2002). *Sustainable development progress metrics recommended for use in the process industries*. Rugby: Institution of Chemical Engineers.

Dearden, H. (2018). *Functional safety in practice* (2nd ed.). CreateSpace Independent Publishing Platform.

England & Wales, Health & Safety Executive. (2018). *EH40/2005 workplace exposure limits containing the list of workplace exposure limits for use with the control of substances hazardous to health regulations 2002 (as amended)*. Norwich: HMSO.

Moran, S. (2016). *Process plant layout* (2nd ed.). Oxford: Butterworth-Heinemann.

Scott, D., & Crawley, F. (1992). *Process plant design and operation: Guidance to safe practice*. Rugby: Institution of Chemical Engineers.

UK, Engineering Council. (2011). *Guidance on risk for the engineering profession* (Online). <https://www.engc.org.uk/engcdocuments/internet/Website/Guidance%20on%20Risk.pdf>. Accessed 25.10.18.

USA, Department of Labor Occupational Health and Safety Administration (OSHA). (n.d.). Permissible exposure limites—annotated tables (Online). <https://www.osha.gov/dsg/annotated-pels/>. Accessed 25.10.18.

# CHAPTER 17

# Success through failure (or "you don't want to do it like that!")

## Introduction

Those of my fellow experienced engineers who don't have a lot to do with undergraduates or new graduates often don't realize just how little those beginners know, or indeed remember how little they used to know themselves. However, engineers of my age at least existed at a time when process safety was less well controlled in the West, and consequently there were large memorable accidents.

I have had a lot to do with undergraduates and new graduates and I know that many of them, worryingly, don't even know about the disasters at Seveso in 1976, Flixborough in 1974, and Bhopal in 1984, which had a major impact on the management of process plant safety, and resulted in the introduction of process safety legislation. So, if this chapter seems a little outdated, it is because I am highlighting incidents which younger engineers may not be familiar with, illustrating hazards which never become old.

## Lessons from disaster

> *Those who cannot remember the past are condemned to repeat it.*
>
> ***George Santanaya***

Trevor Kletz loved that quote. He wrote a great book—one of his many—called *Lessons From Disaster*, in which he discussed (and illustrated with case studies) how organizations have no memory of past accidents. People have memories, but they move on (retire, leave, get promoted, etc.), and therefore avoidable accidents recur. Some areas seem especially forgettable, as I shall discuss in this chapter.

Professions have no memory either, as Petroski discusses in his book *Success Through Failure*, the title of which I have borrowed for this chapter. The process of forgetting the lessons of the past described by Petroski in his field (structural engineering) seems to be the same one Kletz discusses.

> *It is imperative that the realistic prospect of failure be kept in the forefront of every engineer's mind.*
>
> ***Henry Petroski***

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00018-5
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Petroski describes in his books how the history of technology and engineering is littered with failures, but when designers ignore this and focus instead on past successes, they become complacent (reducing that vital sense of vulnerability) and standardize deviations from safe design practice. Over an approximately 30-year cycle, designers lose sight of the limitations of a novel design technique as its use becomes commonplace, and the technique will be pushed beyond its limits, leading to failure.

We learn from our life and professional experience about the limitations of technology, and we retain the information as concepts, to be applied by analogy or metaphor. But the older, experienced engineers are retiring, and their hard-won knowledge (arcane stuff about how a specific plant actually functions rather than book-knowledge of how it should function) risks being lost instead of being passed down to the new generation of engineers replacing them.

Kletz and Petroski are top of my suggested light reading list but *Incidents That Define Process Safety* by Atherton and Gil (BP lead process safety engineers) is also worth a read. It meshes process safety incidents with air crashes, ship sinkings, etc. to make technical process failure causes more readable with incidents beginners are more likely to have heard of.

## Safety second

In practice, other than natural disasters, every failure can be traced to human error—something wasn't designed properly, wasn't constructed properly, wasn't maintained properly, wasn't operated properly, etc. A history of failures by means of specific and concrete examples is instructive to the designer, as most of the causes of failure in the real world do not exist in the mathematical world of "engineering science." These causes often contradict the assumptions which theoreticians have to make (whether they realize they are doing so or not) to perform their mathematical analysis. These failures may be divided into hardware and software failures, but most contain aspects of both the known and unknown limits of designs and the uses to which they are put.

Failures are mostly founded in phenomena which are known about, but not well understood—the known unknowns. Our lack of scientific understanding is reflected in the design codes and margins of safety we apply to an always incomplete mathematical model. Knowing the extent to which we are operating beyond our knowledge should inform our decisions about suitable safety margins, but complacency and pressure from management can conspire to remove these margins of safety. Pressure from risk-tolerant management on risk-averse engineers is commonplace, which can lead to a "safety second" culture.

If they are available and properly developed, near-miss and incident report electronic databases with search facilities can make it much easier to find information than wading through an old filing cabinet. Accident databases also permit easier trending analysis,

identifying common or recurring issues and helping to prioritize corrective actions. However, as Karmarkar points out, histories of chemical engineering industrial accidents on the internet appear to only go back around 20 years, and the IChemE's Accident Database is presently both out of date and hard to obtain. Petroski also discusses how the focus on the very recent past of professional researchers, and a move away from paper to electronic records, has made it difficult to fully explore the history of failure.

On top of this, organizations are increasingly hesitant to share failure stories for risk of reputation damage. (This leads to an ethical dilemma—aren't we engineers first?) There have been many cases where lessons learned by one company were not shared, leading to an unnecessary second disaster. Away from process safety, the American Airlines Flight 191 crash in Chicago is a prime example of this phenomenon, though the aviation industry works very hard to avoid repeating mistakes.

As a result of these factors, the most useful records of the limits of design methodologies are increasingly found only in the minds of highly experienced designers. They are not part of either digital databases or simulation programs.

The article and books listed earlier are all certainly worth reading, but which past disasters do you most need to know about if you are new to process plant design, and what things do you need to look out for?

## Especially forgettable times, places, and things

In reviewing case studies for this book and my previous one, it became clear—from the number of times they recurred as causes of accidents—that there are a number of lessons which are especially forgettable. The first lesson is that the most dangerous kinds of plants are new ones and old ones.

Fig. 17.1 illustrates the prevalence of failures during a plant's life.

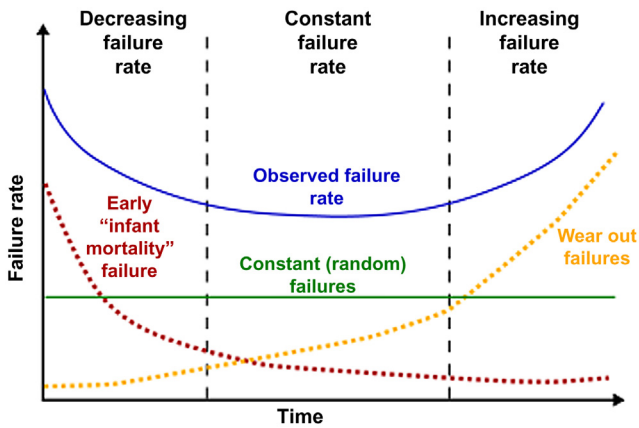



**Figure 17.1** The "bathtub curve."

In chemical engineering, other key lessons are as follows:

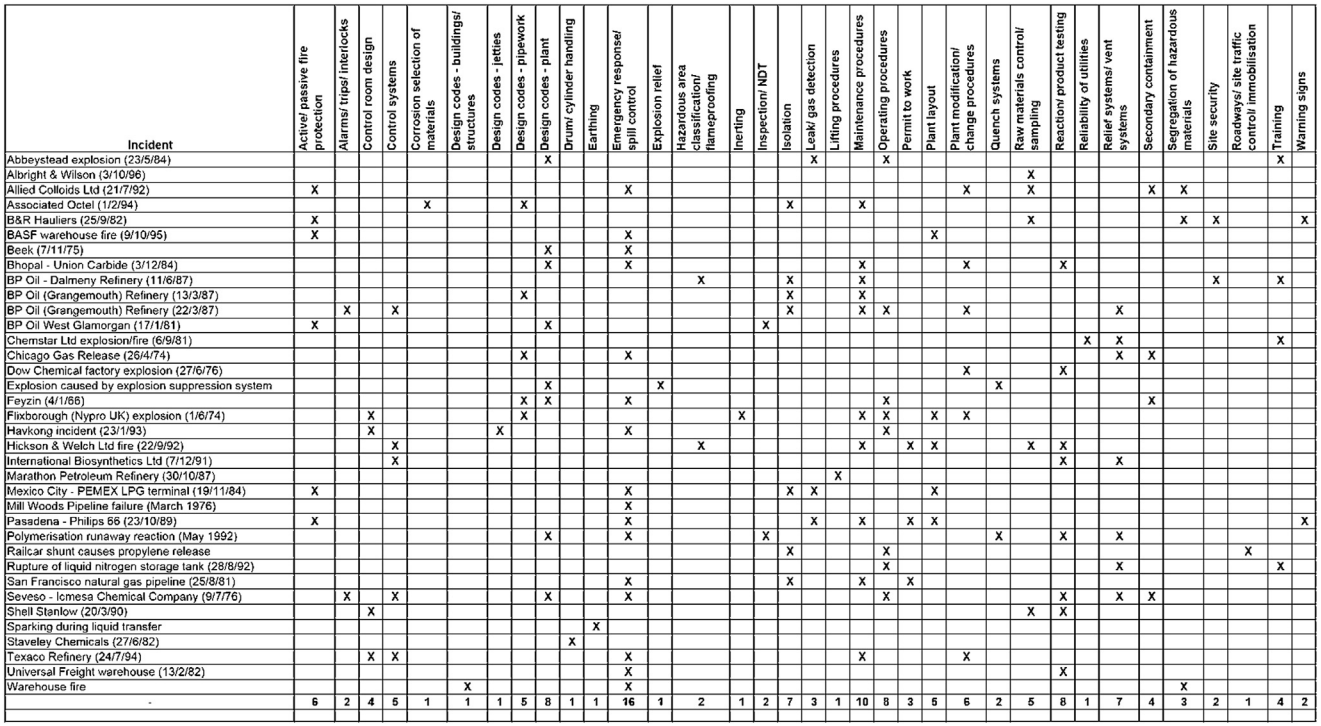
- Explosions are responsible for the maximum acute mortality, morbidity, and environmental impact of chemical plant disasters, but toxic releases can cause more longstanding damage.
- Ammonium nitrate may be hard to detonate, but if it does detonate, it is capable of killing a great many people, as has happened on many occasions.
- LPG is the second most lethal explosive agent in chemical plant disasters after ammonium nitrate.
- We may call them "off-sites," but facilities away from the main process such as warehousing and transport facilities are actually on-site. They are capable of causing great harm to people, the environment, and business continuity, and they all too often do so.
- Commissioning, maintenance, start-up, and shutdown are the most dangerous phases of a plant's operational life.

## Which design errors are the most dangerous?

The UK HSE has produced a summary of the case studies they think are most relevant from the point of view of sites where major accident hazards have to be controlled (Fig. 17.2).

For each accident, the technical measures which failed or were not adequately implemented have been identified, as shown in the list below, arranged in order of number of appearances.

- emergency response/spill control (16);
- maintenance procedures (10);
- *design codes—plant* (8);
- *operating procedures* (8);
- *reaction/product testing* (8);
- *relief systems/vent systems* (7);
- *isolation* (7);
- *active/passive fire protection* (6);
- *plant modification/change procedures* (6);
- *control systems* (5);
- design codes—pipework (5);
- raw materials control/sampling (5);
- *plant layout* (5);
- *control room design* (4);
- *secondary containment* (4);
- training (4);
- *leak/gas detection* (3);



| Incident | Active/ passive fire protection | Alarms/ trips/ interlocks | Control room design | Control systems | Corrosion selection of materials | Design codes - buildings/ structures | Design codes - jetties | Design codes - pipework | Design codes - plant | Drum/ cylinder handling | Earthing | Emergency response/ spill control | Explosion relief | Hazardous area classification/ flameproofing | Inerting | Inspection/ NDT | Isolation | Leak/ gas detection | Lifting procedures | Maintenance procedures | Operating procedures | Permit to work | Plant layout | Plant modification/ change procedures | Quench systems | Raw materials control/ sampling | Reaction/ product testing | Reliability of utilities | Relief systems/ vent systems | Secondary containment | Segregation of hazardous materials | Site security | Roadways/ site traffic control/ immobilisation | Training | Warning signs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abbeystead explosion (23/5/84) | | | | | | | | | X | | | | | | | | | X | | | X | | | | | | | | | | | | X | |
| Albright & Wilson (3/10/96) | | | | | | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | |
| Allied Colloids Ltd (21/7/92) | X | | | | | | | | | | | X | | | | | | | | | | | | X | | X | | | | X | X | | | |
| Associated Octel (1/2/94) | | | | | X | | | X | | | | | | | | | X | | | X | | | | | | | | | | | | | | |
| B&R Hauliers (25/9/82) | X | | | | | | | | | | | | | | | | | | | | | | | | | X | | | | | X | X | | X |
| BASF warehouse fire (9/10/95) | X | | | | | | | | | | | X | | | | | | | | | | | X | | | | | | | | | | | |
| Beek (7/11/75) | | | | | | | | | X | | | X | | | | | | | | | | | | | | | | | | | | | | |
| Bhopal - Union Carbide (3/12/84) | | | | | | | | | X | | | X | | | | | | | | X | | | | X | | X | | | | | | | | |
| BP Oil - Dalmeny Refinery (11/6/87) | | | | | | | | | | | | | | X | | | X | | | X | | | | | | | | | | | X | | X | |
| BP Oil (Grangemouth) Refinery (13/3/87) | | | | | | | | X | | | | | | | | | X | | | X | | | | | | | | | | | | | | |
| BP Oil (Grangemouth) Refinery (22/3/87) | | X | | X | | | | | | | | | | | | | X | | | X | X | | | X | | | | | X | | | | | |
| BP Oil West Glamorgan (17/1/81) | X | | | | | | | | X | | | | | | | X | | | | | | | | | | | | | | | | | | |
| Chemstar Ltd explosion/fire (6/9/81) | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | X | | | | X | |
| Chicago Gas Release (26/4/74) | | | | | | | | X | | | | X | | | | | | | | | | | | | | | | | X | | X | X | | |
| Dow Chemical factory explosion (27/6/76) | | | | | | | | | | | | | | | | | | | | | | | | X | | | X | | | | | | | |
| Explosion caused by explosion suppression system | | | | | | | | | X | | | | X | | | | | | | | | | | | X | | | | | | | | | |
| Feyzin (4/1/66) | | | | | | | | X | X | | | X | | | | | | | | | X | | | | | | | | | X | | | | |
| Flixborough (Nypro UK) explosion (1/6/74) | | | X | | | | | X | | | | | | | X | | | | | X | X | | X | X | | | | | | | | | | |
| Havkong incident (23/1/93) | | | X | | | | X | | | | | X | | | | | | | | | X | | | | | | | | | | | | | |
| Hickson & Welch Ltd fire (22/9/92) | | | | X | | | | | | | | | | X | | | | | | X | | X | X | | | X | X | | | | | | | |
| International Biosynthetics Ltd (7/12/91) | | | | X | | | | | | | | | | | | | | | | | | | | | | | X | | X | | | | | |
| Marathon Petroleum Refinery (30/10/87) | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | | | | | | |
| Mexico City - PEMEX LPG terminal (19/11/84) | X | | | | | | | | | | | X | | | | | X | X | | | | | X | | | | | | | | | | | |
| Mill Woods Pipeline failure (March 1976) | | | | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | |
| Pasadena - Philips 66 (23/10/89) | X | | | | | | | | | | | X | | | | | | X | | X | | X | X | | | | | | | | | | | X |
| Polymerisation runaway reaction (May 1992) | | | | | | | | | X | | | X | | | | X | | | | | | X | | | X | | X | | | | | | | |
| Railcar shunt causes propylene release | | | | | | | | | | | | | | | | | X | | | | X | | | | | | | | | | | X | | |
| Rupture of liquid nitrogen storage tank (28/8/92) | | | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | | | | |
| San Francisco natural gas pipeline (25/8/81) | | | | | | | | | | | | X | | | | | X | | | X | | X | | | | | | | | | | | X | |
| Seveso - Icmesa Chemical Company (9/7/76) | | X | | X | | | | | X | | | X | | | | | | | | | X | | | | | | X | | X | X | | | | |
| Shell Stanlow (20/3/90) | | | X | | | | | | | | | | | | | | | | | | | | | | | X | X | | | | | | | |
| Sparking during liquid transfer | | | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | | |
| Staveley Chemicals (27/6/82) | | | | | | | | | | X | | | | | | | | | | | | | | | | | | | | | | | | |
| Texaco Refinery (24/7/94) | | | X | X | | | | | | | | X | | | | | | | | X | | | X | | | | | | | | | | | |
| Universal Freight warehouse (13/2/82) | | | | | | | | | | | | X | | | | | | | | | | | | | | | X | | | | | | | |
| Warehouse fire | | | | | | X | | | | | | X | | | | | | | | | | | | | | | | | | X | | | | |
| - | 6 | 2 | 4 | 5 | 1 | 1 | 1 | 5 | 8 | 1 | 1 | 16 | 1 | 2 | 1 | 2 | 7 | 3 | 1 | 10 | 8 | 3 | 5 | 6 | 2 | 5 | 8 | 1 | 7 | 4 | 3 | 2 | 1 | 4 | 2 |

**Figure 17.2** Case studies relevant to COMAH. *Courtesy: HSE.*

- permit to work (3);
- *segregation of hazardous materials* (3);
- *alarms/trips/interlocks* (2);
- *hazardous area classification/flameproofing* (2);
- inspection/NDT (2);
- *quench systems* (2);
- site security (2);
- warning signs (2);
- *corrosion selection of materials* (1);
- *design codes—buildings/structures* (1);
- *design codes—jetties* (1);
- drum/cylinder handling (1);
- *earthing* (1);
- *explosion relief* (1);
- *inerting* (1);
- lifting procedures (1)**;**
- *reliability of utilities* (1); and
- *roadways/site traffic control/immobilization* (1).

Issues related to design are in italic type, and the numbers in brackets after each description are the numbers of accidents in this list where this factor contributed. While this is not a formal procedure, it might act as a useful guide to those technical measures where designers should place special attention from the point of view of safety issues. It also broadly aligns with the findings of Kidam and Hurme (see "Further Reading") whose more formal statistical analysis found that 79% of process plant accidents involved a design error, and that the most common type of design error leading to accidents was poor layout.

The design issue highest on the list above is working to codes. This should be unsurprising to anyone who has got this far through the book. Codes and standards codify past experience of what works and what does not, what is safe, and what is not. Codes and standards tell you what to do, and how to do it, but they do not tell you "why." "Why" can only be understood through real-world experience.

While blind compliance with codes does not guarantee safe design, designers ignore codes at their peril. You are under no obligation to follow many codes and standards, but you may find yourself having an uncomfortable few days in court if you don't and there is later a serious incident at the plant you designed.

The position of layout on this list seems anomalous, compared with Kidam and Hurme's findings. This may be to do with how the term is being defined—control room design may, for example, be a subset of plant layout. When researching *Process Plant Layout*, I had no trouble finding 75 case studies where plant layout had caused serious incidents on process plants.

One lesson I learned in carrying out that exercise was that areas and streams that are commonly thought of as "safe" or less hazardous than the process units themselves can lead designers into a false sense of security. Simple utilities such as compressed air, water, and steam regularly kill people, and warehousing and transport facilities are far more dangerous than most process engineers might think. I had too many, too similar case studies for these areas, and had to leave some out. I have included a typical one later in this chapter as an illustration.

Of these, there are some examples which are of the greatest importance, essential illustrations of good design principles. Bhopal, Flixborough, Seveso, and Pasadena are arguably the most important of those, and I have reproduced the circumstances of each of these in the high-impact case studies section.

## High-impact case studies

These incidents are high impact in the sense that many people were killed or badly harmed, and also, in several cases, that they were the trigger for new safety and/or environmental legislation intended to prevent recurrence.

### Flixborough (Nypro UK) Explosion, June 1, 1974

#### *Take-home message*

As Kletz wrote:

> *The most famous of all temporary modifications is the temporary pipe installed in the Nypro Factory at Flixborough, UK, in 1974...Very few engineers have the specialized knowledge to design highly stressed piping. But in addition, the engineers at Flixborough did not know that design by experts was necessary....They did not know what they did not know.*

#### *Effect on legislation/codes/standards*

This incident happened during the writing of the UK Health and Safety at Work Act and had a major effect on the legislation.

#### *Accident summary*

At about 16:53 hours on Saturday June 1, 1974, the Nypro (UK) site at Flixborough was severely damaged by a large explosion. Twenty-eight workers were killed and a further 36 suffered injuries. It is recognized that the number of casualties would have been greater if the incident had occurred on a weekday, as the main office block was not occupied. Offsite consequences resulted in 53 reported injuries. Property in the surrounding area was damaged to a varying degree.

Three months prior to the explosion, it had been discovered that a vertical crack in reactor No. 5 was leaking cyclohexane. The plant was subsequently shut-down for an investigation. The investigation that followed identified a serious

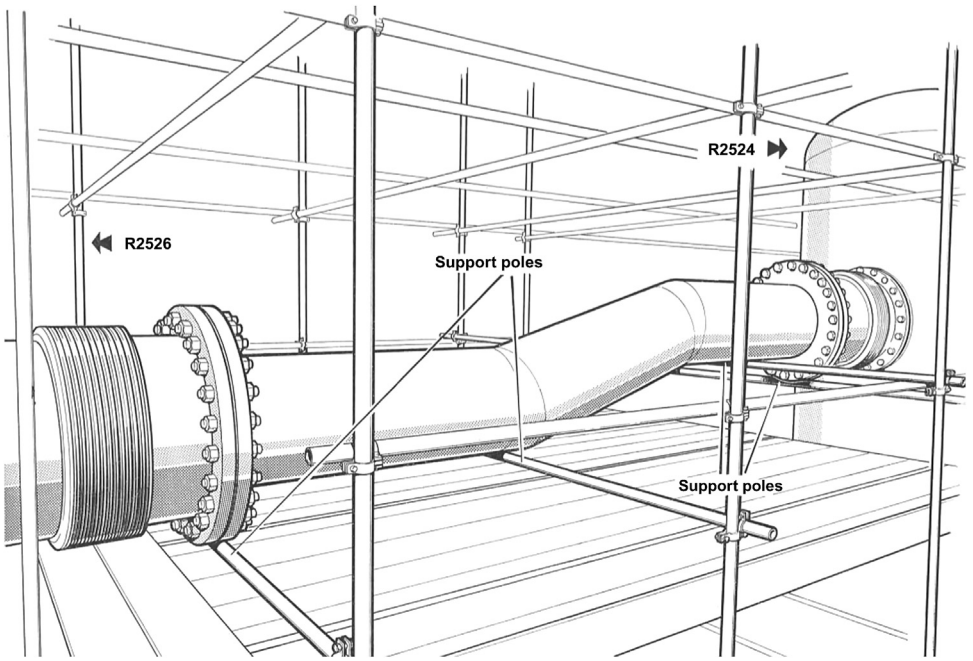



**Figure 17.3** Sketch of the 20-in. pipe scaffolding arrangement at Flixborough.[1] *Reproduced from the Report of the Court of Inquiry, Department of Employment, HMSO, 1975.*

problem with the reactor and the decision was taken to remove it and install a 20-in. bypass assembly to connect reactor Nos. 4 and 6 so that the plant could continue production.

During the late afternoon on June 1, 1974, the 20-in. bypass system illustrated in Fig. 17.3 ruptured, which may have been caused by a fire on a nearby 8-in. pipe. This resulted in the escape of a large quantity of cyclohexane. The cyclohexane formed a flammable mixture and subsequently found a source of ignition. At about 16:53 hours there was a massive vapor cloud explosion which caused extensive damage and started numerous fires on the site.

Eighteen fatalities occurred in the control room as a result of the windows shattering and the collapse of the roof. No one escaped from the control room. (Unless you are in a blast-proof building, your chances of surviving an explosion are better in the open. Assuming you aren't thrown into something, the human body can better withstand overpressure than "standard" buildings.) The fires burned for several days and after 10 days those that still raged were hampering the rescue work.

[1] Crown Copyright: Licensed under the Open Government License 3.0; http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/.

### *Failings in technical measures*

- Plant modification/change procedures: no Hazard and Operability (HAZOP) study was undertaken. A plant modification occurred without a full assessment of the potential consequences. Only limited calculations were undertaken on the integrity of the bypass line. No calculations were undertaken for the dog leg-shaped line or for the bellows. No engineering drawing of the proposed modification was produced.
- Design codes—pipework: use of underdesigned flexible pipes.
- Maintenance procedures—recommissioning: no pressure testing was carried out on the installed pipework modification.
- Plant layout—positioning of occupied buildings; those concerned with the design, construction, and layout of the plant did not consider the potential for a major disaster happening instantaneously.
- Control room design: structural design could not withstand major hazards events.
- Operating procedures: there were a number of critical decisions to be made. The incident happened during start-up when critical decisions were made under operational stress, though very few hazardous events happen so quickly that you can't "sit down for a cup of tea" and discuss what is actually happening.
- Inerting—reliability/backup/proof testing; in particular the shortage of nitrogen for inerting would tend to inhibit the venting of off-gas as a method of pressure control/reduction.
- Personnel: no qualified personnel (e.g., mechanical/piping engineers) were consulted as none were available, and the staff on site did not know what they did not know.

  *Source*: HSE.

## Icmesa Chemical Company, Seveso, Italy, July 10, 1976

### *Take-home message*

Learn from experience: There had been previous incidents leading to the closure of other plants making the same intermediate product.

### *Effect on legislation/codes/standards*

Led to the Seveso Directive, a European Union law aimed at improving the safety of sites containing large quantities of dangerous substances.

### *Accident summary*

At approximately 12:37 on Saturday July 10, 1976, a bursting disc on a chemical reactor ruptured. Maintenance staff heard a whistling sound and a cloud of vapor was seen to issue from a vent on the roof. A dense white cloud of considerable altitude drifted offsite.

Among the substances in the white cloud was a small deposit of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin ("TCDD" or "dioxin"), a highly toxic material.

The release lasted for some 20 minutes. Over the next few days following the release there was much confusion due to the lack of communication between the company and the authorities in dealing with this type of situation.

The nearby town of Seveso, located 15 miles from Milan, had some 17,000 inhabitants. No human deaths were attributed to TCDD but many individuals fell ill. Twenty-six pregnant women who had been exposed to the release had abortions. Thousands of animals in the contaminated area died and many thousands more were slaughtered to prevent TCDD entering the food chain.

### *Failings in technical measures*

- Operating procedures—safe operating procedures: The production cycle was interrupted, without any agitation or cooling, prolonging holding of the reaction mass. (It was decided to leave the reactor full over the weekend as they couldn't empty it before the end of the last Friday shift.) Also, the conduct of the final batch involved a series of failures to adhere to the operating procedures. The original method of distillation patent specified that the charge was acidified before distillation. However, in the plant procedures the order of these steps was reversed.
- Relief systems/vent systems: venting of excessive pressures, sizing of vents for exothermic reactions. The bursting disc was set at 3.5 barg to guard against excessive pressure in the compressed air used to transfer the materials to the reactor. Had a bursting disc with a lower set pressure been installed, venting would have occurred at a lower and less hazardous temperature.
- Control systems—sensors alarms/trips/interlocks: loss of cooling, agitator failure. The reactor control systems were inadequate, both in terms of the measuring equipment for a number of fundamental parameters and in the absence of any automatic control system.
- Reaction/product testing: calorimetry methods, thermal stability. The company was aware of the hazardous characteristics of the principal exotherm. However, studies showed that weaker exotherms existed that could lead to a runaway reaction.
- Design codes—plant: nature of hazardous releases. There was no device to collect or destroy the toxic materials as they vented.
- Secondary containment: catchpots. The bursting disc manufacturer recommended using a second receiver to recover toxic materials. No such vessel was fitted.
- Emergency response/spill control: safety management system, site emergency plan. Information on the chemicals released and their associated hazards was not available from the company. Communication was poor and failed both between the company and the local authorities and within the regulatory authorities.

  *Source*: HSE.

## PEMEX LPG Terminal, Mexico City, Mexico, November 19, 1984

### *Take-home message*

Layout: Designers should consider proximity to highly populated areas, sensitive environmental habitats, watercourses, etc. when selecting a location for new plant.

### *Effect on legislation/codes/standards*

None. Many in Mexico still consider the local investigation and death toll inadequate.

### *Accident summary*

At approximately 05:35 hours on November 19, 1984 a major fire and a series of catastrophic explosions occurred at the government-owned and government-operated PEMEX LPG Terminal at San Juan Ixhuatepec, Mexico City. As a consequence of these events some 500 individuals were killed and the terminal destroyed.

Three refineries supplied the facility with LPG on a daily basis. The plant was being filled from a refinery 400 km away, as on the previous day it had become almost empty. Two large spheres and 48 cylindrical vessels were filled to 90% and four smaller spheres to 50% full.

A drop in pressure was noticed in the control room and also at a pipeline pumping station. An 8-in. pipe between a sphere and a series of cylinders (known in the industry as bullet tanks) had ruptured. Unfortunately, the operators could not identify the cause of the pressure drop. The release of LPG continued for about 5–10 minutes when the gas cloud, estimated at 200 m × 150 m × 2 m high, drifted to a flare stack. It ignited, causing a violent ground shock. A number of ground fires occurred. Workers on the plant then tried to deal with the escape by taking various actions. At a late stage somebody pressed the emergency shutdown button.

About 15 minutes after the initial release the first boiling liquid expanding vapor explosion (BLEVE) occurred. For the next hour and a half there followed a series of BLEVEs as the LPG vessels violently exploded. LPG was said to have rained down and surfaces covered in the liquid were set alight. The explosions were recorded on a seismograph at the University of Mexico.

### *Failings in technical measures*

The total destruction of the terminal occurred because there was a failure of the overall basis of safety which included the layout of the plant and emergency isolation features.

- Plant layout: positioning of the vessels.
- Isolation: emergency isolation means.
- Active/passive fire protection: survivability of critical systems, insulation thickness, water deluge. The terminal's firewater system was disabled in the initial blast, and the water spray systems were inadequate.

- Leak/gas detection: The installation of a more effective gas detection and emergency isolation system could have averted the incident. The plant had no gas detection system and therefore when the emergency isolation was initiated it was probably too late.
- Emergency response/spill control: site emergency plan, access of emergency vehicles. Hindering the arrival of the emergency services was the traffic chaos, which built up as local residents sought to escape the area.

  *Sources*: Multiple.

## Phillips 66, Pasadena, United States, October 23, 1989

### *Take-home message*

Plant layout matters.

### *Effect on legislation/codes/standards*

Influenced and accelerated introduction of OHSA's Process Safety Management PSM 1910.119 Standard.

### *Accident summary*

At approximately 1:00 p.m. on October 23, 1989, Phillips' 66 chemical complex at Pasadena, near Houston (United States) experienced a chemical release on the polyethylene plant. A flammable vapor cloud formed which subsequently ignited resulting in a massive vapor cloud explosion. Following this initial explosion there was a series of further explosions and fires.

The consequences of the explosions resulted in 23 fatalities and between 130 and −300 people were injured. Extensive damage to the plant facilities occurred.

The day before the incident, scheduled maintenance work had begun to clear three of the six settling legs (see Fig. 17.4) on a reactor.

A specialist maintenance contractor was employed to carry out the work. A procedure was in place to isolate the leg to be worked on. During the clearing of No. 2 settling leg, part of the plug remained lodged in the pipework. A member of the team went to the control room to seek assistance. Shortly afterwards the release occurred. Approximately 2 minutes later the vapor cloud ignited.

### *Failings in technical measures*

- Maintenance procedures: isolation. The accident investigation established that the single isolating ball valve was actually open at the time of the release. The air hoses to the valve had been cross-connected so that the air supply that should have closed the valve actually opened it. The incident might have been avoided if the DEMCO valve actuator design had used two different connections supplying air to open and close the valve. Elimination of a hazard might be as simple as using different sizes or types of coupling for hose connections.

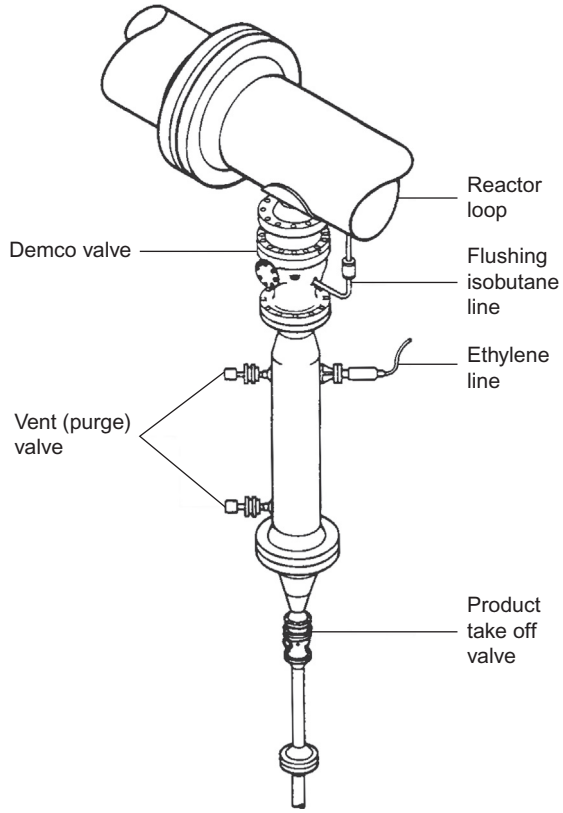



**Figure 17.4** The settling leg arrangement. *Courtesy: US Department of Labor, OSHA. (1990). Phillips 66 Houston Chemical Complex Explosion and Fire; Implications for Safety and Health in the Petrochemical Industry.*

- Maintenance procedures: recommissioning. Site procedures specified that air hoses to valves were to be disconnected prior to maintenance work. This task was not carried out. Both the company and industry safety required isolation by means of a double-block system or the use of a blind flange. However, at plant level a procedure had been adopted which did not comply with this.
- Maintenance procedures: training/competence, management/supervision.
- Leak/gas detection: positioning of detectors. The site held a large inventory of flammable materials under high pressure yet it had no fixed gas detection system.
- Plant layout: positioning of occupied buildings. Ventilation intakes of buildings close to or downwind of the process plant were not arranged so as to prevent the intake of gas in the event of a release.
- Permit to work systems: working in hazardous areas. An effective permit to work (PTW) for both company employees and contractors was not enforced by the company.

- Active/passive fire protection: testing and inspection. There was no dedicated firewater system. Firewater was drawn off from the process water system. This system was severely damaged in the explosions resulting in a loss of water pressure. The firewater pumps failed when the raging fires attacked their electrical supply cables. Of the three standby diesel pumps units, one was under maintenance and another ran out of fuel.
- Warning signs: human factors. Some concern was expressed as to the audible level of the emergency alarm. It was likely that individuals in certain parts of the plant were unable to hear the siren.
- Emergency response/spill control: site emergency plan. The intended control center was damaged beyond use and telephone communications disrupted.
- Plant layout: position of occupied buildings. The location of the control room, separation distances between plant and escape routes (particularly for administrative staff) were all criticized.

  *Sources*: Multiple.

## Texas City Disaster, Texas City, United States, April 16, 1947

### *Take-home message*

Ammonium nitrate is dangerous. This might seem obvious, but this is just one of the many disasters which have occurred as a result of poor handling of ammonium nitrate, a lesson which never seems to be learned. A total of 173 people were killed in Tianjin in 2015 by an ammonium nitrate explosion. The earliest recorded industrial ammonium nitrate explosion was in Faversham, Kent, United Kingdom, in 1919, and an explosion of ammonium nitrate in Oppau, Germany, in 1921 killed only slightly fewer people than Texas City.

### *Effect on legislation/codes/standards*

This incident was the cause of the first ever class action lawsuit against the US government, (Elizabeth Dalehite, et al. vs United States) under the then-recently enacted Federal Tort Claims Act. The case went backward and forward through the US courts until a law was passed by Congress in 1955 to allow compensation to be paid to the victims.

### *Accident summary*

The Texas City disaster has, to date, the highest confirmed death toll of any accident involving chemical transportation. Poor control of a fire on board the SS Grandcamp, docked in the port at Texas City, led to detonation of its cargo of approximately 2000 tons of ammonium nitrate. The captain mistakenly tried to extinguish the fire with steam to avoid damaging the cargo, which only worsened matters.

The initial blast and the subsequent chain reaction of further fires and explosions in other ships and nearby oil storage and refining and styrene manufacturing facilities killed at least 581 people. This toll included all but one member of the Texas City fire department, and scores of onlookers. Many thousands of others were injured.

Lack of crowd control led to onlooker casualties. The unusual yellow-orange smoke from the burning of nitrous oxide (evolved from heated ammonium nitrate) had attracted several hundred spectators along the shoreline, who mistakenly believed they were a safe distance away.

A discarded cigarette is thought to be the most likely ignition source.

### *Failings in technical measures*

- Emergency response/spill control: site emergency plan, emergency operating procedures/training, separation distances between plant and escape routes. The public were unaware of the danger they were in.
- Plant layout: position of occupied buildings, domino effects.
- Active/passive fire protection: no effective measures in place.
- Hazardous area classification/flameproofing: ignition sources identification and elimination.

*Sources*: Multiple.

## Union Carbide India Ltd, Bhopal, India, December 3, 1984

### *Take-home message:*

*What you don't have, can't leak*

### *Effect on legislation/codes/standards*

Seveso II.

### *Accident summary*

In the early hours of December 3, 1984, a relief valve on a storage tank containing highly toxic methyl isocyanate (MIC) lifted. A cloud of MIC gas was released which drifted onto nearby housing.

Prior to this, at 23.00 hours on December 2, an operator noticed the pressure inside the storage tank to be higher than normal but not outside the working pressure of the tank. At the same time an MIC leak was reported near the vent gas scrubber (VGS). At 00.15 hours an MIC release in the process area was reported. The pressure inside the storage tank was rising rapidly so the operator went outside to the tank. Rumbling sounds were heard from the tank and a screeching noise from the safety valve. Radiated heat could also be felt from the tank.

Attempts were made to switch on the VGS but this was not in operational mode.

Approximately 2000 people died within a short period and tens of thousands were injured, overwhelming the emergency services. This was further compounded by the fact that the hospitals were unaware as to which gas was involved or what its effects were. The exact numbers of dead and injured are uncertain, as people have continued to die of the effects over a period of years. The severity of this accident makes it the worst recorded within the chemical industry, though not necessarily by immediate death toll.

### *Failings in technical measures*

- Plant modification/change procedures: HAZOP, identification of safety-critical elements. The flare system was a critical element within the plant's protection system. However, this fact was not recognized as it was out of commission for some 3 months prior to the accident.
- Reaction/product testing: laboratory testing. Hazards associated with runaway reactions in a chemical reactor are generally understood. However, the possibility of such an occurrence within a storage tank had received little research.
- Design codes—Plant: ingress of unwanted material. The ingress of water caused an exothermic reaction with the process fluid. The exact point of ingress is uncertain though poor modification/maintenance practices may have contributed.
- Maintenance procedures: training and competence levels.
- Decommissioning procedures: The decommissioning of the refrigeration system was one plant modification that contributed to the accident. Without this system the temperature within the tank was higher than the design temperature of 0°C.
- Emergency response/spill control: site emergency plan, emergency operating procedures/training. The emergency response from the company to the incident and from the local authority suggests that the emergency plan was ineffective. During the emergency operators hesitated about when to use the siren system. No information was available regarding the hazardous nature of MIC and what medical actions should be taken.

### *Failure to learn from experience*

Other Union Carbide plants in the United States used a continuous rather than batch process, which meant that the MIC was consumed as it was produced, rather than requiring large-scale MIC storage. This wasn't implemented at Bhopal.

*Source*: HSE.

## Three Mile Island Reactor Meltdown, Pennsylvania, United States, March 28, 1979

### *Take-home message*

Elevation of process equipment is important—the small elevation difference between the pressurized water reactor and the steam generator was critical because the piping arrangement resulted in creation of siphon loops in the water circulation lines which caused vapor locking and prevented convection cooling.

### *Effect on legislation/codes/standards*

Federal requirements to correct safety issues and design deficiencies became more stringent.

### *Accident summary*

Loss-of-coolant accidents are not uncommon in the nuclear industry, but Three Mile Island is still the most famous. The coolant in this case was water, and, at Three Mile Island, the failure of feedwater pumps precipitated a chain of events which led to a core meltdown.

The accident began about 04:00 hours on March 28, 1979, when the plant experienced a failure in the secondary, nonnuclear section of the plant (one of two reactors on the site). Either a mechanical or electrical failure prevented the main feedwater pumps from sending water to the steam generators that remove heat from the reactor core. This caused the plant's turbine-generator and then the reactor itself to automatically shut down. Immediately, the pressure in the primary system (the nuclear portion of the plant) began to increase.

In order to control that pressure, the pilot-operated relief valve (a valve located at the top of the pressurizer) opened. The valve should have closed when the pressure fell to proper levels, but it became stuck open. Instruments in the control room, however, indicated to the plant staff that the valve was closed. As a result, the plant staff were unaware that cooling water was pouring out of the stuck-open valve.

As coolant flowed from the primary system through the valve, other instruments available to reactor operators provided inadequate information. There was no instrument that showed how much water covered the core. As a result, plant staff assumed that as long as the pressurizer water level was high, the core was properly covered with water.

As alarms rang and warning lights flashed, the operators did not realize that the plant was experiencing a loss-of-coolant accident. They took a series of actions that made conditions worse. The water escaping through the stuck valve reduced primary system pressure so much that the reactor coolant pumps had to be turned off to prevent dangerous vibrations. To prevent the pressurizer from filling up completely, the staff reduced how much emergency cooling water was being pumped into the primary system. These actions starved the reactor core of coolant, causing it to overheat.

Without the proper water flow, the nuclear fuel overheated to the point at which the zirconium cladding (the long metal tubes that hold the nuclear fuel pellets) ruptured and the fuel pellets began to melt. It was later found that about half of the core melted during the early stages of the accident. Although TMI-2 suffered a severe core meltdown, the most dangerous kind of nuclear power accident, consequences outside the plant were minimal.

### *Failings in technical measures*

Lack of instrumentation and lack of anticipation of the failure mode.

*Sources*: Multiple.

## Esso Gas Plant Explosion, Longford, Victoria, Australia, September 25, 1998

### *Take-home message*

Caused by failure to conduct process hazard analysis during design. For equipment in cryogenic service or exposed to volatile materials which may auto-refrigerate, careful material selection must be made to avoid brittle fracture.

### *Effect on legislation/codes/standards*

Following the Longford accident, Victoria introduced Major Hazard Facilities regulations for plants that contain major chemical hazards, which require facility operators to "demonstrate" COMAH using a Safety Management System and a Safety Case.

### *Accident summary*

This incident, which killed two men and caused massive economic damage, was caused ultimately by a failure to conduct process hazard analysis during design. Selection of materials of construction must consider abnormal as well as normal service conditions including variations in operating temperature or process fluid corrosivity (start-up, trip, shutdown, feedstock supplier).

A pump supplying heated lean oil to heat exchanger GP905 at the Esso Longford facility went offline for 4 hours. Temperatures in this heat exchanger normally ranged from 60°C to 230°C, but investigators estimated that, due to the failure of the pump, parts of GP905 experienced temperatures as low as −48°C.

Ice formed on the heat exchanger, and it was decided to resume pumping heated lean oil into the exchanger to thaw it out. When the lean oil pump resumed pumping oil into the heat exchanger at 230°C, the temperature differential caused a brittle fracture in the exchanger.

About 10 t of hydrocarbon vapor were immediately vented from the rupture, and the released vapor cloud drifted downwind until it reached a set of heaters 170 m away where it ignited. This caused a deflagration, but no explosion, so the nearby control room remained undamaged. When the deflagration front reached the rupture in the heat exchanger, a fierce jet fire was ignited that burned for 2 days.

Damage was localized to the area around and above the affected exchanger, but two men were still killed, and eight others injured. The whole plant was shut down immediately, and along with it the state of Victoria's entire gas supply, which proved devastating to the local economy, incurring losses to industry estimated at around A $1.3 billion (US$1 billion).

### *Failings in technical measures*

- Isolation: emergency isolation means. The Royal Commission of Enquiry found that the Longford plant had been designed in such a way as to make the isolation of any release of flammable vapor very difficult.
- Plant modification/change procedures: No HAZOP was undertaken. A HAZOP study should have highlighted the risk of heat exchanger rupture in the event of failure of the heated lean oil pump.

  *Source*: Multiple.

## Occidental Petroleum OPCAL Piper Alpha, North Sea, United Kingdom, July 6, 1988

### *Take-home message*

Of multiple process and plant design issues that were a factor in this accident, the most significant was the absence of fireproofing on structural steel even though management knew that structural integrity could be lost with 10–15 minutes if a fire was fed from the site's large pressurized hydrocarbon inventory. Furthermore, the gas risers upstream of the emergency isolation valves on Piper Alpha were not protected against fire exposure and, because of the diameter and length of the interplatform gas lines, several days would be required to depressurize the pipelines in the event of a breach. Absence of adequate evacuation routes was another factor in the high death toll.

### *Effect on legislation/codes/standards*

Offshore Installations (Safety Case) Regulations 1992.

### *Accident summary*

An explosion and resulting oil and gas fires destroyed Piper Alpha on July 6, 1988, killing 167 people, including two crewmen of a rescue vessel. Just 61 workers escaped and survived, and 30 bodies were never recovered.

At the time of the disaster, the platform accounted for approximately 10% of North Sea oil and gas production, and the accident is the worst offshore oil disaster in terms of lives lost and industry impact.

The disaster led to insurance claims of around US$1.4 billion, making it at that time the largest insured manmade catastrophe. The total insured loss was about £1.7 billion ($3.4 billion), making it one of the costliest manmade catastrophes ever. The insurance and reinsurance claims process revealed serious weaknesses in the way insurers at Lloyd's of London and elsewhere kept track of their potential exposures and led to their procedures being reformed.

The report of the Cullen inquiry into the incident made 106 recommendations for changes to North Sea safety procedures: 37 recommendations covered procedures for operating equipment, 32 the information of platform personnel, 25 the design of

platforms, and 12 the information of emergency services.Most significant of these recommendations was that operators were required to present a safety case under the Offshore Installations (Safety Case) Regulations 1992, and that the responsibility for enforcing safety in the North Sea should be moved from the Department of Energy to the Health and Safety Executive.

### *Failings in technical measures*

- Maintenance procedures: isolation. The initial condensate leak was the result of maintenance work being carried out simultaneously on a pump and related safety valve.
  *Sources*: Multiple.

## Explosion at BP Texas City Refinery, Texas, United States, March 23, 2005

### *Take-home message*

The high death toll from this incident was mainly due to there being occupied trailers and vehicles so close to the site of the explosion, in violation of safety standards which were written following a similar past incident.

### *Effect on legislation/codes/standards*

The U.S. Chemical Safety and Hazard Investigation Board (CSB) made 26 recommendations after their investigation of this incident. These included modifications to API, ANSI, NPRA, CCPS, and OHSA advice. Some of the recommended practices affected such as API RP521 are de facto international standards in the oil and gas industry.

### *Accident summary*

A hydrocarbon vapor cloud exploded at the ISOM isomerization process unit at BP's Texas City refinery, killing 15 workers and injuring more than 170 others. BP's own accident investigation report stated that the direct cause of the accident was "heavier-than-air hydrocarbon vapors combusting after coming into contact with an ignition source, probably a running vehicle engine. The hydrocarbons originated from liquid overflow from the F-20 blowdown stack following the operation of the raffinate splitter overpressure protection system caused by overfilling and overheating of the tower contents."

### *Failings in technical measures*

Both the BP and the US Chemical Safety and Hazard Investigation Board reports identified numerous technical and organizational failings at the refinery and within corporate BP, but the consequences of the accident were considerably worsened by the proximity of trailers and vehicles used by contracting staff.

- Plant layout: positioning of occupied buildings. The presence of temporary structures in a location susceptible to severe damage in the event of an explosion was found to be ultimately due to management deficiencies, since this was a well-known hazard, reflected in written safety procedures.

#### *Failure to learn from experience*

In 1995, five workers had been killed at a refinery belonging to Pennzoil when two storage tanks exploded, engulfing a trailer which they were in. The recommendation of the investigation was that trailers should not be located near hazardous materials. However, BP's procedures, intended to implement these recommendations, were not followed in Texas City.

*Sources*: Multiple.

## Layout-related case studies

### Fukushima Daiichi Nuclear Disaster, Fukushima, Japan, March 11, 2011

#### *Take-home message*

Consideration should be given by designers to environmental and climatic factors affecting plant location (low temperatures causing icing-up of critical safety equipment, dust, or sand storms interfering with lubrication of critical rotating machinery, earthquake causing major structural damage, tsunami causing floods which disable critical safety equipment, etc.).

#### *Effect on legislation/codes/standards*

In 2014 Japan enacted the State Secrecy Law. The Fukushima incident falls under this law and independent investigations and reports are prohibited by law.

#### *Accident summary*

The Fukushima Daiichi nuclear disaster was a nuclear disaster at the Fukushima I Nuclear Power Plant that began on March 11, 2011, and resulted in a meltdown of three of the plant's six nuclear reactors. The failure occurred when the plant was hit by a tsunami that had been triggered by the magnitude 9.0 Tōhoku earthquake. The following day, substantial amounts of radioactive material began to be released, creating the largest nuclear incident since the Chernobyl disaster in April 1986 and the only one other than Chernobyl to measure Level 7 on the International Nuclear Event Scale.

The disaster arguably occurred entirely as a result of a failure to ensure continuity of utility supply. A significant contributor to the severity of the outcome of the accident was the power requirements of emergency equipment, and the failure of

designers to ensure that backup generators would continue to function in the entirely foreseeable event of inundation of the site by a tsunami.

Safety-critical instrumentation, emergency reactor cooling systems, and systems controlling radiation release in the event of meltdown were all dependent on electricity supplied by standby generators in low-lying rooms, unprotected from inundation. Insufficient allowance had been made in the design for the possibility of tsunami—ironically—in the country which coined the term.

### *Failings in technical measures*

The Fukushima Nuclear Accident Independent Investigation Commission in fact found that the disaster was "manmade," as its causes were all foreseeable. The report also found that the plant was incapable of withstanding an earthquake or tsunami. Japanese regulators were found to have failed to require plant owners to meet the most basic safety requirements, such as assessing the probability of damage, preparing for containing collateral damage from such a disaster, and developing evacuation plans.

The original plans separated the piping systems for two reactors in the isolation condenser from each other. However, the application for approval of the construction plan showed the two piping systems connected outside the reactor. The changes were not noted, in violation of regulations.

After the tsunami, the isolation condenser should have taken over the function of the cooling pumps, by condensing the steam from the pressure vessel into water to be used for cooling the reactor. However, the condenser did not function properly.

*Sources*: Multiple.

## Arkema Plant Explosion, Crosby, Texas, United States, August 29, 2017

### *Take-home message*

Make sure your disaster plan is robust.

### *Effect on legislation/codes/standards*

The CSB report on the incident made a number of local recommendations as well as a suggestion that the CSB require broad and comprehensive guidance to help companies assess their US facility risk from all types of potential extreme weather events, addressing "actions required to prepare for extreme weather, resiliency and protection of physical infrastructure and personnel during extreme weather, as well as recovery operations following an extreme weather event."

### *Accident summary*

The 2017 Arkema plant explosion was an industrial disaster that took place during Hurricane Harvey in Crosby, Texas. Flooding from the hurricane disabled the refrigeration system at the plant which manufactured organic peroxides.

A 12-person rideout crew had been assigned to manage the facility during the hurricane. According to the staff log, the employees were assuming minor flooding at the site. Instead, flooding rapidly outpaced the company's disaster plans. The plant flooded up to six feet deep, refrigeration was lost on August 29, and people within a 1.5-mile radius were evacuated the following day. Ignited by a runaway reaction of the organic peroxides, the first explosions took place around 1:00 a.m. on August 31.

As floodwaters receded, officials decided to stop the delay for the return of the Crosby community of 2300 by igniting the remaining trailers, on Sunday, September 3, 2017. The evacuation zone was lifted on September 4, 2017.

In addition to the explosions, two wastewater tanks overflowed during the storm, releasing more than 23,000 pounds of contaminants that were carried by floodwaters into nearby homes, including heavy metals, polycyclic aromatic hydrocarbons, dioxins, and semivolatile organic compounds which were identified in homes and soil in neighborhoods near the plant. It is uncertain what proportion of the chemical residues originated in gases released by the plant, and what proportion flowed out of the flooded wastewater tanks.

On Thursday, August 31, 2017, the same day as the first fire, the US Chemical Safety Board announced an investigation, and the Environmental Protection Agency began formally asking questions of Arkema on September 7, 2017. A 2016 analysis carried out by the Houston Chronicle and Texas A&M identified the Arkema facility as a facility posing a high potential for harm to the public. The analysis and subsequent series by the newspaper revealed major flaws in the regulation of chemical facilities. In February 2017, OSHA issued safety fines regarding general safety and maintenance to the sum of $91,724.

### *Failings in technical measures*

Flood risk had not been managed to ALARP, and disaster plan was inadequate.

*Sources*: Multiple.

## Conoco Humberside Refinery Incident, Killingholme, United Kingdom, April 16, 2001

### *Take-home message*

Layout is important. For high-hazard plants, designers should consider siting permanent occupied buildings outside the perimeter fence and avoid positioning them downwind of the plant. The incident could have been much worse if the contractor's canteen had been occupied at the time of the explosion.

### *Effect on legislation/codes/standards*

The causes of the incident were found to be a failure to apply existing industry good practice, codes, and standards.

### *Accident summary*

The 2001 Humber Refinery explosion was a major incident at the then Conoco-owned Humber Refinery at South Killingholme in North Lincolnshire, England. A large explosion occurred on the Saturate Gas Plant (SGP) area of the site on Easter Monday, April 16, 2001, at approximately 2:20 p.m. There were no fatalities, but two people were injured.

The incident temporarily shut down the entire refinery and caused oil prices to increase. Damage was caused to the nearby villages of North and South Killingholme as well as the nearby town of Immingham—mainly doors being blown from their hinges and windows being blown in.

ConocoPhillips (now Phillips 66) was investigated and subsequently fined £895,000 and ordered to pay £218,854 costs by the Health and Safety Executive for failing to effectively monitor the degradation of the refinery's pipework. The company pleaded guilty to these charges in court and has since implemented a risk-based inspection program.

### *Failings in technical measures*

#### Management of pipework inspection

ConocoPhillips failed to implement an effective system for the inspection of pipework on the SGP, to complement that in place for process equipment. The system used fell far below recognized industry good practice at the time.

#### Management of change

The design and installation of the water injection point was not subject to any MoC assessment. Had such an assessment been carried out the corrosion risk that the injection point introduced for the downstream pipework could have been identified.

#### Management of corrosion

ConocoPhillips corrosion management was not sufficiently thorough or systematic to prevent the failure of P4363. Some positive actions were taken, including the appointment of a full-time corrosion engineer for the refinery, introduction of divisional corrosion reviews, and monitoring of process streams by sampling and the installation of corrosion probes, following receipt of specific information in 1992 about the vulnerability of carbon steel pipework in the vicinity of water injection points.

#### Communication

Two significant communication failings contributed to this incident. First, the various changes to the frequency of use of water injection were not communicated outside plant operations personnel. As a result, there was a belief elsewhere that it was in occasional use only and did not constitute a corrosion risk. Second, information from the

P4363 injection point inspection, carried out in 1994, was not adequately recorded or communicated with the result that the recommended further inspections of the pipe were never carried out.

*Sources*: Multiple.

## Valero McKee Refinery Fire, Sunray, Texas, United States, February 16, 2007

### *Take-home message*

Spacing and fire protection of facilities handling toxic substances require special attention if fire exposure could lead to equipment failure and toxic releases.

### *Effect on legislation/codes/standards*

The CSB made four recommendations for changes to API recommended practices in their report on this incident.

### *Accident summary*

On February 16, 2007, a leak of high-pressure propane on a propane deasphalting (PDA) unit at Valero McKee refinery (Texas, United States) formed a large flammable vapor cloud which found an ignition source causing a series of jet fires and collapse of an elevated pipe rack which further fueled the fire. Three employees suffered serious burns and several others suffered minor injuries. The fire was so large that the whole refinery had to be evacuated and the resulting damage forced the refinery to remain shut down for nearly 2 months. It then operated at reduced capacity for nearly 1 year. The massive fire in this incident almost had further catastrophic consequences. One of the jet fires caused a large release of highly toxic chlorine gas stored in pressurized cylinders near the PDA unit (used as biocide in cooling water). Fortunately, first responders and all other refinery personnel had already been evacuated from the refinery by then. The intensity of the fire caused by collapse of the elevated pipe rack resulted in blistering of the paint on the surface of a neighboring butane storage sphere and prevented emergency responders reaching the firewater deluge valves provided to protect the sphere from overheating due to fire exposure. If the wind direction had been different and flames had impinged directly on the sphere or if the sphere had been exposed to significant overheating for an extended duration, there could easily have been a catastrophic rupture of the sphere and a major explosion.

This was incidentally not the first fire at this refinery. On Sunday, July 29, 1956, there had been a severe fire-related mass casualty event at the site, which killed 19 firefighters, considered to have caused the fourth highest number of casualties of firefighters in the United States for a single fire event.

### *Failings in technical measures*

According to the CSB report, root causes included (1) inadequate risk assessment (of plant modification and fire exposure of neighboring process equipment), (2) inadequate design [absence of remote-operated emergency block valves (EBVs) and structural steel fireproofing], and (3) inadequate freeze protection practices (including periodic inspection of dead-legs and infrequently used piping and equipment).

Critical factors included (1) a passing isolation valve at the control valve station due to a piece of metal debris trapped between the valve gate and seat, (2) absence of positive isolation of the dead-leg from the propane supply system, (3) absence of fireproofing on the steel support columns of an elevated pipe rack some 23 m (77 ft) away, and (4) absence of remote-operated EBVs to minimize the quantity of flammable hydrocarbons leaking.

Other lessons learned included switching to inherently safer biocide chemicals and relocating pressurized storage vessel water deluge valves to ensure they are accessible in an emergency.

### *Failure to learn from experience*

There was a failure to learn from the experience of the previous fire at the site. The immediate cause of the propane leak was a freeze-related rupture in an elbow below an isolation valve at a redundant control valve station on one of two propane feed lines to an extractor tower which had been taken out of service some 15 years earlier.

*Sources*: Multiple.

## Fire at Feyzin Refinery, Lyon, France, January 4, 1966

### *Take-home message*

Bunding of LPG storage is important. All phases of a plant's life should be considered by designers.

### *Effect on legislation/codes/standards*

Correction of many of the design deficiencies of Feyzin, with insulation, permanent water sprays on the spheres, reinforcement and fireproofing of support legs, and ground below spheres being sloped to avoid accumulation beneath the sphere are now incorporated into codes of practice.

### *Accident summary*

On January 4, 1966, an operation to drain off an aqueous layer from a propane storage sphere was attempted at Feyzin Refinery. Two valves were opened in series on the bottom of the sphere. When the operation was nearly complete, the upper valve was closed and then cracked open again. No flow came out of the cracked valve, so it was

opened further. The drain system on the base of the tank was poorly designed, requiring manual operation and no insulation or tracing to prevent ice blocking the valves.

The blockage—assumed to be ice or hydrate—cleared and propane gushed out. The operator was unable to close the upper valve and by the time he attempted to close the lower valve this was also frozen open. The escaping liquid accumulated beneath the storage sphere rather than draining away from it to a place where it could be allowed to burn harmlessly.

It took 10 minutes to raise the alarm as the operator traveled on foot 800 m to alert other people. He was afraid to use the local telephone or start his truck and drive. There was no strategy for raising the alarm in the event of a flammable release. The alarm was raised and traffic on the nearby motorway was stopped. The resulting vapor cloud is thought to have found its source of ignition from a car about 160 m away. The storage sphere was enveloped in a fierce fire and upon lifting of the relief valve a stream of escaping vapor was ignited.

The LPG tank farm where the sphere was located consisted of four 1200 $m^3$ propane and four 2000 $m^3$ butane spheres. The fire brigade arrived on site, but were not experienced in dealing with refinery fires, and it appears they did not attempt to cool the burning sphere. They concentrated their hoses on cooling the remaining spheres.

About 90 minutes after the initial leakage, the sphere ruptured, killing the men nearby. A wave of liquid propane flowed over the compound wall and fragments of the ruptured sphere cut through the legs of the next sphere which toppled over. The relief valve on this tank began to emit liquid.

The fire killed 18 people and injured 81 others. Five of the storage spheres were destroyed.

### *Failings in technical measures*

- lack of insulation;
- permanent water sprays on the spheres;
- reinforcement and fireproofing of support legs; and
- ground below spheres not being sloped to avoid accumulation beneath sphere.

*Source*: HSE.

## Fire at Hertfordshire Oil Storage Terminal, Buncefield, United Kingdom, December 11, 2005

### *Take-home message*

Avoid domino effects. Do not neglect bunding.

### *Effect on legislation/codes/standards*

API 2350 Tank Overfill Protection Standard updated.

### *Accident summary*

A large fuel/air explosion occurred at the Hertfordshire Oil Storage Terminal at Buncefield on December 11, 2005, at around 06:00 hours, leading to further explosions which eventually overwhelmed 20 large storage tanks.

Considering the magnitude of the explosion, the consequences were limited, if by luck rather than judgment. There was a great deal of damage on site, much short-term disruption offsite, and some limited contamination of groundwater. Things could have been very much worse.

> *Buncefield was clearly a major emergency, but luckily the public health impact was rather small. The situation could have been very different if the initial explosion had happened at a different time, or if the weather conditions had been less favorable for dispersing the plume. So we need to analyse our response carefully and make sure any lessons are learnt.*
>
> ***Professor Pat Troop***

The fuel/air explosion appeared to have been caused by a previously unknown effect, hedgerows of deciduous trees accelerating the flame front to such a degree its pressure wave caused the remaining fuel/air mixture to detonate.

The Health Protection Agency and the Major Incident Investigation Board provided advice to prevent incidents such as these in the future, but the primary need highlighted by the incident was for safety measures to be in place to prevent fuel escaping the tanks in which it is stored. Further safety measures are needed for when fuel does escape, mainly to prevent it forming a flammable vapor and prevent pollutants from escaping to the environment.

### *Failings in technical measures*

Failure to prevent/control/monitor tank overfilling.

*Sources*: Multiple.

## Fire at Universal Freight Warehouse, Yorkshire, United Kingdom, February 13, 1982

### *Take-home message*

Warehouses are more dangerous than you think.

### *Effect on legislation/codes/standards*

None.

### *Accident summary*

This incident shows how quickly fire can take hold in a warehouse full of assorted loads of poorly characterized chemicals, and what the environmental consequences of such a fire can be.

At approximately 10:00 hours, workers on site noticed the electrical lights flickering and saw smoke coming from the warehouse. On opening the warehouse door to investigate, a wall of thick smoke confronted an employee. Shutting the door, he raised the alarm and called the fire brigade. The warehouse was used for storing large quantities of ICI herbicides in plastic bottles and drums with plastic liners and octyl phenol in paper sacks.

The fire brigade responded promptly and was automatically issued with TREM cards (Transport Emergency Cards) relating to the herbicides and octyl phenol. However, by this time the fire had become established and had broken through the roof of the warehouse. The intensity and speed at which the fire developed surprised the firefighters, as they believed the warehouse contents to be largely incombustible.

Some of the drums/bottles had burst in the fire and their contents were washed down the road and into Hey Beck, a small stream that drains from the site. This resulted in a major pollution incident. Because of the large volumes involved the decision was taken to allow the material to continue to flow into the drains, washed down by the fire brigade.

This washing down activity continued for over 2 days after the incident. The diluted herbicides turned the stream into a brown foaming torrent for several miles. The River Calder was affected by this pollution. The firefighters were faced with additional problems because of the physical properties of octyl phenol, which floats on water producing a flowing pool of burning liquid.

This was a widespread major pollution incident of local watercourses and land. The seriousness of the pollution prompted action to be taken to contact police, the water authority, local radio stations, and the press to warn the general public of the dangers of coming into contact with the contaminated water. Farmers were warned to keep livestock away from riverbanks.

### *Failings in technical measures*

The exact cause of this accident is unknown. A worker had been shrink-wrapping paper sacks of octyl phenol onto wooden pallets using a plastic film and a hand-held cylinder heat gun, shortly before the incident occurred. It is feasible that the flame from the gun passing too close overheated one of the pallets, causing one or more bags, or the pallet, to smolder, eventually bursting in flames.

Octyl phenol was not considered to present a significant fire risk and the local fire brigade believed the warehouse contents to be largely incombustible. The management had received insufficient information from the owners of the chemicals on whose behalf they were being stored. Also, the warehouse had no control regarding the quantities or types of chemicals delivered for storage.

The rapid spread of the fire quickly engulfed hazardous materials. Adequate precautions must be taken so that in the event of a fire the risk of its spreading to hazardous materials is prevented.

*Source*: HSE.

## What were they thinking?

Not every incident involving process plant is caused by factors too complex to be obvious, though all three of the following incidents involved a lack of planning of maintenance or experimental activity. Designers should always consider what will happen if maintenance staff, contractors, operators, or those carrying out process trials do not do what you would like them to, because it is human nature to do so, sooner or later.

### Fire in a Crude Oil Storage Tank, BP Oil Dalmeny, Scotland, June 11, 1987

#### *Take-home message*

Unsupervised workers (especially contractors) sometimes do stupid things. Supervise them.

#### *Effect on legislation/codes/standards*

None. As one of my reviewers opined, you cannot legislate for or design out stupidity.

#### *Accident summary*

On June 11, 1987, a team of four contractors was cleaning a crude oil storage tank at the Dalmeny Oil Storage Terminal. The tank was of the floating roof type and the roof had been lowered due to the tank being empty. It was resting on a series of 219 support pillars. Three of the contractors worked inside the tank with one on duty outside along with a BP employee.

The tank had been emptied of its contents and three roof manhole covers opened to allow natural ventilation. However, the evolution of a vapor with the risk of forming an explosive atmosphere was not considered sufficient to merit either mechanical ventilation or rigorous monitoring of the vapor concentrations within the tank. As a precaution though, the workers were required to wear airline-breathing apparatus supplied by a compressor located outside the tank bund.

At 13:20 hours the outside man looked in and saw a ring of fire surrounding the three men. Two of the employees managed to escape the fire but the third man died from the effects of asphyxiation and burns. The fire escalated rapidly with flames and smoke coming out of the open man ways.

The cause of the accident was one of the contractors smoking inside the oil tank. It was apparently common practice for the workers to remove their breathing apparatus while inside the tank, with some workers choosing to smoke while the supervisor was not looking. On this occasion one of the men working in the tank had dropped a lit cigarette on to the floor where it had ignited the crude oil.

### *Failures in technical measures*

- Maintenance procedures: management/supervision. Several workers disregarded basic safety procedures, resulting in a lit cigarette being dropped inside the storage tank. In addition, the management of the contractors and the contracting company by both the contractor and BP could have been more thorough.
- Site security: control of ignition sources brought onto site. Terminal rules required all matches and lighters to be surrendered at the security gate, but this was not enforced.
- Hazardous area classification/flameproofing: ignition sources identification and elimination. No forced ventilation of the tank to reduce the flammable vapor concentration was considered necessary.
- Maintenance procedures: isolation/draining/flushing.
- Training: maintenance training. The contracting staff working inside the storage tank had not been properly informed of the toxic risks of working without the appropriate breathing apparatus and the potential for a flammable vapor at the oil surface.
- Isolation: emergency isolation.
  *Sources*: Multiple.

## Sverdlovsk Anthrax Disaster, Sverdlovsk, Russia, March/April 1979

### *Take-home message*

Operators accustomed to even the most dangerous materials can become complacent about their dangers, as the Sverdlovsk incident makes clear. Designs should never have a failure mode with consequences of the magnitude of this incident.

### *Effect on legislation/codes/standards*

None known. All aspects of the incident are contested, and a cover-up is widely suspected by Western sources.

### *Accident summary*

A biological weapons facility was built after World War II in Sverdlovsk which produced the highly virulent "Anthrax 836" strain for use in biological weapons. The produced anthrax culture had to be dried to produce a fine powder for use as an

aerosol. Large filters over the exhaust pipes were the only barriers between the anthrax dust and the outside environment.

In March 1979, a technician removed a clogged filter while drying machines were temporarily turned off. He left a written notice, but his supervisor did not write this down in the logbook as he was supposed to do. The supervisor of the next shift did not find anything unusual in the logbook and turned the machines on. In a few hours, someone found that the filter was missing and reinstalled it.

All the workers at a ceramic plant across the street fell ill during the next few days. Almost all of them died in a week. The death toll was at least 100, though numbers are disputed, along with many other details of the incident.

It is however clear that a biological weapons facility was located in a built-up area, and it is widely believed that a single filter was the only barrier preventing the release of weaponized anthrax to the environment.

### *Failings in technical measures*

- Operating procedures: safe operating procedures not written.
- Maintenance procedures: insufficient management/supervision. No lockout when being maintained.
- Relief systems/vent systems: venting to street in built-up area of lethal biological weapon.
- Isolation: no shutoff of route to street during maintenance operation.
- Plant layout: a bioweapon plant located in a built-up area was clearly inappropriate.
- Secondary containment: no secondary containment.
- PTW: a PTW system with lockout should have been required.

*Sources*: Multiple.

## Explosion in Decanter Centrifuge, Redstone Arsenal, Alabama, United States, May 5, 2010

### *Take-home message*

Ill-thought-out design and failure to follow established guidance can lead to fatalities when coupled with lack of risk assessment, safety procedures, and discipline.

### *Effect on legislation/codes/standards*

This was another incident caused by failure to follow existing guidance. To quote the OHSA citation "The hazard could be abated by following the requirements in the US Army's Standing Operating Procedures for Energetic Processing Module (EPM) Prototype Ammonium Perchlorate Recovery dated March 02, 2009 (SOP RA-0000-P-WD-GM-064) which stated the centrifuge operations would be remote."

### *Accident summary*

Two men died when a decanter centrifuge handling ammonium perchlorate (AP) (an oxidizer used in solid rocket propellant) exploded at Redstone Arsenal. They were working on demilitarization operations that involved using *n*-Butanol to dissolve impurities in AP. AP wet with *n*-Butanol can be explosive, but AP and *n*-Butanol were mixed together to form a slurry, then a decanter centrifuge was used to separate the *n*-Butanol and AP.

Friction from rotating parts inside the decanter centrifuge generated enough heat to cause the mixture of AP and *n*-Butanol to ignite, leading to an explosion within the centrifuge causing fragmentation and an intense flash fire that engulfed personnel present in the building.

The investigation found that the deaths were the result of personnel conducting decanter centrifuge tests involving potentially explosive materials as an attended operation instead of running the tests remotely. Responsible personnel did not develop safety procedures specific to the use of the centrifuge and exercised poor safety discipline. The investigation concluded that this type of centrifuge was unsuitable and unsafe for processing explosives.

The most surprising aspect of this incident is that it is so recent. Mixing a powerful oxidizer with an organic solvent in such a way as to create an explosive, as was done here, and then subjecting the mixture to friction is a process which is unlikely to have survived a hazard analysis. Standing next to it during operation demonstrates a lack of understanding of the hazards of the system.

### *Failings in technical measures*

- Operating procedures: safe operating procedures not written;
- Plant modification/change procedures: HAZOP, identification of safety-critical elements;
- Operating procedures: ran test as attended procedure.
  *Sources*: Multiple.

## Tesoro Anacortes, Washington, United States, April 2, 2010

### *Take-home message*

This incident might have been avoided if the heat exchanger shell had been fabricated from 1.25 Cr/0.5 Mo steel instead of carbon steel. Breathing air and nitrogen hose connections should always be different to avoid the risk of asphyxiation for personnel wearing fresh air breathing apparatus.

### *Effect on legislation/codes/standards*

Following this incident, the Nelson curve for carbon steel was updated.

### *Accident summary*

At 12:30 a.m. on April 2, 2010, while personnel were performing post-maintenance heat exchanger restart operations, a heat exchanger on an adjacent bank catastrophically and violently ruptured. The pressure-containing shell of the heat exchanger burst at its weld seams, expelling a large volume of very hot hydrogen and naphtha, which spontaneously ignited upon contact with the surrounding air. The ensuing explosion was so violent that many in Anacortes felt the shock wave across Fidalgo Bay. A giant fireball lit up the sky above the refinery, and a plume of black smoke was pushed toward the town by a southeast wind. It took about 90 minutes to put the fire out.

Tesoro agreed to pay millions to families of the victims, but as of 2015 the company continued to fight government accusations that it willfully put its workers in harm's way. The Tesoro refinery had been fined $85,700 in 2009 for 17 "serious" safety violations—meaning there was a risk of "death or serious physical injury" from each violation. Those fines were later reduced to three violations and a $12,250 settlement.

The accident was the state's worst industrial disaster in 50 years. A similar incident occurred in November 1998, when six men were killed in an explosion at the Equilon Puget Sound Refinery in Anacortes.

### *Failing in technical measures*

According to the final report released by the CSB, the explosion was caused by high-temperature hydrogen attack, which severely cracked and weakened carbon steel tubing and led to the rupture. As a result, the CSB recommended the state adopt more rigorous process safety management attributes and features based on the team's regulatory analysis. The Nelson curve for carbon steel was also reduced, prohibiting the use of the material in processes that operate in temperatures above 400° Fahrenheit.

*Sources*: Multiple.

## Further reading

Atherton, J., & Gil, F. (2008). *Incidents that define process safety*. Hoboken, NJ: Wiley-Blackwell.
Karmarkar, M. (2013). Led Astray. *TCE*, August 2013.
Kidam, K., & Hurme, M. (2012). Design as a contributor to chemical process accidents. *Journal of Loss Prevention in the Process Industries*, *25*(4), 655–666.
Kletz, T. A. (1993). Lessons from disaster: How organizations have no memory and accidents recur. Houston, TX: Gulf Publishing Co.
Petroski, H. (2008). *Success through failure: The paradox of design*. Princeton, NJ: Princeton University Press.

PART V

# Advanced Design

# CHAPTER 18

# Brownfield process plant design

## Introduction

There are many "shades" of brownfield, from plant troubleshooting or debottlenecking exercises into more or less pure greenfield design. I have covered pure greenfield design in the rest of this book, but my experience and that of most practicing engineers these days encompasses all the shades of field, from Bourbon brown[1] to Stuart Semple green.[2]

There are basically two ideas of what a brownfield process plant design is. One of these is even more complex and skillful than a greenfield process plant design, while the other is arguably not really design at all. Unfortunately, the latter often forms the basis of what is thought of as process design in much of academia, which can add to the confusion around brownfield design.

To complicate matters, a lot of upgrading, extending, debottlenecking, and so on goes on in all process sectors, but this deepest brownfield design is often not really process plant design. It tends to be led by operations company staff, based upon extensive databases of real plant operating data, which have probably been used to validate a highly detailed process simulation model. The essence of design (uncertainty, creativity, and the opportunity to exercise professional judgment) has been largely eliminated. This kind of activity is a set of tasks, not the problem-solving of the designer.

A further issue with brownfield design is that the distinctions between equipment design and process plant design become blurred. The closer we move toward the design of a single new bit of kit, or a small number of bits, the less complexity there is, and the less concern for interconnections, but process plant design is all about complexity and interconnectedness. The design of an individual pump, heat exchanger, or distillation column is not process plant design. It may not even be chemical engineering. Process plant designers specify equipment; they do not design it. But academia tends to prefer equipment design to process plant design, as it is more like engineering science and less like real design.

[1] "The brownest of the brown liquors" according to "The Simpsons."
[2] The world's greenest green, available to anyone other than Anish Kapoor—look it up.

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00019-7
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## Blackfield design

Many engineers are of the view that greenfield design, like chemical engineering, is dying out, and that the only work left for us is just adding portions to existing plants, that is, brownfield design. I take issue with this view on various levels, though it does contain an element of truth, which I shall discuss in this chapter.

The main problem with the idea that greenfield design or, more broadly, chemical engineering, is dying is its parochiality. It may well be the case that "traditional" chemical engineering (oil and gas, commodity chemicals, specialty chemicals, and pharma), aka the "chemical process industry" (CPI) is indeed dying in the United States (and is already dead in the United Kingdom). Indeed, many chemical engineers in the Western world have lost their jobs as these sectors have moved their production bases eastward and southward.

So, for the many people laid off from those industries in the United States and United Kingdom, it may well seem that the profession is dead. The process sectors which do not fall under the CPI definition will not employ them. Even the other subsectors of the CPI will not do so, as many unemployed oil and gas engineers wanting to switch to pharma have found out.

"Traditional" CPI, however, does not include those process industries which still build lots of new plants in the West and which still need process design. Water and effluent treatment, energy from waste, nuclear power, food and drink, concrete, and other mineral processing are all examples of sectors which still rely on process plant design. So, there is actually plenty of process design work going in the West, as discussed in Chapter 6, Neglected industries and processes.

Even within the Western traditional CPI sector, there will always be a need for modifications to existing plants in order to ensure that they continue to maintain their economic output. In addition, there are still occasional major reconfigurations of process plants in order to streamline processes and incorporate technologies not available at the time the original plant was built.

Yes, much of our CPI has moved to low-wage economies. There is often nothing stopping us following the work to where it has gone if we want to remain in that sector, but many of those who espouse the idea that chemical engineering is dead are older and they don't want to move to Asia. It doesn't mean that an industry which is actually growing has died just because it no longer exists within walking distance. There is plenty of CPI going on in the East and South.

A further issue is that companies in the West willing to train someone up to be a process designer in their sector have a plentiful supply of cheap graduates to choose from. A lot of the people who complain to me on social media about the death of "chemical engineering" tell me that there is still some work going, but at a tiny fraction of the rates they are used to, basically graduate rates. This should tell them who they are competing with.

So, we can either go where "CPI" has gone, or we can stay at home and expand our idea of what process engineering is about. Either of these things will be very difficult indeed for someone moving toward the end of their career, who knows everything there is to know about an item of process equipment which may never be commissioned in their home country again. But that doesn't mean that chemical engineering is dead.

## Brownfield process plant design and its near enemy: nofield process design

In Buddhism, the concept of the "near enemy" is used to describe something which seems similar to something else, but is actually more like its opposite. For example, the "far enemy" of love is hatred, and its "near enemy" a needy dependency.

Throughout this book, I distinguish between process design and process plant design, using greenfield as the base case. When it comes to brownfield design, I would argue that the academic process design approach—or "nofield" process design (NPD) as I like to think of it—is the near enemy of professional "brownfield process plant design" (or BPPD).

As my section heading implies, "NPD" does not consider a physical field, as it does not include consideration of layout. A professional version of this academic approach may be carried out by staff who do not work for the company which will build the plant (and do the real nitty-gritty design). I have tried really hard to find someone willing to recount how they had used modeling and simulation (the weapon of choice of the NPD aficionado) to design a plant which was actually built as they had designed it. I had no problem finding modeling fans, but not one of them had designed a plant which had been built. It turned out that the overwhelming majority of them agreed with my views on the proper role of such programs. Those I consulted included the actual programmers as well as many expert users (although I did encounter one company staffed exclusively by academics offering a computer program which, they claimed, could design process plants better than a team of experienced process designers).

There is a minority, mostly with an R + D background, who insist that these programs *can* design plants and feel strongly that they *should* be used to design plants but, as far as I am aware, none of these people have actually done so: where a plant is actually built, it is always designed by a specialist EPC company. The same people tend to believe that labwork and pilot plant work are design, which is not the case, although (like modeling and simulation) they are certainly capable of supporting the designer.

Why is NPD not design? Because it is no more than the application of raw, "stupid" computer power. BPPD is, however, not stupid. It is actually harder than its greenfield equivalent due to the additional constraints involved.

*There's never enough to go around. Not enough time. Not enough money. Not enough people. That's a good thing...*

*Constraints are often advantages in disguise. Forget about venture capital, long release cycles, and quick hires. Instead, work with what you have.*

*37Signals "Getting Real"*

## Why is nofield process design stupid?

As I (and everyone who knows anything about engineering design) will tell you, all design problems are poorly defined, and all is heuristic in engineering. All design decisions are based on incomplete, inconsistent, and conflicting information. NPD, on the other hand, tends to be precisely defined, complete, and consistent with no apparent need for rules of thumb, nor any place to use them. It is therefore neither engineering nor design.

Let me start by defining what NPD appears to be, based on my discussions with its practitioners. It may well start, as real design does, with a statement of some commercial need, but instead of looking at how the need might be met via an initial technical and economic evaluation, the end user usually carries out extensive labwork.

Doing this suggests that we are in the area of traditional CPI, with money to burn, or that we can only compete with those low-wage economies by being really innovative. While this is a highly plausible idea, it has been tried before, and I would suggest that those who subscribe to this idea should consider the lesson of Imperial Chemical Industries (ICI).

ICI, based in the United Kingdom, was once one of the largest CPI companies in the world. When faced with competition from bulk chemical manufacturers in low-wage economies, they turned to their researchers and chemists, who came up with all kinds of innovative product and process ideas. To consider just two of these, "Pruteen" was developed to be an animal feed, but proved so uneconomic that it has only survived as a premium human food, "Quorn"; similarly, ICI's "deep shaft" effluent treatment process had very few installations. To summarize, the research-led commercial strategy didn't work and ICI, once a billion-pound turnover company, no longer exists (though a so-called "ICI mafia" of people who used to work there is still a thing).

Anyway, after the lab work comes the pilot plant work, and either concurrently or afterwards, all of the data from the real plant, as well as all of this lab and pilot plant data, are fed into a modeling and simulation program.

Then the virtual plant is optimized within this program using tools such as pinch analysis, an approach more widely called "process synthesis." As I have written before,

this "optimization" can be done by a computer program in a few hours. No need to involve any engineers. All you need are some lab staff and a "Hysys jockey."

Cheaper, quicker, more certain seeming. What's not to like? Just that it is a fantasy. To the best of my knowledge, NPD is at best wishful thinking. What actually works is a lot harder, and smarter, but it's a lot messier too.

## Why is brownfield process plant design smart?

Take greenfield process plant design and make it harder: that's BPPD. You may well not have labwork or pilot plant work to guide you. You may well not have the budget or data to carry out modeling and simulation studies. None of this is, however, a problem for the professional process plant designer.

The problem is often that the client has already spent money on such work, but it is of questionable utility, because the researchers who did it had their own agenda. Unlike the research types, the real designer of a plant which will actually be built has to design something which will definitely work. The contract conditions will usually be very clear on design responsibility, and those expensive studies which the client commissioned will only, at best, provide guidance.

So how is brownfield design harder than greenfield? Well, for starters, we can't just lay the plant down on the ground, in the order it is on the process flow diagram, in a nice neat line running downhill, so that we get gravity flow, as is frequently possible in greenfield design. It is a lot more likely that "sensitive receptors" will be found close to the site boundary, due to residential development growing up around the plant during its lifetime. The original process is probably nowhere near as competitive as it was when it was first built, and some of its components may well no longer work as they did when new. There may be a lot of data, but they are contradictory. There may be a lot of consultancy reports, modeling, and labwork, but they are often wrongheaded, and it would not be politic to point this out. The local population may have become far more risk-averse than they were back in the day. Constraints, finance, politics, people. All the things which make real engineering real. All things that computer programs know nothing about, and chemical engineering curricula do not cover.

## Tackling brownfield process plant design

I have seen all shades from brown to green when it comes to process plant design, and my fellow engineers who helped review the manuscript of this book have covered more industry sectors than I ever will. I am, however, going to largely ignore the deepest brownfield design, as:

1. It isn't really process plant design at all, it is optimization of plant by operational companies.

2. There are any number of academic textbooks which cover an approximation of this approach.
3. I could not find any practitioners who actually do it, and this is a book about professional practice.

With all other types of brownfield design, we must first define the problem, a stage often missing from the education of engineering graduates.

## First, define the problem

*Recognizing the need is the primary condition for design.*

***Charles Eames.***

As I am not going to include the operational disciplines of troubleshooting/optimization and debottlenecking under the heading of process plant design, the brownest fields I have encountered within my personal experience of process plant design are major plant upgrades. Most commonly, such upgrades are intended to accommodate increases in production. However, they can also involve changing technologies (sometimes to a new technology, and sometimes back to an older, more reliable one, after a fashion has passed), accommodating alterations in the plant feedstock (as with the Jellyholm plant which I have used as one of my teaching exercises, see Appendix 5: Teaching practical process design), or meeting (usually legislation-driven) changes in the requirements for the plant's main product or waste stream.

While my background is mostly in design consultancy and EPC companies, I nonetheless have more than 15 years' experience in operations. I know how it all works, and I know the strengths and weaknesses of both sides.

By the time the design company gets to make a start, the problem has supposedly been diagnosed, and the remedy specified. Personally, whichever part of the process I am working on, I prefer to start by verifying the diagnosis from scratch for myself. It will surprise the newcomer who does this to find how many times a solid-looking brief falls apart on scrutiny. For example, I once received a 1000-page tender document for a potable water treatment plant which was full of errors including, most troublingly, the requirement for designers to take an estuary water (on occasion almost pure seawater) and turn it into (virtually salt-free) drinking water without any desalination process. This fact was clear from a moment's inspection of the water quality analysis provided in the document but did not seem to have been noticed by either the client or their consultant.

You may be asked for a brownfield solution, but it may turn out on investigation to be best to completely demolish the existing plant in order to use the same space to build a new plant. This happened in the United Kingdom at the Saltend Chemicals

Park, where old plants have been removed and replaced with larger ethyl acetate (EtAc) continuous operation plants. Other small-batch plants have also been removed because market demand for the chemicals they produced diminished to such a point that it was no longer economical to operate them. These plants were demolished and the land cleaned up to remove any traces of the previous process, prior to the building of a completely new process plant on the same land.

### *Read the design brief and supporting documentation*

Yes, all of it. There can be an awful lot. Get a hard copy and a pack of highlighters. Skim-read it first, looking for design data, specs, performance requirements, and highlight accordingly. Compare what you have gathered with the drawings and with itself. Don't forget to read the legal/contractual content. Get other disciplines to read their parts and give you their comments as soon as possible.

Ask yourself:

- Is the documentation sufficiently complete to define what is wanted?
- Is the documentation internally consistent?
- Is it possible to do what is asked?
- Is it safe to do what is asked?
- Are the contract conditions, program, performance tests, etc. reasonable?

It would be unusual for all of the questions to be answered with a yes, and that is even before we get into "Is this the best way to do this?" Experienced designers will form a view on this question quite quickly and intuitively, whilst beginners will need to take a more formal approach, and may need help from more experienced engineers.

Having read the documentation, you need to be sure you understand what the problem is. In the next section, I offer some more questions to help with this.

### *Framing questions*

Questions we need to answer to define the problem include the following:

#### Contractual and general

- What is the design horizon? (How long into the future is the design update required to work for?) There are two aspects of this in my field: what capacity is forecast; and how robust does the kit have to be?
- What budget accuracy is required/what stage of design are we at?
- Can the upgrade be done with the facility operating or do we need to run both processes together, or wait for an extended shutdown? Is this economically viable?
- Is there enough land available on site to perform the upgrade, and provide material laydown areas, contractor site establishment, and work locations?

- What are the safety and capacity implications of additional resources on site (power supplies and utilities, security issues, waste disposal, etc.), whether integrated or stand-alone?
- What is the potential impact on the neighborhood of additional traffic and parking?
- Are there restrictions/opportunities on equipment delivery? Do we need to consider weather windows, roads with tunnels/buildings built near to highways, weight limits, navigable waterways, etc.?
- Are site ground conditions suitable for the proposed new process plant?

**Health, safety, and environmental**

- Are there (current or potential) regulatory changes which are likely to apply to the facility?
- Has a gap analysis of the site's existing compliance versus current requirements been completed?
- Are the company's policies on health, safety, and the environment being complied with? If not, what changes to plant or procedures are needed to ensure future compliance?
- Do the safety systems function correctly and meet their intended functionality?
- Have safety and environment reviews and audits been kept up-to-date and recommendations implemented?
- Have up-to-date consequence models been developed for the site if required?

**Technological**

- Has the technology moved forward?
- Is the existing technology still the best option, rather than investment in new technology?
- Can an offsite modular approach work better than a "stick built" one?
- Are there bottlenecks in the process; are items too big or too small based on the product delivery requirements?
- Are the utilities supporting the process able to cope with changes to the processes, (e.g., increased loading on wastewater treatment systems, increased power requirement)?
- Are control rooms too close to the operations which may need to be moved?

**Operational**

- Have there been any historical problems/issues with operations and maintenance activities?
- Have there been any historical problems/issues at similar sites around the world?

- Has the piping suffered significant fatigue over the years, and will it maintain integrity for more than the design horizon? If not, do we need to include an upgrade at this stage?
- Are there lines that need relocating, decommissioning, positively isolating, etc.?
- Are there any issues with corrosion and erosion?
- Are the relief valves designed for all anticipated cases and sized accordingly?
- Are the foundations and overhead pipe racks for the equipment in a good state of repair? Are they adequately protected in a fire to prevent further hazardous events?

These are just a few key headlines. I cover the required questions in far more detail in *Process Plant Layout*.

Whilst you are considering these questions, you should also be gathering supporting information. You need to be clear as you do this about the quality of the data you are gathering.

### *Supporting information 1: hard data*

Hard data, as I define them, come from measurements taken on the real plant in question. They might come from lab analyses of samples, or from online instruments. Of course, such data have margins of error, and the statistics generated from them have confidence intervals, but this is as hard as data get.

Data of the same kind from another plant (even another nominally identical plant on the same site, operated by the same staff) are less firm, because no two plants are identical in construction, or in operation.

Data from scientific papers must be treated with the greatest caution.

Modeling and simulation exercise outputs are not data at all. This is not just my opinion, it is also the opinion of the people who write the software, and of many expert users. The accuracy of such models, when well-developed, is more or less entirely due to their having been validated with hard data, such that the model simply acts as a wrapper for the data. If this fact is not transparent to the user, the wrapper is obscuring its contents.

### *Supporting information 2: human intelligence*

Always visit site. It's always best to speak to operators and managers (preferably separately) about how the plant is really operated, and past problems at the site.

To give an example from my personal experience, operators at a site in Scotland told me (when managers were not present) that they had changed the grade of polymer used in a sludge-thickening centrifuge from that specified, without seeking permission from management. This was because the original polymer produced too dry a cake for their liking, requiring them to visit the sludge press several times a day to knock down the peak on the dumpster the sludge was discharged into. (I had noticed the stick they knocked the peak off with and asked what it was for.) This requirement

to go out on the plant was interfering with their tea breaks, and they did not care that the extra mass of sludge their "improvement" produced cost their employers a lot more money to have transported away.

On another occasion, during a site visit to a paint factory, I noticed a chair placed by the side of a separation vessel used to decant hot xylene from wastewater. The operator had to open a 6-inch valve on the bottom of the vessel by hand, with hot xylene free-falling several feet into a floor drain in a small, unventilated room. I was told that the chair was there because operators would "feel like a bit of a sit down" after xylene started coming out of the valve. In the absence of instrumentation, the only way for operators to tell that the water fraction had all been sent to drain was to allow the xylene to come out. Operators were being overcome by xylene fumes so frequently that they had provided themselves with a chair to sit in whilst they recovered. It seemed no manager had thought to ask what the chair was for.

### *Supporting information 3: the customer is always right*

The customer is likely to be your first stop when answering the framing questions given in the earlier section, though if independent verification is available, it should be sought as a matter of due diligence. This is because the customer is actually often wrong. However, there are different degrees of wrongness, and if the client isn't too wrong, you might find that:

> *Discretion is the better part of valor. Caution is preferable to rash bravery.*
>
> ***Falstaff.***

The client is likely to be completely right about what it is they want (though it is not guaranteed that this desire matches the definition given in the documentation, or that it is well enough described for there not to be disappointment if the client is given what they actually asked for).

Whether the client is right to want what they want is a question the designer should answer to their own satisfaction, and then exercise judgment over whether to share their own considered opinion with the client.

If what is being asked for will definitely not work, be unsafe, or environmentally damaging, then the designer's hand will be forced. There will be a professional obligation to speak up. This will not always be popular. A lot of time and money probably went into producing the design brief, and making people look foolish is rarely welcome.

If you think what is being asked for is suboptimal, you must tread far more carefully. You might be "engineer right," but "manager wrong." Sometimes, in brownfield design, it really doesn't matter what the best way to do things in a greenfield situation would be. The client's staff might know how to operate that suboptimal technology and have had a bad experience with new, better technology back when it

wasn't as well developed. It will cost a lot of money to retrain those staff to operate new kit, and there is a certain tendency for equipment which operators don't like to suffer mysterious breakdowns.

The commonest and most straightforward way to address these issues is by asking the client questions, especially if you are not in a competitive bidding situation. Asking such questions is, however, often a formal procedure if you are bidding competitively, and other bidders may have to be copied in on the answers. Sometimes it is better from a commercial point of view to simply tender based on a better design, and state that you were obliged to do so as the requested design was impossible. There are risks associated with this approach, but there are some clients with whom it is highly effective, especially if your alternative is cheaper than what they asked for, and/or if you can manage to make your competitors look stupid rather than the client.

### *Putting it together*

Having done the above, we are in a position to know what the problem is. We should certainly know what the customer thinks it is, and have a pretty good idea of what we think it is. When these more or less align, we are ready to move on to designing a solution.

## Second, solve the problem

From here on, it's basically the same as greenfield design, except that the definition of the problem is likely to include more constraints. Even the firmer data and tighter specifications usually available are kinds of constraint. However, without constraints, there is no design, so don't resent constraints, celebrate them. To quote Eames again:

> *Here is one of the few effective keys to the design problem: the ability of the designer to recognize as many of the constraints as possible; his willingness and enthusiasm for working within these constraints.*

### *Key constraints*

In brownfield design, layout is likely to be tight and things are likely to be in nonideal orientations. I cover how to accommodate this in great detail in *Process Plant Layout*.

Operator skills and training also matter a great deal, which is why we tend to give them more of the same processes they already have where possible.

More generally, operations staff may get a bigger say in the design, and this might mean that the plant is designed for low running costs or whole lifetime costs rather than the lowest capital cost basis of most greenfield designs. It might also mean that it is better designed, in the sense of being a better fit to the site and operators.

# CHAPTER 19

# Professional practice

## Introduction

Engineering is a collaborative human activity. Humans vary in their technical, intellectual, social, and verbal capabilities, though engineers may not encompass the full range of variation.

While there may be a few individuals with high levels of ability across the range, good collaboration allows those with high technical ability but poor social or verbal abilities (you know, nerds) to complement those with less technical ability, but more charisma and communication skills (the managers of the future). The most creative designers may be rather questioning of authority and intolerant of conventional rules, for the same reasons as they are good at finding creative solutions and are consequently often freelancers.

There are a number of formal interactions among engineers which facilitate communication between those who may be uncomfortable with unstructured conversations. Those which are commonly thought of as work might broadly be termed various types of design reviews, negotiations, and company QA/MOC procedures, though there are crossovers between these categories.

There are less formal interactions and consultations still commonly thought of as work, and there is a final type of interaction which is very useful to engineers, follows a well understood format, but doesn't usually stick to our working hours (especially when it is done in a bar): discussing what not to do based on personal anecdotes.

## Formal interactions

### Interdisciplinary design review

The point of design reviews is to make sure that the design is reasonably optimal in the opinion of more senior engineers.

Designs need to balance the needs of (at a minimum) the process, mechanical, civil, and electrical engineering disciplines. Consideration of installation, commissioning, operational, and maintenance issues is also mandatory—take for example an installation with a melting furnace: where electrical routing may become very important to avoid damage to cables by hot metal.

A design review will therefore bring together the senior engineers of each discipline within the company to focus on the design drawings. The atmosphere of such meetings is normally reasonably informal, but engineers can be quite challenging in

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00020-3
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their investigations. There may also be internal company political issues at play. Strong chairmanship and negotiation skills are a requirement if such meetings are to work well.

Beginners will learn a lot in such meetings, and should miss no opportunity to attend one, even though the first few for their own designs might include some learning experiences they might not entirely enjoy.

### Value engineering review

Value engineering reviews have many similar characteristics to the design reviews of the last section, though their focus on cost and value will attract more management types, sales and marketing people, and so on. As the name suggests, they are an attempt to get the price right—usually aiming for a downward adjustment. These are sometimes conducted in the presence of client representatives, which can on occasion result in a rethink from scratch of some constraint on the design which the client had not realized the full financial implications of.

### Safety engineering review

This is most often a formal approach such as a Hazard and Operability Study (HAZOP), but it is culturally very similar to the last two types of review.

## Informal interactions

### Consultation with equipment suppliers

The people who sell unit operations and other process kit usually have a very deep knowledge of its practical characteristics, and those of competing products. Obviously, they would like to sell you their kit, but they will scarcely ever lie in order to achieve this. See a good few of them, and you can learn how to play a game which will allow you to incorporate their detailed practical knowledge into your designs.

### Consultation with electrical/software partners

Sometimes you will have in-house electrical or software engineers, but nowadays there will normally be an external electrical installer, motor control center supplier, and software designer. These may all be under one roof, or there may be combinations. If you don't have in-house specialists to back you up, combinations are better, but as with all in engineering, the less you know the more you pay.

Electrical and software components of the job are very significant nowadays and are perhaps the single biggest opportunity for cost overruns at the installation and commissioning stage, so there is a potential liability to manage, as well as big opportunities for cost savings if a well-integrated and controlled design can be devised.

## Consultation with civils/buildings partners

As with electrics, civils and buildings are often not designed in-house. Civil engineering companies often work on very small margins and may consequently have a somewhat inflexible approach to contract documentation.

They are far more likely to employ quantity surveyors (QSs) than other disciplines. QSs are a kind of engineering accountant-cum-lawyer and are not well loved by engineers.

A sign commonly seen on the wall of an EPC contractor's office goes as follows:

*Architect—Someone who designs a combined monument to himself and tombstone for the contractor*

*Architect's estimate—The cost of construction in heaven*

*Contractor—A gambler who never gets to shuffle, cut, or deal*

*Subcontractor—Someone who is expected to correct all mistakes made by others and to provide financing for contractors and owners*

*Pre-Construction Conference—A meeting held by the client, contractor, and subcontractors while they are still on speaking terms*

*Bid—A wild guess carried out to two decimal points*

*Bid opening—A poker game in which the losing hand wins*

*Completion date—A predetermined period during which, under ideal conditions, about 70% of the project can be completed, and the point at which liquidated damages begin*

*Critical path method—A management technique for losing your shirt under perfect control*

*Liquidated damages—A penalty for failing to achieve the impossible*

*Low bidder—A contractor who is wondering what he left out of his bid*

*Profit—A small amount of money remaining after the completion of a project, sometimes large enough to pay taxes*

*Project manager—The conductor of an orchestra in which every musician is in a different union*

*Quantity surveyors—People who go in after the battle is lost and bayonet the wounded*

*Lawyers—People who go in after the quantity surveyors and strip the bodies*

Civil engineering companies are commonly considered to be far more litigious than other disciplines by chemical engineers. Experienced engineers are consequently

generally very cautious in their dealings with civil partners, though design and costing are normally separate parts of the operation for civil contractors and consultants.

There is, however, potential for both good design savings and, more importantly, good control of potential construction stage cost overruns, if the civil aspects of design are well integrated and defined. The things you learn in discussions with civil engineering partners can also alter the starting point of your future designs in such a way as to give them better cross-discipline integration.

## Consultation with peers/more senior engineers

Some people like to keep things to themselves, and some need a sounding board to develop ideas. I am in the second category, so I have learned a lot from others during these interactions. The other party does not, however, always have to be a more experienced engineer. Sometimes you just need to get an idea out there and play with it to see its strengths and weaknesses. Sometimes it needs a fresh pair of eyes to see things which an idea's author cannot.

Unless you are in the fortunate position of being allocated a personal mentor, senior engineers may often not have a great deal of time to talk to you, but few will refuse to help you out with a knotty problem.

Peers and near-peers will probably be the people you spend most time discussing things with and, while they can be useful, you should bear in mind that they are more likely to suggest investigating blind alleys or using inappropriate design techniques than old hands.

## Informal data exchange

Engineers love to talk about things which have gone wrong. This might seem like gossip, and there may be a component of that, but actually it spreads the knowledge of what doesn't work.

Engineering experience consists far more of knowing what doesn't work than knowing what does. Good engineering judgment is based in experience, which is in turn based on the results of bad judgment.

## Quality assurance and document control

> *Engineers . . . are not superhuman. They make mistakes in their assumptions, in their calculations, in their conclusions. That they make mistakes is forgivable; that they catch them is imperative. Thus, it is the essence of modern engineering not only to be able to check one's own work but also to have one's work checked and to be able to check the work of others.*
>
> ***Henry Petroski***

Control of the design process and design documentation is incredibly important in professional practice. There are strong negative safety implications of poor control of the design process.

Engineering documents are, for example, always marked with revision numbers and dates. If the document is changed in any way, it is given a new dated revision number. This prevents a lot of potential confusion.

Once a design is at the point where the major design difficulties have been resolved (after usually two or three revisions), revision zero will normally be issued. Any remaining issues on the P&ID may be highlighted within an irregular outline known as a "cloud" and marked HOLD. Once this is done, the design is considered sufficiently complete for the drawings to be used as the basis for commencement of design and procurement.

Once it has been decided that the design is sufficiently complete to issue for construction, the design will be "frozen," which is to say that no significant change will be allowed.

So, document change control is very important—it is usual to specify the engineering discipline and degree of seniority required to modify any given documentation, and for there to be checking of all changes by a second engineer of an appropriate discipline with a specified level of seniority.

The ISO 9000 series European Standard (derived from BS5750, a British Standard for quality assurance in product design and manufacture) gives a very widely used formal methodology for the control and audit of all processes. The ISO 9000 series is now applied away from product design and manufacturing, and there are less formal approaches used everywhere in engineering which cover more or less the same ground.

ISO 9000 requires that there are documented procedures for:

- control of documents;
- control of records;
- internal audits;
- control of nonconforming product;
- corrective action; and
- preventive action.

It also requires that you keep permanent records of the following:

- management reviews;
- education, training, skills, and experience;
- evidence that processes and product or service meet requirements;
- review of customer requirements and any related actions;
- design and development including: inputs, reviews, verification, validation, and changes;
- results of supplier evaluations;

- traceability where it is an industry requirement;
- notification to customer of damaged or lost property;
- calibration;
- internal audit;
- product testing results;
- nonconforming product and actions taken;
- corrective action; and
- preventive action.

These records are needed to provide evidence that you are actually following your specified processes. ISO 9000 is actually a system to ensure consistency rather than quality. If your company makes a bad product, ISO 9000 will allow you to consistently produce bad products.

More generally, professional process plant design is a very highly controlled and documented process, and design decisions are recorded formally for future reference. It should be borne in mind that your decisions may have to be defended in court long in the future.

Like many other engineers, I keep my own dated, handwritten notebooks in which I record my decisions. They may come in handy if you ever have to appear in a court case in respect of a decision you made 10 years previously (and though I have not as yet had to do this, I do know engineers who have). Contemporaneous notes are admissible evidence, as well as an *aide-memoire*.

## The literature of professional practice

Since professional practice is what engineers do, and how they do it, its study demands systematic social science, and many engineers and engineering academics find it difficult to read papers in the humanities. It's all a bit too vague and fluffy for the taste of many of us. Dealing with all the possible interpretations and observer biases presents demanding reading.

Harvey Dearden has however produced a book which helpfully sets out many of the unwritten rules of professional engineering culture, and which I would recommend to all new engineers (see "Further Reading")—though you may wish to skip the Jane Austen chapter.

Even more helpfully, because its scope is broader, James Trevelyan has described his own and others' research in the area in an accessible style. Engineers may well find it more palatable to read *The Making of an Expert Engineer* than to plough through the research Trevelyan had to read in order to write it.

Whereas most engineering writing aims for technical understanding, Trevelyan focuses on the technical collaborations which bring engineers' ideas to fruition through the efforts of many other people, maybe thousands on large projects. For most

engineers, these collaborations take up more time and energy than any other aspect of their work. So, the challenge is to ensure that technical ideas are implemented closely enough to the original intentions to satisfy project investors and end users, despite all the different potential human interpretations (or misunderstandings) of those ideas.

For many young engineers, this comes as a shock in their first jobs because they usually expect that their job will involve mainly solitary technical design and problem-solving. This is no surprise because engineering schools do not appreciate the subtleties and complexities of technical collaboration, an inescapable part of engineering practice. Few, if any, of those teaching engineering have any actual commercial engineering experience. On top of this, there is hardly any research on engineering practice and the little research that is now available is only just beginning to influence accreditation standards and curriculum design.

This lack of knowledge about professional engineering practice allows students to develop many misconceptions which persist throughout their careers. Trevelyan's book is worthwhile because it identifies these misconceptions and also more than 100 engineering practice concepts, almost all of which will be completely new ideas for most engineering graduates.

The book explains expert performance by engineers with a fascinating historical case study, and then provides a practical understanding of the different kinds of knowledge used by engineers:

- explicit, codified propositional knowledge: knowledge that is written;
- procedural knowledge: knowing how to do something;
- implicit knowledge: knowledge that could be written down but usually is explained verbally;
- tacit knowledge: knowledge acquired by practice, often without awareness;
- embodied knowledge: knowledge embodied in artifacts; and
- contextual knowledge: knowledge that depends on where you are.

It explains the idea of "distributed expertise": the notion that the know-how needed for engineering is carried collaboratively by all the people involved. Trevelyan explains how this distributed expertise is shared through social interactions and collaboration, rather than being passed from one person to another.

Trevelyan also shows how engineers collaborate in several different ways, using a combination of learned social skills and their technical knowledge:

1. *Relationship building*: gaining the trust of others is an essential part of collaboration;
2. *Discovery learning*: in which all the participants are unsure about what they know or don't know; unlike normal learning, there is no clear idea about what is to be learnt;
3. *Informal teaching*: facilitating learning by others, including explanations, instructions, monitoring their performances, providing them with feedback to improve their performances, and assessing their performance quality;

4. *Seeking approval*: helping the approver to develop confidence that one can be trusted to use given resources to perform intended actions while complying with regulatory limits or other requirements, as well as to gain permission to proceed without direct supervision;
5. *Informal technical coordination and leadership*: gaining the willing and conscientious cooperation of others who contribute their special knowledge and skills according to an agreed timescale for the work to be performed;
6. *Project management*: while normally taught in terms of preparing project planning documents, the key issue for engineers is diversity of human interpretation, and managing ways to monitor and contain resulting performance variations, along with the underrated skill of writing technical specifications; and
7. *Multistakeholder negotiation*: even technical problem-solving is often in practice a negotiation where securing agreement on the problem to be solved is the first step, and sustainability issues are often most effectively resolved through multiparty negotiations.

Trevelyan's book also takes a detailed look at engineering finance and investment decisions based on his research with engineers, focusing on the importance of investor risk perceptions; as well as the culture and economics of engineering practice in developing countries. He also provides practical advice for engineering graduates on finding paid work.

I, however, have one point of disagreement, though it may be more of a difference of emphasis. Trevelyan considers that, whilst engineers do not (as I have pointed out) ever use most of the mathematics they learn at university, this is not an argument for teaching less. As students work through practice problems, they build tacit understanding which underpins rapid technical decision-making in professional practice.

In the same way, an intuitive feel for the practical implications of an engineering choice is to my mind a significant advantage for all engineers.

## Further reading

International Standards Organization. (2008). *ISO 9001: Quality management systems—Requirements*. Geneva: ISO.

Dearden, H. T. (2017). *Professional engineering practice: Reflections on the role of the professional engineer* (2nd ed.). Createspace Independent Publishing Platform.

Trevelyan, J. (2014). *The making of an expert engineer*. Boca Raton, FL: CRC Press.

# CHAPTER 20

# Beginners' errors to avoid

## Introduction

> *It takes an engineer to undertake the training of an engineer and not, as often happens, a theoretical engineer who is clever on a blackboard with mathematical formulae but useless as far as production is concerned.*
>
> ***The Rev E.B. Evans***

Many of the errors outlined in this chapter are often hard-wired into academic process design techniques. In summary, it might be best for the new graduate to simply forget everything they were told in academia about process design. Those who taught them almost certainly never designed a unit operation which was actually built, let alone a whole plant.

## Issues based in the shortcomings of academic engineering courses

### Lack of consideration of the needs of other disciplines

Real process plant designers have to take into consideration the needs and desires of several other engineering disciplines, most notably civil, mechanical, electrical, and software in that order. The idea that a chemical engineer can sit down and design a plant in glorious isolation probably comes from the inadequacy of links between disciplines and professional practice in academia. Even the simplest "brownfield" management of change projects on existing facilities almost always require multidisciplinary input and expert reviews before they can be progressed.

### Lack of consideration of the natural stages of design

It is one thing to consciously accelerate a program by rolling a couple of stages of design together. It is quite another to attempt to apply techniques intended for a hypothetical scenario where these natural stages do not exist.

### Excessive novelty

Academics progress in their careers by being a particular kind of innovative. Being novel in this way is important to researchers, who need to get published to advance their careers. Many of them teach their students to value novelty too, even though only about 4% of engineering graduates go into research careers. Professional engineers are however no more novel than absolutely necessary. Being right is far more

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00021-5
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important to us than being original. (There may however be potential value in being a quick follower after others have paid the price of being first to try, particularly with lower risk plant elements.) The closest thing to novelty in upgrading an existing facility is what is termed as most effective technology, but this requires proof that the proposed processes have been tried and tested in a commercial environment, on similar processes and conditions elsewhere. Truly novel technologies are simply too risky when production rates and reliability (and of course safety) are top priority, as they are in professional engineering.

## Lack of attention to detail

"Block flow diagrams" are commonplace in university, and process flow diagrams (PFDs) are commonly the highest level of definition of plant interconnectedness. I have never used a block flow diagram in professional practice—I often go straight to piping and instrumentation diagrams (P&IDs). I only produce PFDs as engineering drawings if I need them to envisage mass flows, or if a client asks for them.

This is symptomatic of the different levels of attention applied by professionals and theorists. Having trained many university lecturers in the basics of process design, I know that it is commonplace for some to think that all design problems below the level of mathematical theory are trivial. Only the exceptional ones are willing to throw themselves into the point where they learn that the devil is in the detail.

There is a useful checklist in *Practical Process Engineering* to check for P&ID completeness which will draw a beginners' attention to frequently neglected issues, and which I have reproduced in Appendix 4, Checklists for engineering flow diagrams.

## Lack of consideration of the design envelope

Universities are graduating chemical engineering students who have never considered anything beyond static steady-state design. Even Master's level "advanced chemical engineering" modules use very simple models in simulation programs so that they can spend longer on pinch analysis. This approach is at best an oversimplified one used for teaching total beginners—but it is not how design is done.

A design envelope must be generated which considers all relevant aspects of a specific proposed plant and site in order to determine which approach is likely to be best. The regulatory environment, climate, price of land, skills of available operators and construction companies, reliability of power supply, risk of natural disasters, and proximity of people are often at least as important as the theoretical yield of a process chemistry.

Neither is there a "one size fits all" right answer to any design brief. The right design in a less developed country will not be the right one for a more developed

country. The right design for a client with a lot of experience with a particular process will differ from that for another client.

Choosing a "right enough" design requires integrated value—cost—risk—process design—operability—maintainability—reliability considerations. Many new process engineers focus purely on the "technical" (i.e., the process design) and ignore the crucial cost, risk, operability, maintainability, and reliability aspects.

## Lack of consideration of nonsteady states

This is a subset of the above error. If your plant doesn't work during commissioning and maintenance it doesn't work at all. Get it right—consider all stages of the plant's life.

Principal maintenance activities to consider during design are isolation, release of pressure, draining, and any requirement to make safe by purge or ventilation. Remember to allow for isolation of utilities as well. Isolation, block, double-block, and double-block-and-bleed valves are used for these duties, supplemented by spades, slip plates, and blinds. Any purge lines should ideally be temporary to prevent backflow contaminating the reservoir.

If there is going to be hot maintenance (carried out while the rest of the plant is working), the layout and process piping must be suitable for this. Isolation of vessels for maintenance must not isolate them from the pressure-relief system, and the possibility of inadvertent connection to the still-live process via this route needs to be considered.

Process safety containment events are most likely to occur during start-up and shutdowns following plant turnarounds. The transient, nonsteady states associated with these conditions can result in process equipment not functioning as it was designed to. To address this, it is important to understand issues such as the different types of purging and inerting regimes they might be subject to, e.g. dilution, pressure cycling, and vacuum purge, and to know which is most appropriate for the circumstances. Similarly, the selection of an isolation scheme (e.g., single isolation, double block, and bleed or spectacle blinding) will depend on the nature of the process fluid as well as process conditions such as pressure and temperature.

## Parallel and series installation

Beginners often have a very limited feel for the differences between parallel and series duplicate equipment installations, and when each is appropriate. They may, for example, think that the headlosses of units in parallel are additive (they are not). The heuristic is as follows: units in series—add heads, units in parallel—add flows. The issue of when parallel kit is appropriate is covered in the next section.

## Lack of redundancy for key plant items

Standby capacity can be something of a mystery to beginners. Generally speaking, if an instrument or item of rotating machinery is crucial to plant operation, you need at least one full-size online standby unit. For economic or other practical reasons, you may alternatively choose to have three 50% duty units instead of two 100% units (duty/assist/standby vs duty/standby).

If the item is really crucial, you might want to make sure that a common-cause failure of the units cannot happen. So, you might specify, at a minimum, separate cabling all the way back to the motor control center (MCC) for electrically driven items or follow the example of the oil and gas industry in having steam-powered backups for crucial electrically driven pumps. (Off-line standby can also be an alternative to online, particularly in more remote locations.)

It is not only unit operations which may need backup; utility failure can lead to hazardous situations [as it did at Fukushima—see Chapter 17: Success through failure (or "you don't want to do it like that!")]. I also give a number of other relevant case studies in my *Process Plant Layout* book (see Further Reading). We need to assess the required reliability and include standby as required early on. Electrical power to crucial items usually requires twin feeds and/or generator/battery backup. Note that generator/battery reliability and the length of trouble-free operation they yield is proportional to their cost, and that generator-supplied power is not necessarily as "clean" as mains power. It may be that "load shedding" needs to be specified, such that only the most essential plant processes have power backup.

Emergency cooling or reactor dumping to a quench tank may be used to bring the plant to a safe and reliable stop rather than provide for continued operation in the event of utility failure.

This is important for critical safety instrumented system (SIS) control in a plant which has undergone layers of protection (LOPA) analysis. Although SIS valves can exist on different control loops (e.g., level transmitter and high-level switch), if the valves are of similar build and technology they are likely to have similar common-cause failure modes if subjected to similar process conditions or fluids.

## Lack of consideration of processes away from the core process stream

Assume nothing. If the client has not told you explicitly that water, air, electricity, effluent treatment, odor control, and so on are available free of charge and suitably rated for your process, assume you need to provide them. If the client has told you they are, check that you are happy with what is offered. Mark your P&ID with termination points making clear where your scope begins and ends.

Feedstock, intermediate, and product storage often take up more space and present more hazards than the main process plant. Note that a few big tanks are probably cheaper than lots of small ones but the consequences of failure of a single tank are greater.

Designers need to consider emergency releases from the plant, allowing fenced-off out-of-bounds sterile areas for flares and vents, and adequate scrubbers for toxics. We need to make sure drainage systems are adequately designed. We need to avoid pits which might collect heavier-than-air flammable vapors if leaks could produce them, unless these are specifically designed as impounding basins to allow leaks of flammable vapors to be burned off without damaging other equipment.

Tanks should be contained in bunds with 110% of the largest tank volume being the usual minimum allowance. We need to consider precipitation/firewater drainage requirements when designing bunds. They may need covering or additional capacity. Access (which does not breach the bund) to any equipment inside the bund also needs to be provided.

## Lack of consideration of the price implications of choices

The best academic pricing techniques are greatly inferior to professional practice, and many design practices considered perfectly acceptable in academia would be woefully inadequate in professional practice. Making choices between technologies or configurations without pricing them as well as you possibly can at that stage of design is unprofessional. Don't do it.

## Academic "Hazard and Operability Study"

There is a procedure called Hazard and Operability Study (HAZOP) (or sometimes CHAZOP) by many in academia which consists of reviewing a BFD or PFD using a version of the HAZOP procedure to generate the required control loops. This is neither HAZOP nor CHAZOP (CHAZOP is the term properly used for HAZOP of a computer control system), and neither is this how professional engineers determine how to instrument and control our plants. If you don't know how to achieve the basic control of your plant, look at Chapter 13, How to cost a design, and/or ask an experienced engineer (you'll only be doing it their way come the design review anyway).

A specialist safety engineer recently told me that she meets a lot of fresh graduates who, when asked why the safety and control aspects of their design are so ill-thought-out, regularly reply that they expect any issues to be picked up in the HAZOP. This is bad practice, and this is not what HAZOP is for. More generally, this is not what design checking is for.

Another colleague offers an anecdote about an instance where inherent safety was only picked up at HAZOP.

> *In all designs I've worked on, there is pressure to move the design forward as quickly as possible, and sometimes a poor understanding of what the critical path is. [On] one process ... a HAZOP decided that the solvent that the design was using should be switched out for something more benign. The design went ahead on that basis, but back in the lab, it turned out that the solvent switch impacted extraction/reaction kinetics and of course had different volatility. Thus, the size of several vessels and pipes needed to change, but the project engineers*

*weren't prepared to wait for real data on these changes and went ahead with (as it turns out quite inaccurate) guesses. By the time the true data was generated, the design was frozen, and the project went ahead in the hope that the design would be able to take up the slack. It was re-engineered during commissioning.*

HAZOP in the conventional sense is perhaps less frequently used in operating facilities than other process safety studies such as process hazard review or process hazard analysis (PHR/PHA) and LOPA. PHRs are used periodically (e.g., every 5 years) as a modified HAZOP to provide process plants with a set of actions to reduce the risk of certain conditions from intolerable to ALARP. Often, safety improvement projects are derived from these studies. HAZOP is only really used in this context when new technologies are incorporated or there are significant process changes.

## Uncritical use of online resources

The internet is full of all kinds of potentially useful resources. I once asked one of my students the source of some pricing data, and he said "Chinese websites" (which usually means Alibaba.com). Without getting as obsessed with "proper referencing" as academia, we do need to put a little more thought into the reliability of any internet resources we use.

There are all kinds of online calculators for sizing pipework, equipment, and so on. There are sites which advertise chemicals and equipment for sale. Some of these are good (such as, e.g., lmnoeng.com for fluid flow calculations), whilst some are very misleading.

Professional engineers do not offer printouts of stuff from the internet as a substitute for their own calculations based on reliable information. I have, however, been known to use sites such as lmnoeng.com as a quick check that I have any novel hydraulic calculations about right if there isn't a second engineer available to check me. I don't automatically assume I have it wrong if the website disagrees, but if it agrees with me, I am happy to assume my calculations are about right.

There are however those who consider that self-checking is not an acceptable practice and cite instances where this has proven a problem. One colleague reports:

*In Canada, any calculation stamped by a Professional Engineer (their equivalent of CEng) does not require a secondary check. The assumption is that a PEng wouldn't stamp it unless it is correct (there are potential legal repercussions). This does not however, protect against simple errors that all humans are prone to. Even if performing your own secondary check, if the error lays within the base assumptions, both calculations will be flawed. I have first-hand experience of investigating a major accident which resulted from a fundamental design error.*

Without doubting my source, there is no way of knowing whether the same error would have been picked up by checking. Checkers are often under a great deal of time pressure. I have come across many examples from my expert witness practice

where nominally "checked" calculations were full of serious errors. The example above essentially suggests that professional engineering bodies side with me on this issue.

Professional judgment is what engineers get paid for. Don't do anything without exercising it. Don't assume that a checker will catch your errors. Assume instead that checking will be pretty perfunctory.

## Lack of knowledge of many types of unit operations

The law of the hammer (if all you have is a hammer, everything looks like a nail) operates if you know too little about your options.

Universities tend to concentrate on a small selection of unit operations important in the petrochemical industry. All chemical engineering students tend to see scrubbing, stripping, distillation, and drying several times during their course. The other 99% of unit operations are a mystery to them.

This book attempts in some of the tables in Chapter 10, How to do hydraulic calculations, and Chapter 11, How to design and select plant components and materials, to address the issue of lack of knowledge of separation processes and so on. More generally, new designers need to discuss the things they are doing with more experienced engineers, so that they at least get a chance to know what they do not know.

## Lack of knowledge of many materials of construction

New graduates generally know about two materials of construction, which they use for everything—carbon steel and stainless steel (they usually aren't sure which grade). There is rather more choice than that, as Table 11.1 shows.

## Lack of awareness of utility requirements

Make sure all required utilities are included at the earliest stages, for example, cooling water, nitrogen, and refrigeration as well as steam, process water, electricity, and compressed air. Their quality as well as quantity needs consideration—for example, power stability, compressed air/steam dryness, etc. High utility quality can cost a lot of money.

If you are handling highly flammable materials, one way to make them safe is to exclude oxygen from vessel headspaces with inert gas. Nitrogen is cheapest, though sometimes more exotic gases are required. You will need to make and/or store this on site.

Gain knowledge of utility equipment such as steam traps, compressed air dryers, etc. and why they are needed. Equipment suppliers such as Spirax Sarco are very useful for this.

## Lack of equipment knowledge

### Pumps

#### *Lack of knowledge of pump types and characteristics*

There are two main kinds of pumps (rotodynamic and positive-displacement), whose characteristics were explained in an earlier chapter. There are many subtypes of pumps which differ from each other in nontrivial ways.

The type of pump selected by the process designer affects the way the pump needs to be controlled and protected, the precision of pumping, the suitability for a given fluid in terms of its viscosity and solids content, the power utilization for a given duty, the maintenance requirements, and so on.

Until design newbies apply the knowledge of pump characteristics outlined in Tables 11.3 and 11.4, they will consistently make schoolboy errors in the selection of pumps and surrounding systems.

A further common error is lack of attention to pump shaft seal arrangements and to more complex pumping situations such as low NPSHa (hot water pumps or pumps discharging from vacuum vessels in particular).

#### *Lack of knowledge of the affinity laws for centrifugal pumps*

I have included a set of affinity laws at the end of Chapter 10, How to do hydraulic calculations. Many are surprised by the implications of these, such as that power consumption decreases if the pump is throttled. An awareness that increasing the speed will increase the discharge pressure is also crucial. Troubleshooting centrifugal pumping problems is critical for commissioning but the required underlying theory is seldom taught.

#### *Attempting to control positive-displacement pump output with a valve*

This is one of the knock-on effects of the broad class of errors covered in the last section, and one of the commonest errors of those with little design experience (which I have seen in supposedly bright young engineers applying for chartership, 5 years or more postgraduation).

Do not attempt to control the output of a positive-displacement pump with an in-line throttling valve—this does not work and will damage the pump.

#### *Multiple pumps per line*

There is nothing wrong with having multiple pumps in parallel as an assist or standby arrangement, but pumps in series are usually an error. Pumps in series, especially multiple positive-displacement pumps in series, are not a feature of professional designs.

Professionals know that we can get multiple stages of centrifugal pump in a single unit if we want higher delivery head, and if you can't get a given pump type to do your duty, you are probably looking at the wrong kind of pump.

We also know that multiple positive-displacement pumps in series do not work, as we are throttling suction or delivery when they pump out of sync.

### *Throttled suctions*

Don't ever try to control the output of a pump by throttling the suction, so as to avoid cavitation, among other things.

## Valves

There is more about valves and actuators in Chapter 14, How to design a process control system, but I will deal here with the most common holes in the knowledge of beginners.

### *Lack of knowledge of valve types and characteristics*

There are essentially three broad classes of valve duties: isolating, on/off-, and modulating- control valves. Different industries use different valve types for these duties, but all industries have these requirements. All designs should reflect this understanding. Table 11.5 is intended to help beginners to understand more about what is available. Actuated valves should be considered as rotating machinery, in that if their reliable operation is crucial to the process, standby capacity is required.

### *Lack of knowledge of actuator types*

Rotating actuators are of two main types—quarter-turn and multiturn. Butterfly, plug, and ball valves use quarter-turn actuators. Globe and needle valves use the multiturn type. There are also linear actuators for rising spindle-type valves such as the globe type, especially common for emergency shutoff duties. These may all be electrically, hydraulically, or pneumatically driven. Note that pneumatically and hydraulically driven actuators require a reliable motive fluid supply and additional control equipment (such as solenoid valves to control airlines) to function.

### *Use of actuated bypass valves*

Back when I was in university, it was reasonably common practice to control the output of a pump with an actuated valve in a bypass connecting pump discharge to suction. It does at least sort of work, for positive-displacement pumps, but times have moved on, and we tend to use inverters now. I never used this technique to control centrifugal pumps even back then, though this approach is still used to prevent surge in centrifugal compressors.

### *Use of control valves*

These remain in broad use, but I personally don't make a lot of use of in-line control valves for liquids nowadays at all. While this is my personal preference, the greater power efficiency of inverters is a fact. In the United Kingdom there are tax breaks for using inverters because of this. They are usually a lot cheaper than control valves for small pump sizes too.

If you are using a valve, consider whether you want it to fail open or fail closed, and specify accordingly.

### *Multiple valves per line*

Universities sometimes teach a clever way of using multiple valves in the same line with different control loop lags to control flow based on multiple variables, but I would not recommend trying this in design practice unless there is absolutely no other way of achieving your aim. Apply the KISS ('Keep it simple, stupid!') principle. Try to control flow in a line only once. In any case, most of the multiple valves per line I see in beginners' designs are not sophisticated cascade control, they are simply errors.

### *Lack of isolation valves*

Every unit operation needs at least one isolation valve on every inlet and outlet. Include it.

### *Lack of safety valves*

Nonreturn valves, pressure-relief valves, pressure sustaining valves, etc.: if you haven't included them you haven't really considered all that can happen on the plant. More experienced engineers will hopefully notice what you have omitted, but why not save them the trouble?

### *Lack of redundancy for key valves*

Key actuated valves may well need actuated standby valves, and all actuated valves on units which are not themselves entirely duplicated are likely to need a bypass with isolation and a manual standby control valve for maintenance in service (see Fig. 11.1).

## Lack of consideration of the details of drainage systems

Badly designed drainage systems can be the cause of very serious problems—they can allow the accumulation of hazardous material from leaking equipment through undersizing or lack of provision for removal of solids build-up, allow incompatible materials to mix, and/or carry toxic gases, fire, or explosions from one section of the plant to another. They are consequently nontrivial. I give a couple of case studies in my plant layout book of serious incidents arising from this cause.

Appropriate vents and drains are also essential for maintenance, allowing "proving" of lines prior to intrusive work. They help in providing reassurance that a valve is not passing and that energy sources, for example, pressure, temperature, fluids, etc. have been isolated properly.

## Lack of understanding of commissioning requirements

### Lack of tank drains and vents/other valves necessary for commissioning

A word of warning: don't upset the commissioning engineer. Commissioning (and operations) engineers want to be able to drain tanks down in a reasonable time—say half an hour. Make it so. Air will need to come in to replace the fluid, so be sure to include a vac/vent or other valve to allow this.

Think about the commissioning operation—additional valves may be needed to commission unit operations in isolation, or add services needed during commissioning. Put them in.

If you are unsure about what commissioning engineers need or want, ask them. If you do, exercise professional judgment and be prepared not to add absolutely everything they ask for. Give them what they need, not what they want. They are not employed to care about whether the company gets the job.

### Lack of sample points

Commissioning engineers will also berate you for omitting the valves and lines they need to take samples while commissioning. As with all the things which upset commissioning engineers, operating staff won't thank you either. Think about where they will need to take a sample to test whether a unit operation is working. Put a sampling valve in there, or a more complex arrangement (but no more complex than absolutely necessary) if containment is an issue. These sampling points need to be reasonably accessible to humans.

### Lack of room and equipment for commissioning and maintenance

This is the layout version of steady-state design myopia. Detailed consideration needs to be given by the designer to how the plant will be accessed during commissioning and maintenance activities. The safety implications of this make it a high priority.

## Layout errors

I have covered this area in great detail in my layout book, but the most common errors are as follows.

## 2D layout

Beginners to plant layout consistently fail to think in three dimensions—they position pipework and plant on the floor in plain view, in a way which renders it a dense series of trip hazards, instead of fixing it to the walls or grouping it on pipe racks and bridges like real engineers.

## Lack of control rooms and motor control centers

As mentioned previously, new designers may be unaware that we need MCCs to control the plant, and that we normally put these in a control room. The size of the control room should be determined after considering the direction from which the panel is to be accessed for maintenance and the directions the cables are to come in from and go out to. It must also be big enough for safe access with the MCC doors open. There will also normally be a table with a PC on for system control and data acquisition, room for filing cabinets for paperwork, etc.

### *Other control room motor control center considerations*

You should be aware of the relative costs of high-voltage versus medium-voltage wiring and that, consequently, the MCC should be located as close to large motors as possible.

You should also be aware of the impact of design decisions on insurance costs. Higher spec electrical designs such as Form 3-B + or fire-rated MCCs can reduce insurance costs (assuming they are not already mandated).

The colocation of MCCs and control rooms is not permitted in some areas and even if it is permitted, the fire control requirements for each may differ. It is also important to remember that a clean, noncorrosive, temperature-controlled atmosphere must ideally be maintained in these areas.

## Lack of consideration of "offsites"

Facilities for utility production, product storage, handling, warehousing, and transport are dangerous. The location of highly populated offices, labs, canteens, and workshops needs to be safe. That these things are often not well thought out is illustrated by many of the examples in Chapter 17, Success through failure (or "you don't want to do it like that!"), and many more in *Process Plant Layout*.

# Process control errors

## Instrument location

Dead areas in reactors and other vessels need to be considered with respect to potential lag time impact, etc.

### Lack of redundancy for key instruments and safety switches

Beginners tend to miss out key instruments entirely, and slightly more experienced engineers can fail to allow for standby capacity for safety- or process-critical instrumentation. Such standby provision needs to be balanced against the need for simplicity.

### Lack of isolation for instruments

Instruments need maintenance, calibration, and replacement. Unless you only propose to do this with the entire plant shut down and drained, isolation valves and other arrangements as required are recommended to allow removal and replacement when the plant is running.

### Measuring things because you can, rather than because you need to

Don't measure things you can't control. It will only cost you money, and it might upset you needlessly. Not only that, don't measure things which do not matter. For instance, you could measure the pH of water entering a heat exchanger, and you could control it, but this is not process-critical, so why would you? A more useful measurement in this instance might be the inlet and outlet temperature of the water.

### Alarm overload

Consider the number of alarms you are generating—don't overload operators with more alarms than they can take in. This will make the plant less, rather than more, safe. If additional alarms are installed during commissioning, remove them when no longer needed. Too many plants experience alarm overload because this stage is ignored.

### Piping and instrumentation diagrams Notation

We mostly control plants with programmable logic controllers or distributed control systems nowadays, so P&IDs should usually not show control loops as if they were wall-mounted proportional, integral, differential controllers as shown in Fig. 20.1.

## Troubleshooting errors

These two categories of error are more operational issues than design ones, but they matter to designers, especially in brownfield design.

### Lack of appreciation for "technician-level knowledge"

There is a lack of awareness of the need to work alongside operators, tradesmen, etc. as a plant engineer. A new engineer in a plant environment will probably be treated as

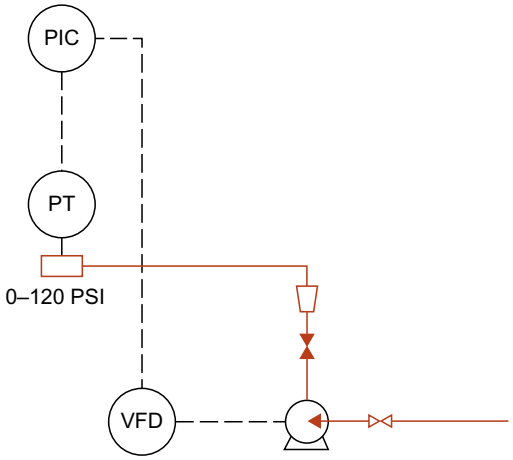


**Figure 20.1** Piping and instrumentation diagram (P&ID) notation.

a person of somewhat limited intellect by the operators until they have proven their ability to help or at least not get in the way. After that their standing will increase but the engineer jokes will probably continue until they are old and gray. The ability to get the operators on side is crucial if you are part of an operations team and want to get anything done. In my experience, 18 months seems to be the time required for a graduate to become useful.

## Lack of willingness to go and directly look at process problems

It is more comfortable to sit in your warm (or cool, depending on climate) office and try to visualize what could be happening in the plant, but if a problem occurs (especially if it's the first time you've seen these symptoms) you really do need to go and take a look. Second-hand information from operators will generally be mixed with numerous well-intentioned red herrings. I have seen graduate engineers spend 10 minutes debating the best thickness of replacement gasket to install in a leaking flange when all they needed to do was walk over and see that the bolts were loose.

If you don't go and look, you don't know what is really happening. A colleague offers an anecdote which chimes with my own repeated experience:

> *There's often a lot of tension between the design team, who are trying to build understanding of how the process works, and the operations team, who are trying to minimize disturbances and keep things simple. In one pilot plant (and many production plants) I was getting very variable samples from a reactor, so spent some time in the field with the operators. The sample valve was at the end of a long dead-leg (to get it well away from the high temperature/pressure space). Some operators were following protocol and running material through the line before sampling; some weren't. Those that weren't were trying to minimize product loss,*

*following the direction of the operations manager. In another plant, the operations team decided that the sample port was just inconveniently placed, so removed it, making it nearly impossible to get the reactor yield. I could sample from the product tank (12 h holdup) downstream, and 'the plant was usually pretty stable'.*

## Further reading

Moran, S. (2016). *Process plant layout* (2nd ed.). Oxford: Butterworth-Heinemann.
Sandler, H. J., & Luckiewicz, E. T. (1987). *Practical process engineering: A working approach to plant design*. New York, NY: McGraw-Hill.

# CHAPTER 21

# Design optimization

## Introduction

*Premature optimization is the root of all evil.*

***Donald Knuth.***

In contrast to academic methodology, a lack of availability of accurate information means that design optimization is most usually and always best applied after a plant has been built, commissioned, and operated for a while.

Design optimization tools such as modeling, simulation, and pinch technology are poorly suited to use during the plant design process, with a few notable exceptions. Their use in academia is almost always due to a lack of understanding of both the constraints of professional practice, and the tools being used.

## Matching design rigor with stage of design

Attempts to apply academic process optimization techniques to process plant design are ill-conceived because the iterative nature of real design processes means that there is already a complex design optimization process going on.

Professional engineers understand that each stage of design has its own natural resolution. There is no practical point in applying an optimization technique with a resolution finer than the model it is being applied to.

In addition, the academic approach does not acknowledge that we cannot meaningfully optimize a model which has not been verified by input of real-world data.

Like microscopes, all design techniques have what we might call a limit of resolution. Microscopic resolution allows us to distinguish accurately between two lines. A microscope with insufficient resolution for the task to which we put it may give the appearance of two lines where there is really only one, or one line where there are actually two. Similarly, a design technique with insufficient resolution may make two options seem equal where one is actually better, equal options significantly different, or even the better one worse. Trying to use process optimization tools for design is to me akin to what is known in microscopy as "empty magnification," where you make an image look bigger, but it actually holds no additional information.

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00022-7
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## Process integration

The concept of "process integration" in academic circles is not design integration. It probably isn't even really process integration. The professional process designer's "process integration" balances a number of mutually dependent considerations. The process plant design needs to be safe, robust, and cost-effective, but safety and robustness do not come for free. A balance has to be struck.

As piping and instrumentation diagrams (P&IDs), general arrangement (GA) drawings, process flow diagrams (PFDs), process, and hydraulic calculations are developed, many choices have to be made about finer and finer details of plant layout, equipment, and safety.

Potential hazards have to be identified, quantified, eliminated, or controlled. Materials and equipment have to be specified. While doing this, installation, commissioning, maintenance, and other nonsteady-state operational states of the plant have to be considered. Past experience with other similar plants needs to be incorporated.

The process designer does not do this in a vacuum—they need to integrate the requirements of and insights from other disciplines. Optimizing a few aspects of the process, or even the whole process chemistry, is not optimizing the overall plant design. It may actually be making it less optimal if it does not consider other constraints.

In academia, "process integration" often means a mathematical analysis of a system using one of what is now a wide range of mathematical, graphical, or computer-based tools originally developed to allow beginners to try their hands at design.

The task (rather than problem) these tools solve is one of handling a multiplicity of possible solutions to a well-defined case. It isn't so much that there are an infinite number of possible solutions to the question, each of which has a number of subtly different implications, as that there are a great number of permutations to winnow for the best value of a single numerical selection criterion.

The tools can perform this winnowing process for us, but the fact that there is essentially one right answer, and a computer can find it better than a person, tells us that this isn't really engineering, and the "problem" is essentially trivial.

These tools may have some limited use in the final stages of designs which use a lot of energy, and have clear possibilities for substantial recovery of that energy. They may also be of use in identifying potential improvements to existing processes.

However, starting a design from heat integration of a process at steady state without consideration of cost or other implications is trying to fit a job to a tool rather than the reverse.

Another buzzword in academia is "process intensification." All that needs to be said about this is that professional engineers make processes as intense as they practically can, but no more so (to paraphrase Einstein).

## Indicators of a need to integrate design

Professional process plant designers always integrate their designs (it's the most important aspect of process design) though they are integrating different aspects from those using the term in academic contexts. There are, however, certain contexts where we address the same issues as the theorists, most notably where there are likely to be big cost implications.

### High utilities usage/waste

Engineers will always be concerned that their design might be less than optimal if they see that a design has high operational costs due to high utilities usage.

I worked for some years for a UK government scheme called Envirowise which involved visiting process plants and factories to audit resource usage. What was clear to me after doing a hundred or so of these visits is that there are a number of areas where such wastage is commonplace. In fact, Envirowise eventually gave its consultants a table for the best places to start looking, which I have reproduced at Table 21.1.

The use of this table is far more economical in terms of designer resources than carrying out a mathematical network analysis such as pinch. Designers have to conserve their own resources too.

### High feedstock use/waste

Feedstocks cost money, and the waste streams generated by wasted feedstocks often cost money to dispose of. This does not imply that the optimal feedstock conversion rate is 100%. Each incremental increase in conversion usually costs more than the last similarly sized increment.

Back when I worked for Envirowise we were encouraged to nudge people in a direction toward zero waste, but there is almost always a point on that road beyond which economic viability becomes questionable. It is, however, true to say that uncritical acceptance of traditional levels of resource inefficiency is unlikely to yield optimal design either.

A bit of analysis of resource usage is almost always informative and worthwhile for operating companies. Designers should, however, already be taking these issues into consideration using the standard combination of mass balance, appropriately accurate costing, and sensitivity analysis.

## How to integrate design

> *Since the mathematicians have invaded the theory of relativity, I do not understand it myself anymore.*
>
> ***Einstein.***

**Table 21.1** Resource efficiency measures for process plant

**Cost-effective water-saving devices and practices for industrial sites: process plant**[a]

| Item/ application | Description/purpose | Equipment/technique | Applicability | Other benefits | Other considerations | Potential cost | Potential payback |
|---|---|---|---|---|---|---|---|
| Liquid ring vacuum pumps | Reuse of sealing water after treatment | Tanks/pumps/ separators/cooling | Widespread | Energy savings from cooling seal water | Seal water: temperature and quality control | H | M |
| | Eliminate water use | Mechanical vacuum pumps | Widespread | | Liquid trap | H | M |
| Cooling towers | Automatic blowdown—operation at maximum acceptable total dissolved solids (TDS) level | Conductivity-base control | Widespread | Reduced chemical use | | M | S |
| | | Cooling load reduction—minimize evaporation and blowdown | Widespread | Reduced chemical use | | M | M |
| | | Alternative cooling processes to avoid evaporation of water: | | | | H | M–L |
| | | (1) Air blast | High cooled water temperature ($>40°C$) | | Monitoring requirements | | |
| | | (2) Heat exchangers | Widespread | Waste heat could be used elsewhere | | H | M |
| Heat exchangers | Water reuse through closed-loop system | Tanks/pumps/heating source/cooling source | Widespread | Heat sink/ cooling tower/ water quality | | H | M–L |
| Hydraulic power packs | Optimize water use by varying water flow depending on oil temperature | Bulb-and-capillary operate control valves | Widespread | | Essential cooling requirement | L–M | S |
| | Reuse after cooling—through closed-loop system | Tanks/pumps/cooling source | Large installations | | Cooling tower/ water quality | H | L |

Potential costs and paybacks are for guidance only. Actual costs and paybacks will vary due to project-specific details.

[a]Risk assessment required. Potential cost: L = low (minor alterations) (£0 to a few £100s); M = medium (a few £100s to a few £1000s); H = high (extensive alterations or new plant required) (many £1000s).
Potential payback: S = short (a few months); M = medium (less than a year); L = long (over a year).

Source: Courtesy: WRAP/Envirowise.

Professional designers are employed to produce integrated designs, but the things they balance are practical things like cost, safety, and robustness, process controllability and operability, and the conflicting demands of the various disciplines and stakeholders involved.

They never optimize designs for a single variable or small number of variables, which is why process plant design is more like playing chess than doing logic puzzles. In fact, it is far harder than chess, which is why people can still out-design computers, but computers are now the world's best chess players (the fact that computers can do it better than people shows that chess is in fact a very complex task, rather than a problem-solving exercise). There may be no right answer to a design exercise, but there are better and worse answers, and better and worse players.

Those who think that process plant design is or will ever be a form of applied mathematics simply do not understand the nature of design. They have simplified an activity to a level where its essence has been lost.

## Intuitive method

Much professional engineering knowledge is qualitative or semiquantitative. Envirowise produced a series of graphs and tables to facilitate increased resource efficiency of existing processes which designers can use to inform their design process. These are reproduced in Tables 21.1–21.3 and Figs. 21.1 and 21.2.

There are also useful tables on waste heat recovery in *Practical Process Engineering* (see "Further Reading").

These tables and charts are as useful to a beginning plant designer as an operating company, as they show us where to look for improvement to our designs, and the rough cost/benefit profile.

## "Formal" methods

### Pinch Analysis

Originally intended for optimizing heat recovery in an operational environment, pinch analysis has also been applied to analysis of mass flows, including water flows. It is neither novel, nor much to do with professional design, but academics love to apply it to design. I learned it in university, and not only did I never once use it, I never once heard it mentioned until I entered academia again 20 years later.

An outline of the most commonly used method for the production of water purity profiles with a fixed flow rate for a single contaminant is as follows (Fig. 21.3):

1. Draw a graph of flow rate versus concentration for all sources and sinks of water on a plant, where $x$-axis is flow, ascending from zero, and $y$-axis is concentration of contaminant, descending from zero.

**Table 21.2** Resource efficiency measures for cleaning and washdown

**Cost-effective water-saving devices and practices for industrial sites: cleaning and washdown**[a]

| Item/application | Description/purpose | Equipment/ technique | Applicability | Other benefits | Other considerations | Potential cost | Potential Payback |
|---|---|---|---|---|---|---|---|
| Pressure control/flow restriction | Reducing instantaneous flow at point of use | Valves, orifices, pressure-reducing valves | Variable or intermittent supply, pressure, or demand | | | L | S |
| Countercurrent rinsing | Reuse of rinse water | Tanks | Multistage unit processes | | Water quality requirements | M | L |
| Spray/jets | Appropriate application of water | Nozzles | Widespread | Improved cleaning | | L–M | S–M |
| | | Spray nozzles | Widespread | Improved cleaning | Spray mist drift | L–M | S–M |
| | | High-pressure spray packages | Washing processes | Improved cleaning | Power consumption | M–H | S–M |
| Automatic supply shutoff | Use of water only when needed | Solenoid valves in pipelines | Small-bore pipes | | Essential water requirement | L–M | M |
| | | Actuated valves in pipelines | Large-bore pipes | | Essential water requirement | M | M |
| | | Jets/spray guns on hoses | Widespread | More efficient application | Theft of spray guns | L | S |
| Reuse of wash water | Reuse of wash water in other areas | Tanks/pumps | Widespread | | Cross-contamination/ water quality control | M | S–M |
| Scrapers/ squeegees/ brushes | Sweeping up of slurries | Dry cleaning methods | Large areas | Possible reuse of materials | Dry collection systems | L | S |
| Cleaning-in-place (CIP) technology | Countercurrent reuse of rinse water with multiple reuse of chemical cleaners | Proprietary plant | Processes with frequent cleaning | Hygienic plant/ minimal downtime for cleaning | Water quality requirements | H | S–M |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Recycle after treatment | Treatment of wastewater to an acceptable standard for reuse | Filtration/ sedimentation | Coarse solids removal/ phase separation | | Waste disposal and water quality | M | M–L |
| | | Centrifugation/ flotation | High-quality solids removal/phase separation | | Waste disposal and water quality | H | M–L |
| | | Biological treatment | Removal of dissolved biodegradable solids | | Waste disposal and water quality | H | M–L |
| | | Ion exchange | Removal of dissolved contaminants | | Waste disposal and water quality | H | M–L |
| | | Distillation/ stripping | Solvent recovery | By-product | Waste disposal and water quality | H | M–L |
| | | Absorption/ adsorption | High-quality treatment, solvent recovery, removal of toxic substances, color, etc. | | Disposal of spent absorbent | H | M–L |

Potential costs and paybacks are for guidance only. Actual costs and paybacks will vary due to project-specific details.
[a]Risk assessment required. Potential cost: L = low (minor alterations) (£0 to a few £100s); M = medium (a few £100s to a few £1000s); H = high (extensive alterations or new plant required) (many £1000s). Potential payback: S = short (a few months); M = medium (less than a year); L = long (over a year).
Source: Courtesy: WRAP/Envirowise.

**Table 21.3** Typical water savings

| Water-saving initiative per project | Typical reduction per site (%) |
|---|---|
| **Commercial applications** | |
| Toilets, men's toilets, showers, and taps | 40 (combined) |
| **Industrial applications** | |
| Closed-loop recycle | 90 |
| Closed-loop recycle with treatment | 60 |
| Automatic shutoff | 15 |
| Countercurrent rinsing | 40 |
| Spray/jet upgrades | 20 |
| Reuse of wash water | 50 |
| Scrapers | 30 |
| Cleaning-in-place (CIP) | 60 |
| Pressure reduction | See Fig. 21.1 |
| Cooling tower heat load reduction | See Fig. 21.2 |

Source: Courtesy: WRAP/Envirowise

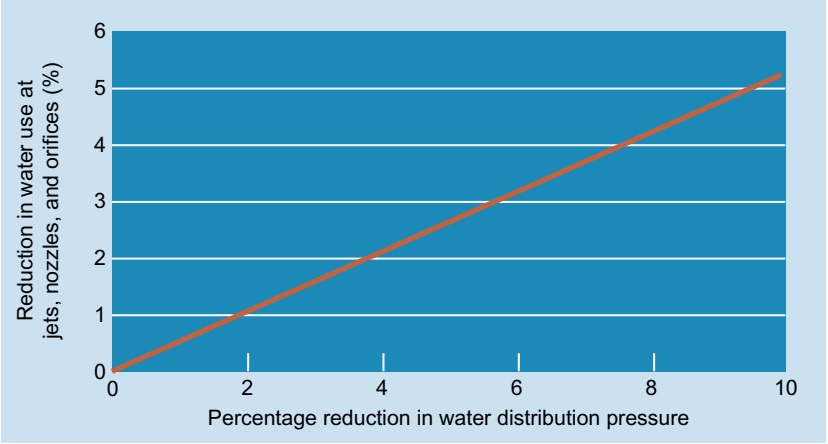


**Figure 21.1** Effect of pressure reduction on water use at jets, nozzles, and orifices. *Courtesy: WRAP/Envirowise.*

2. Start on the left plotting flow rate/concentration pairs for potential sources of water, in increasing order of purity (dirtiest on the left).
3. Join the points to form a stepped "curve."
4. Next plot flow rate/concentration pairs for potential sinks and join the points to form a second "curve."
5. Move the sinks curve to the left until the curves just touch.
6. Where the two curves touch is the pinch point.

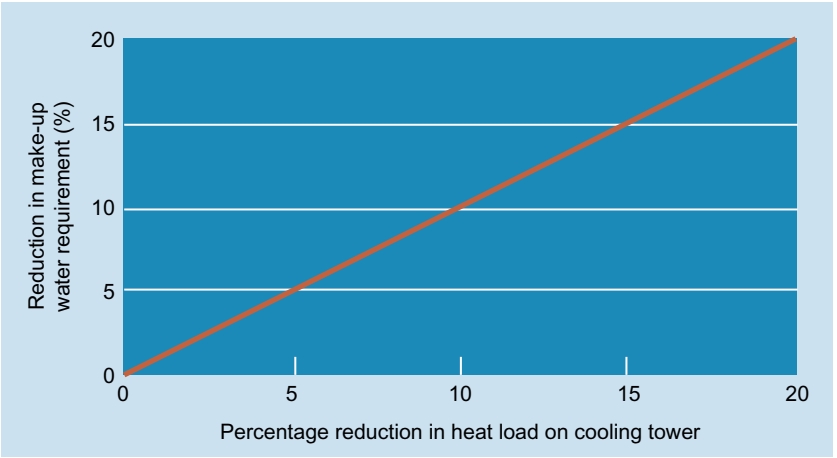


**Figure 21.2** Effect of heat load reduction on make-up water requirement for a cooling tower. *Courtesy: WRAP/Envirowise.*

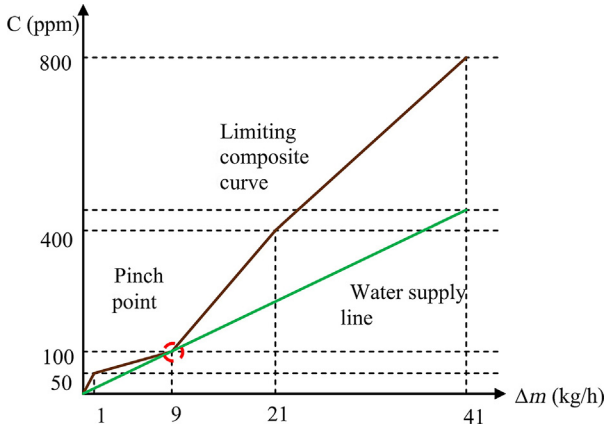


**Figure 21.3** Limiting composite curves for water pinch analysis. *Reproduced from Klemes, J. J., Varbanov, P. S., & Kravanja, Z. (2013). Recent developments in process integration.* Chemical Engineering Research & Design, 91, *10, with permission from Elsevier.*

7. Where these two curves overlap represents the scope for water reuse.
8. Area to the left of any overlap represents wastewater generation.
9. Area to the right of any overlap represents clean water use.

Next, we can use sensitivity plots of potential cost saving versus concentration change for multiple contaminants, to identify areas where variation in maximum allowable inlet and outlet concentrations would yield the greatest savings.

We can consider four possible levels of investigation of the water reuse possibilities while carrying out our pinch analysis.

The cheapest and quickest analysis assumes that all sinks are presently at their maximum allowable inlet concentrations. This level of analysis will identify some cheap modifications which will yield small benefits.

Next, we might consider the possibility of increasing the maximum allowable inlet concentrations in those areas where our sensitivity analysis has indicated that large savings might be available. There are technical limits on how far these concentrations can be increased without causing corrosion or other problems, which should be established and considered. Greater savings are likely to be obtained by this more in-depth analysis than for the simpler one above, and the costs of identified modifications are likely to be quite low.

A more rigorous analysis still considers the possibility of reuse after regeneration by water treatment technologies of a number of key streams. This can involve significant expenditure on water treatment plant.

Similarly, we might consider distributed effluent treatment techniques—rather than mixing all effluents together prior to treatment, we can consider treating or partially treating wastewater streams individually. It is claimed that this technique can offer improved contaminant removal efficiency at reduced cost.

Note that we need meaningful data on water quality and quantity produced and used to even start this process. People operating a real plant can obtain such data, but they are not available to plant designers. The same is true of all other pinch analysis techniques, which is the first reason why real process plant design engineers don't use it—they can't.

Whilst it might make for an entertaining academic exercise, pinch analysis has no part in professional design exercises, and its inclusion in the design process would not merely be an extraordinary waste of time—its use necessarily leads to suboptimal design.

## Where's the harm? The downside of academic "process integration"

### *Capital cost of "integrated" plants*

When applied to energy use, the marginal cost/benefit ratio of each additional heat exchanger is not really considered by many of the techniques used by pinch analysis enthusiasts. This means that they are likely to be recovering heat at a greater cost than it can be purchased for. Real engineers don't do that. Even my students know better—see Fig. 21.4, in which one of my former students shows how, past a certain percentage heat recovery, the savings fall away.

More generally, it can be seen from Table 21.1 that the cost of additional heat exchangers is rated as "high," but that the potential for payback is only medium–high. Every additional increase in energy recovery needs to make financial sense. These very

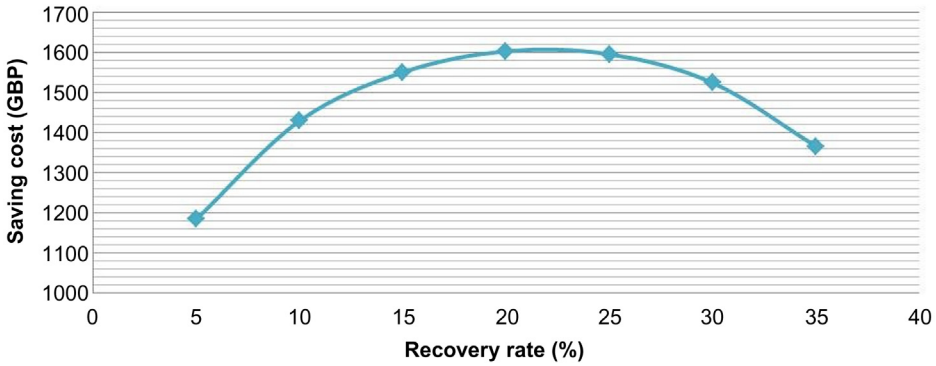


**Figure 21.4** Cost optimization of heat recovery in a heat exchanger.

significant costs are not taken into consideration by process integration techniques as applied to design.

### *Commissioning "integrated" plants*

The integration of heat exchanger networks means that any plant produced by such a design approach would be normally operated in a highly interdependent manner, and (theoretically at least) with reduced energy inputs.

The process commissioning engineer will have to get such a plant from an initial condition, in which even single systems are not locally balanced with respect to their flows and control loops, to one in which there is extensive cross-system mass and energy balance. This is going to take additional time and other resources in the most resource-pressured part of the job.

If the designer has not included backup heating and cooling services capable of providing the full heat loads, ignoring integration, the commissioning engineer will need to make provision for them. These additional resources may be very expensive, and they may be needed again after every shutdown.

In summary, the small incremental savings in energy recovery may end up saving less over the plant lifetime than the extra commissioning time and resources cost. These very significant costs are not taken into consideration by process integration techniques.

### *Maintaining "integrated" plants*

Maintenance of integrated plants will carry the same problems as commissioning, and all the additional equipment will have its own additional maintenance requirements. These very significant costs are also not taken into consideration by process integration techniques.

## Further reading

Sandler, H. J., & Luckiewicz, E. T. (1987). *Practical process engineering: A working approach to plant design*. New York, NY: McGraw-Hill.

UK Department of Trade & Industry, Envirowise/WRAP. (2005). *GG523: Cost-effective water saving devices and practices—For industrial sites* (Online). <http://www.wrap.org.uk/sites/files/wrap/GG523_industrial%20Cost-effective%20water%20saving%20devices%20and%20practices%20-%20for%20industrial%20sites.pdf> Accessed 25.10.18.

# CHAPTER 22

# Developing your own design style

## Introduction

There is a great deal more to engineering than the stuff they teach you in university. Most of it is to do with people rather than engineering science, and I'm not talking here about the embedded humanities modules which sometimes get shoehorned into curricula. There are even a few useful books on the subject.

## The art of engineering

Engineering design is not applied science. It is an art, learned and refined through practice, though it might be argued that it becomes less creative as it proceeds past the design freeze.

Engineers use all that they are in the practice of their profession. Intelligence and knowledge, which are neither scientific nor mathematical, are of crucial importance.

When I teach design to mature postgraduate students, it can seem as if they are more creative than the undergraduates, as they come up with a lot more ideas than the students with no industrial experience (but higher entry qualifications). I do not think that this is pure creativity. I think it is that they have more life experience to be creative with. Judgment, intuition, and the knowledge and experience which teach us what doesn't work and enables us to reason by analogy all take time to develop.

Back when I was learning to teach I wrote a blog reflecting on my experiences, from which an excerpt follows:

> *I went to see a client today. He had a problem and had changed five things which might have caused it, as well as several others which might not (though he didn't understand that). I knew which two were the causes in ten minutes.*
>
> *I think to myself: 1. Engineering is easy (for engineers). 2. How did I learn how to do that? How can I teach others to do it? I could try this example as a case study and see how hard it is to people earlier in their training. It seems to me at present that more so than amassing factual knowledge, it's to do with acquiring the engineer's perspective. Whilst it may have its limitations, on its home turf, it can cut through confusion, obfuscation, and misunderstanding in a flash.*
>
> *There is, however, no substitute for having a firm grasp of practical math and physical science. Theory underpins practice and is available for verification of intuitive understandings. An experienced professional is not necessarily doing math and science in their heads when*

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00023-9
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*troubleshooting a problem. It is more like pattern-matching 'Oh, yes, this reminds me of that time when. . .' and not necessarily even the words, just seeing into the problem, pruning the tree of possibilities. This involves people, and discourse (though engineers do not call it that).*

*I spent far more time talking to the maintenance technician yesterday than I did looking at the machinery. In talking to him, I have to get him to talk freely, so that he tells me what he thinks has been happening. I have to assume that he will see what he expects to see, and make sure I trust nothing of what he says which I have not verified personally. I look for areas where what he says is self-contradictory and explore those areas with him in a way which does not make him feel I am trying to trap him into admitting he screwed up or rubbish his pet theory.*

*I am, however, quite ruthless in making sure that I get to the bottom of what is happening to my own satisfaction. I'm going to find out what is wrong, and I'm going to fix it. How much I tell his boss is, however, negotiable. He knows how I work, since we have been interacting for a year or so, and we conduct an unspoken negotiation between us.*

*I am commercially interested in extending and upgrading the plant but am constrained by professionalism not to milk the client. He is paid to maintain the plant but would like it to be as automated and reliable as possible to make his job as easy as possible. He is, however, also paid to minimize costs, consistent with meeting the required effluent quality.*

*Between us we come up with a plan which makes us both look good, him cost-conscious to his boss, and the client to be actively addressing the effluent failures from the point of view of the authorities. It also has a bit of what both he and I want, which is to pay me to make the plant better from the point of view of the maintenance staff as well as the other parties.*

*I'll also put some nice things in my report to his boss about the build quality of the modifications he has made and underplay their contribution to the problems. He in return will not mistreat the plant in between visits and blame it on my design. All of this is unspoken, but I know it is going on, and I think he does too.*

*Away from engineering practice, they might think chemical engineering is all about numbers and chemicals, but it seems to me that professional practice has far less of this than academia. Working with other people, their fears and desires, their wishful thinking and self-deception, strengths and shortcomings (as well as our own) is a crucial part of the job—but that doesn't mean a psychologist could do it.*

## The philosophy of engineering

When I came to have to teach others what I had learned, but what no one had taught me, I needed to figure out what I knew and how I knew it to be true. I initially thought philosophy might help, but ultimately the philosophy of engineering is as useful to engineers as philosophy of science is to scientists. (Not very!)

*Philosophy of science is about as useful to scientists as ornithology is to birds.*

***Richard Feynman (supposedly)***

You might, however, have noticed that I have read more books on the philosophy of engineering than you would expect of someone generally dismissive of philosophy. I have, however, only recommended those books on the philosophy of engineering which were written by engineers. It seemed to me before I read books on the philosophy of engineering that they would be useful in figuring out what I knew about engineering and how I knew it. However, it turned out that the subject of books on philosophy of engineering was philosophy itself rather than engineering. I did find out one useful thing though, which was that much of what I knew was far from scientific.

Until this point I still thought that engineering was applied science. Anyone that has actually practiced the profession and had time to reflect upon it will see that it is far more art than science (though those who have never practiced, and those who have never reflected upon their practice, might disagree).

So, philosophy of engineering might be useful after all, as a way to get nonpractitioners to understand in an abstract intellectual way that engineering's foundation is not science and math, but *praxis*, the process of design.

This intellectual knowledge would not, however, be the fruit of praxis itself, and an academic informed by philosophy as to the nature of engineering would be a philosopher who understood what engineering was rather than an engineer. They might try to remember that if they write books on engineering.

## The literature of engineering

I read a lot of books on process design in preparation for writing this book, and most of them were worthless. Books on design by people who had never designed anything (whether they are philosophers or any other kind of academic) are as accurate and informative as a Braille list of rainbow types written by a person who had only ever heard them described.

I did not read those books to learn what process design is. The approach given in this book is not derived from the books I recommend, I have merely recommended those books which seemed to be informed by an understanding of what design is about.

Of far greater use to engineers than philosophizing are readable books which move our understanding of the nature of engineering design forward. We can actually learn what doesn't work and why it doesn't more efficiently from such books than from practice.

I would recommend, at a minimum, reading:

- Trevor Kletz, *An Engineers View of Human Error* (or anything else by him).
- Henry Petroski, *To Engineer Is Human* (or almost anything else by him, though later books are not so good).
- Harvey Dearden, *Professional Engineering Practice: Reflections on the Role of the Professional Engineer.*

If you are in a situation later in your career where you need to understand what you know without getting lost in abstraction, I would recommend:

- Walter G. Vincenti, *What Engineers Know and How They Know It.*
- Eugene S. Ferguson, *Engineering and the Mind's Eye.*
- Donella H. Meadows, *Thinking in Systems.*
- Billy Vaughn Koen, *Discussion of the Method.*
- James Trevelyan, *The Making of an Expert Engineer.*

## The practice of engineering

Accept no substitute, for there is none. Psychologists disagree with each other about the relationship between practice and mastery, but only because they aren't really scientists. They think that if some never achieve mastery despite great amounts of practice, and some achieve mastery with very little (reported) practice, it means that practice may be irrelevant to mastery. However, common sense tells us (but not psychological researchers apparently) that people lie, and anyone who teaches anything can see that some people have little aptitude for their subject. Whatever your starting point, there is no substitute for persistence.

> *Nothing in the world can take the place of persistence. Talent will not; nothing is more common than unsuccessful men with talent. Genius will not; unrewarded genius is almost a proverb. Education will not; the world is full of educated derelicts. Persistence and determination alone are omnipotent. The slogan Press On! has solved and always will solve the problems of the human race.*
>
> ***Calvin Coolidge***

Some will find during practice that they are practicing the wrong thing, and change course, and there will always be an advantage to those with talent, but those who persevere will become engineers.

Like Casey Ryback, I also cook, and I find practicing engineering is far more like cooking than it is like doing exam questions. If your educational assessment only consisted of completing exam questions you might find that what you are good at is exams, rather than engineering.

## Personal sota

Koen calls the set of heuristics used by an individual their sota (for state of the art), and uses quasimathematical notation to show it as being that of an individual at a given time thus: sota $|_{\text{sean moran; 2019}}$ would be mine as of now. This may be a little gimmicky, but it does allow him to illustrate the relationships between individual sotas and good practice as the intersection on a Venn diagram of all sotas. So, this book is a

subset of sota |sean moran; 2019, which I have gone to some effort to ensure corresponds with current good engineering practice, sota |Eng; 2019.

My sota depends upon my background, as does yours. Engineers are not generic—there are reasons why I am the kind of engineer I am (but feel free to skip this bit if you think it self-indulgent).

All of my siblings are engineers. My father was not a professional engineer, but he was a pipefitter and mechanic who worked in engineering, specifically the operation and maintenance of power stations.

I have therefore spent most of my life hearing stories from those who work in engineering, telling of what works and what does not, along with explanations of the bits of kit involved. I also heard the stories maintenance staff tell about the folly and arrogance of green professional engineers, who think book-learning alone is superior to experience and "technician-level knowledge."

We didn't have a lot of money when I was a kid, and I had to learn how to mend my own stuff, as well as help my dad mend the car and do on. I also used to take apart any bits of machinery I found to see how they worked, and when I wanted a bike, I built more than one from discarded bits. I also built myself various types of computers. So, I went into education already knowing quite a lot of useful things about the nature and culture of engineering, and with hundreds of hours of fiddling with engineered products.

A very un-PC technician got us all together when we covered process technology in my first degree and said to us all "those of you who like fixing your own cars and bikes are going to do well in this course. Those of you (and I'm talking about the girls and Asians here) who don't aren't going to like it at all." He was wrong about women and people of Asian descent, but he was right about the link between a history of tinkering and a feel for engineering.

I am, by original education, an applied biologist. Biology was more about classification than deep understanding back when I started studying it. Molecular biology has elucidated the mechanisms behind much that was obscure back in the 1970s, but despite progress in systems biology, multicellular life is still very far from complete explanation. The subject is still mostly about the readily observed but ill-explained emergent properties of irreducibly complex systems.

The most important math in biology is still statistics, and often the nonparametric statistics of populations which do not meet the assumptions underlying the more commonly used kinds of statistics. Biologists understand that statistics is itself a set of heuristics, true only if their underlying assumptions are true. The most commonly used kinds of statistics are not very robust but are frequently used where their underlying assumptions are not true, rendering them at best meaningless. There is no such thing as 2.4 children.

Biology is an essentially qualitative field of study, whose objects are complex biochemical and physical processes controlled by homeostasis, in which variables are

regulated so that internal conditions remain fairly stable and relatively constant. Despite this vagueness, we have for a very long time been able to make biology do things that we want it to.

So, for me, a process plant is like a biologist's plant. I don't worry about whether I understand every aspect of the reductionist science of its subcomponents, or even whether it is possible to do so. They are unimportant to the job of engineering a plant which will give me the yield I want of product in a safe, reliable, and cost-effective way.

Then there is the element of chance and the opportunities available to us—I originally trained as a biochemical engineer and ended up in water treatment plant design due to unexpected political resistance to biotechnology, and the cyclical nature of the water industry. My process plant design experience was mostly with contracting companies, and my original job title was proposals engineer, rather than process engineer. I had to design whole plants, coordinate all disciplines, and care a great deal about cost, risk, footprint, and so on.

This is a key reason why this book has a different scope from those from other professionals whose job title was or is process engineer. Such books tend to be limited in scope to very detailed design of unit operations, because that is what "process engineers" are often asked to do. Engineers of other disciplines (notably mechanical) coordinate the design effort, and process engineers are just used to carry out the "chemistry" bits the mechanical engineers cannot do. This is my working explanation for why process plant design books by process engineers are narrow, deep, and limited in scope, and why the best book I could find on the subject was written by mechanical engineers.

Then there is the question of attitude—I started out overconfident, nearly won a job which I would have regretted winning, and became more cautious. I have seen initially overcautious engineers tread a reverse path.

> *The fundamental cause of the trouble is that in the modern world the stupid are cocksure while the intelligent are full of doubt.*
>
> ***Bertrand Russell***

Expert engineers have a certain humility because we work with poorly defined problems and incomplete data and we tend to be very mindful of the limitations of what we know. Humility is not, however, pretending that the highest level of knowledge is that we know nothing, as those who mistranslate Plato's Socrates frequently claim. What Socrates is more likely to have said -than 'the highest level of knowledge is to know that we know nothing'- is:

> *I am wiser than this man, for neither of us appears to know anything great and good; but he fancies he knows something, although he knows nothing; whereas I, as I do not know anything, so I do not fancy I do. In this trifling particular, then, I appear to be wiser than he, because I do not fancy I know what I do not know.*

This quotation is not intended to reflect the correct attitude for the product of long training in a subject, but that at the beginning of learning (in the opinion of a philosopher). Those who adopt it as the correct attitude when master of a subject are guilty of false humility. Engineers are not paid to pretend not to know the answers.

Though they are not paid to pretend to know the answers either, it's hard to show nonengineers or even nonchemical engineers the reasoning behind our decisions; and practical demonstration is usually impractical. Blue-chip management types tell us that a certain amount of bluff (for want of a better word) is needed in order to be effective because we need to persuade others to follow our recommendations. It could be argued that an important component of style is the ability to convey confidence without compromising the truth.

Experienced professional engineers still differ from each other in their risk aversion, but both overconfidence and its opposite are corrected by experience in those who stay in engineering. Other personality traits also often tend toward the middle way as a result of practice.

What do people with Asperger's syndrome (like myself) bring to the party? My greatest advantages as an autistic designer are my obsessive interest in my subject area and tireless quest for the truth of a situation combined with an ability—like that of color-blind people—to see through camouflage. Social conventions are pretty much as invisible to me as variegated colors are to the color-blind.

I can be relied upon to ask the questions no one else would think to ask, of the people others don't dare to question. I don't really care about whether people like the truth, I just want to know it. I don't even care about whether I like the truth, and I (often, I am afraid, wrongly) assume others want to know the truth too.

(Design teams need someone like this, particularly in design reviews, to avoid groupthink. It doesn't necessarily need to be someone with Asperger's—it just needs to be someone who is comfortable being the devil's advocate. If diversity has a business case, this is where it is to be found.)

I have studied, written, practiced, talked, and thought about science and engineering more or less all day, every day, for the better part of 30 years. If you have met me, you will know I talk about little else. I have nothing to contribute to small talk. I am intellectually aware that "neurotypicals" are having a "reading between the lines" communication during such exchanges, but I'm only able to reliably read the lines.

The world is a different place to me than it is to neurotypicals, and I consequently routinely come up with ideas which no one else thought of. I am "neurodiverse," and I am fortunate that my area of obsessive interest is one in which a good living can be made by someone with lesser social skills if their technical skills are sufficiently great. Only 16% of autistic people are in full-time paid employment, and bullying and discrimination are commonplace for those who are in work, which is why even those who know me professionally will not have previously known that I am autistic.

I know that I am not the only engineer "on the spectrum," though I only know one other who is "out." The part of the profession I practice seems ideally suited to our strengths and weaknesses. I am frequently the third (or even sixth) person to look at a problem, but I am (so far at least) always the last. I will think and talk of nothing else until I understand how to solve it.

Anyway, your background and experience will be different, but practice will shape you into a particular kind of engineer. You will have a personal state of the art. You will find yourself seeing all kinds of problems away from professional life as soluble with the tools of engineering. You will come to understand that in life, as in engineering, "all is heuristic," as Billy Vaughn Koen says. Until then you'll have to take my word for it.

## Further reading

Dearden, H. T. (2017). *Professional engineering practice: Reflections on the role of the professional engineer* (2nd ed.). Createspace Independent Publishing Platform.
Ferguson, E. S. (1994). *Engineering and the mind's eye*. Cambridge, MA: MIT Press.
Kletz, T. (2001). *An engineer's view of human error* (3rd ed.). Rugby: IChemE.
Koen, B. V. (2003). *)*. Discussion of the method: Conducting the engineer's approach to problem solving. Oxford: Oxford University Press.
Meadows, D. H. (2008). *Thinking in systems—A primer*. London: Routledge.
Petroski, H. (1992). *To engineer is human: The role of failure in successful design*. New York, NY: Vintage Books.
Trevelyan, J. (2014). *The making of an expert engineer*. Boca Raton, FL: CRC Press.
Vincenti, W. G. (1993). *What engineers know and how they know it: Analytical studies from aeronautical history*. Baltimore, MD: Johns Hopkins University Press.
Wilson, C. (2018). The autistic advantage. *New Scientist*, *239*(3186).

# CHAPTER 23

# Practical ethics

## Introduction

There was a time when philosophy was practical, and ethics was at the heart of that useful discipline. But Aristotle spoiled all that, and now philosophy is mostly pointless beard-stroking. Even what philosophers nowadays call "practical philosophy" is actually deeply impractical.

Theoretical ethics may be a luxury we cannot afford in professional engineering practice. I don't mean that we cannot afford to act ethically, but that our choices are always constrained in professional practice in a way which they are not in a theorist's thought experiments. The essential feature of a genuine ethical dilemma is that there is no soft consequence-free option; there must be real consequences for safety, the environment, and/or your career. Dilemmas have no right answer.

The relationship between practical professional ethics and the ethics of philosophers is therefore at least as convoluted as the relationship between pure mathematics and the mathematical intuition of professional engineers.

What kinds of ethical issues do engineers have to deal with, anyway? A recent article on ethics in *Chemical Engineering* magazine suggested that engineering ethics is to do with "doing the right thing, as opposed to doing things right," and sets out seven principles to help engineers act ethically:

- know what you believe in;
- recognize ethical problems;
- identify stakeholders;
- analyze interests;
- examine alternatives;
- execute decision; and
- document everything.

It is clear from these principles and the discussion in the article that engineering ethics would not so much generate an immediate answer to the scenario I give in Example 2, as inform how to prevent it happening again.

These principles do however provide a framework to act professionally in situations where you have the luxury of time to think about the best course of action deeply. Such situations are commonplace in professional life, though I have rarely had to think for that long about them. I do know what I believe in.

*An Applied Guide to Process and Plant Design*
DOI: https://doi.org/10.1016/B978-0-12-814860-0.00024-0
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## Example 1

Let us first of all take an example from early in my career. I was asked to do a job which involved working with a client from an industry I had strong political/ethical objections to. I declined to do so on ethical grounds. My boss found someone else willing to do the job but told me that if there had not been an alternative engineer available, my refusal to comply with a reasonable management instruction would have been grounds for dismissal.

In an academic exercise, it might seem that the right thing to do the next time he asked me to work for what I thought an unethical industry (which he did, and there was no second choice that time) would be to resign, or to be fired for insubordination, but to do this so early in my career would have made it very difficult to get another job.

Was it self-serving rationalization when I decided that my refusal to do work which cleaned up the industry whose environmental footprint I objected to was more egotistical than moral, as the work would get done whether I got myself fired or not?

At least that situation was one where there was an opportunity to think long thoughts about my best course of action and to discuss it with others. The most difficult ones are far more constrained by circumstances and played for still higher stakes.

## Example 2

The next example is one which I use in my training courses on operation and maintenance of effluent treatment plants, based on my professional experience.

*You are called out to a groundwater treatment plant at around midnight by plant operators who say they have had a few problems and want to go home having already done twelve hours on site. They say the lagoon is a bit on the high side, and it's raining a little.*

*The lagoon contains abstracted groundwater contaminated with diesel, polychlorinated biphenyls (PCBs), suspended solids and sewage. The water is treated by the plant to remove PCBs down to limit of detection (0.005 mg/l). PCBs are 'red list' persistent organic pollutants—which means that no detectable trace of them must be discharged to the environment. The hydrocarbons floating on top of the lagoon are heavily contaminated with the hydrophobic PCBs. If the lagoon were to overtop, the hydrocarbons would spill first, and they might potentially spill beyond the site boundary.*

*You arrange for your assistant to come with you, load up your tools and testing kit, PPE, walkie-talkies, lighting etc., and drive to site, arriving around 2AM. You look at the weather forecast—it's been raining hard for a week and is set to continue for another week.*

*The operators also neglected to tell you that they ran the GAC filters without backwashing for ten straight days prior to your arrival, and now they are so clogged that will only treat half of their design flowrate.*

*Now no-one is answering their 'phone any more.*

*When you inspect the plant, you find that you have maybe an hour before the lagoon will overtop, spilling onto the ground on site, and potentially offsite after a time. You are seemingly faced with a choice between allowing that to happen or making changes to the plant which mean that you will knowingly break the law by discharging insufficiently treated water to sewer.*

The constraints you are operating under (in no particular order) are as follows.

It is the early hours of the morning. You are tired and under great pressure, and you have no other professional engineers to consult with. Nevertheless, there is a potential that your actions will be judged after the fact in court by people operating under none of these constraints. Stress and tiredness can make people prone to indecision and mental inflexibility but finding the best solution to this situation will require mental flexibility and decisiveness.

Even to get to the point where it is clear you have a choice to make requires a cool head and unusual technical skill—75% of the professional engineers I set the exercise in a training scenario cannot see the possibility of a choice, even though they are not in the real high-pressure situation.

You are obliged to act lawfully, both as a citizen, and as a professional engineer. Failure to do so will in any case expose you to the risk of criminal prosecution and very significant fines, possibly even imprisonment.

You would like to avoid doing anything which will invalidate your professional indemnity insurance for fear of incurring significant uninsured losses.

You would like to avoid doing anything which will expose your client to criminal prosecution and losses, both out of professionalism, and the self-interest of continuing to obtain work from them.

You would like (if required in future) to be able to make a case that you have done the least bad thing you might have done under the circumstances—you don't just need to do the 'rightest' thing that you can, you need to be able to prove later that you did.

What do you do? Will any version of a philosopher's ethics help you to choose? Or is it all down to pragmatically working with the personal, legal, and technical resource constraints you are operating under?

Practical engineering ethics aims to address the obligations of an engineer to their client, society, and profession. In professional practice, these obligations are however highly specified. They are not subject to ad hoc modification as we see fit. We do not have a free choice, and are required to follow the instructions of society, client, and profession other than in extremis.

To break this down, we have a contractual relationship with our client, and our role, authority, and responsibilities are usually set out in writing. For example, my company's standard terms and conditions say that we will

*carry out Services*

*2.6.1 with reasonable care and skill,*

*2.6.2 in accordance with Good Engineering Practice,*

*2.6.3 in accordance where relevant with the Client's Standard Operating Procedures and QA procedures as notified to the Consultant in the relevant Services Schedule,*

*2.6.4 in accordance with applicable Health and Safety regulations,*

*2.6.5 whilst on the Client's premises in accordance with the Client's applicable site security and health, safety and environmental regulations and procedures notified to the Consultant,*

*2.6.6 in accordance with all lawful and reasonable instructions of the Client concerning the provision of the Services, and*

*2.6.7 in accordance with the Consultant's own relevant procedures.*

Larger clients in particular may have documents which fall under the heading of "Standard Operating Procedures and QA Procedures," "Applicable Site Security and Health, Safety and Environmental Regulations and Procedures," and "Relevant Procedures."

I am contractually obliged to follow such procedures, unless so doing will be illegal or cause significant harm. If I decide not to do so, I am in breach of my contract, and entirely responsible for the consequences of not following procedures. "I was only following orders" might not be much of a defense, but it is a better one than "I didn't feel obliged to comply with the law, my contract, or professional responsibilities."

Society also tells us how we have to act by means of legislation. We would be unwise to ignore the law, whether we agree with it or not. In the case of the example we are working with here, the Water Industry Act is of prime importance. The Act states that there are:

*Restrictions on use of public sewers. . .no person shall throw, empty or turn, or suffer or permit to be thrown or emptied or to pass, into any public sewer, or into any drain or sewer communicating with a public sewer. . .any matter likely to injure the sewer or drain, to interfere with the free flow of its contents or to affect prejudicially the treatment and disposal of its contents.*

It also states that:

*A person who contravenes any of the provisions of this section shall be guilty of an offence and liable. . .on conviction on indictment, to imprisonment for a term not exceeding two years or to a fine or to both.*

Our professional ethics are set out by our engineering institutions. The Institution of Chemical Engineers, for example, states:

*Members shall comply with the Code of Professional Conduct as published in the Regulations from time to time. In particular. . .members shall at all times so order their conduct as to uphold the dignity and reputation of their profession and safeguard the public interest in matters of safety, health and otherwise. They shall exercise their professional skill*

*and judgment to the best of their ability and discharge their professional responsibilities with integrity.*

That's a bit vague, so we might look at the Royal Academy of Engineering Statement of Ethical Principles for more detailed guidance.

*There are four fundamental principles that should guide engineers and technicians in achieving the high ideals of professional life. These express the beliefs and values of the profession and are amplified below*

1. *Accuracy and rigor*

   Professional engineers and technicians have a duty to ensure that they acquire and use wisely and faithfully the knowledge that is relevant to the engineering skills needed in their work in the service of others.

2. *Honesty and integrity*

   Professional engineers and technicians should adopt the highest standards of professional conduct, openness, fairness and honesty.

3. *Respect for life, law and the public good*

   Professional engineers and technicians should give due weight to all relevant law, facts and published guidance, and the wider public interest.

4. *Responsible leadership: listening and informing*

   Professional engineers and technicians should aspire to high standards of leadership in the exploitation and management of technology. They hold a privileged and trusted position in society, and are expected to demonstrate that they are seeking to serve wider society and to be sensitive to public concerns.

So, before we convene our personal ethics committee, we need to consider our options in the light of these professional, legal, and contractual obligations. When we have considered all that is legally and professionally required of us, do we have any wiggle-room? Before we can answer that, we need to consider the technical feasibility of possible solutions.

I set out the simplest form of the professional and legal constraints on engineering decision-making applicable to the scenario set out earlier.

These are however not the only constraints on our decision-making. There are also practical constraints which we need to take into consideration:

- The volume of rain falling on the catchment of the plant exceeds the rated plant throughput even with the GAC filters in a clean condition.
- All of the pumping stations feeding the plant are full. There is no spare underground capacity.
- The GAC filters are backwashed to the lagoon, so they cannot be backwashed until the lagoon level has dropped considerably.
- As it is the middle of the night, we will not be able to get tankers to site to take away the excess water before 9 a.m. at the earliest, and the volumes of water are so

great that we will need a great many tankers to make any useful impression on the lagoon level.

So, on the face of it, we need to find a way to make a plant with clogged filters run faster than it was designed to do in a clean condition, whilst maintaining a legally compliant discharge to sewer. As this is simply not physically possible, we have a limited range of options:

1. Get back in our car, go home, and go to bed, after sending many texts and an email to the client complaining about the hospital pass his staff have given us, and our unwillingness to get involved in a mess which they made.
2. Make the plant run far faster than it was designed to go, shortening equipment life, and sacrificing effluent quality, after sending an email to the client saying that we consider this the least bad option under the circumstances.
3. Do nothing and make arrangements to clean up the inevitable spill from the lagoon, which will continue until we can lower the lagoon level using tankers, after sending an email to the client saying that we consider this the least bad option under the circumstances.

Option 1 seems to me an unprofessional approach, even if I did not create the situation, and I am only on site as a result of misinformation. The fact is I am the only one there, and if I don't fix it, it isn't going to get fixed. I have the tools, knowledge, and manpower required to mitigate the situation, so I am obliged to try.

I therefore personally favor option 2, though this option is only available to engineers skilled enough to see how to make it happen, and there is a calculated risk that the overloaded equipment will fail, leaving you in a worse situation.

Option 3 will look to be the only alternative to option 1 to those without the required skill to see the possibility of option 2. Option 3 will cost the client a great deal of money, and those taking it will not have washed their hands of the job as they might by pursuing option 1.

Option 3 carries a very real chance of being sued for professional incompetence, defending ourselves against the report of an expert witness who has identified option 2, and considers that any competent engineer should have taken it. Option 1 is therefore actually the right option for anyone who thinks themselves not competent to handle the situation.

I took option 2 in the real situation the exercise is based on. I didn't read the Water Industry Act, any ethical policies, or even refresh my memory of my business terms and conditions before I made it. Neither did I have a discussion or consult Socrates. I did what seemed intuitively right, the least bad thing I could do under the highly constrained circumstances in which I was operating. I have never thought of a better option I might have taken in the years since it happened, and neither has anyone on any of the courses I have used the example on.

I have studied philosophy since this event happened, but it has given me no new insights into this kind of situation. Philosophy is not about solving real-world problems, it is a clever zero-sum game of ideas and words, and it isn't an engineer's kind of clever.

Engineering ethics (like engineering itself) is necessarily intuitive, heuristic, and highly constrained. I am aware of no evidence that engineers are made better at engineering by studying ethics. Neither am I aware of any evidence that anyone makes more moral decisions after studying ethics (whatever "more moral" might mean, as a philosopher might add).

*Chemical Engineering* magazine runs interesting articles about practical ethics every couple of years with a quiz and some advice. It's worth a read, even if their quiz examples are perhaps a little oversimplified, and the advice unsuited to a high-pressure situation.

A lot can be lost in such simplification, notably the important facets of engineering problems which are required in order to turn them into example scenarios. As I set out Example 2 above, it might seem as if there might really have been three discrete, consecutive, and well-defined stages (outline scenario, consider legal aspects, consider technical aspects) leading to three well-defined options (bale out, attempt a risky fix, or fiddle while Rome burns).

While no one so far has disagreed with option 2, the loss of complexity, and the loss of resource pressure has still made it rather an intellectual exercise, which might be worked through sequentially. The real situation was far more like this:

> *You arrive on site as described, expecting a fairly straightforward situation which the operators basically had under control.*
>
> *You are surprised to find that there are pages of uncancelled level 1 alarms on the SCADA system, and a number of key items of equipment are inoperable due to the interlocks linked to these alarms.*
>
> *As you study the SCADA system, you notice that all of the level readings on the pumping stations and the lagoon are flashing red, and where there are duplicate level sensors, their readings differ wildly.*
>
> *You also notice that the differential pressure sensors on the GAC filters are giving nonsensical readings, and the flowmeter which measures outgoing flow from the plant is reading 0 $m^3$/h.*

Which if any of your instruments do you trust? What do you do if you do not trust an instrument?

Leaving aside how to resolve this issue, it might take a good hour to characterize the scenario you are in to a reasonable degree of certainty, and experience with this scenario in training situations suggests that many people would not discover it before

the lagoon overtops. Having discovered it, it should be noted that our fix will have to be undertaken in a situation where we cannot trust key instruments.

In the real world, at the point where the scenario was outlined, and you had come up with an outline solution, the situation changed. The site representative of the ultimate owner of the site came over to say (rather forcefully) that the high level in your pumping stations was flooding their building and preventing their staff from working. An immediate fix which emptied key pumping stations was required immediately, or your client was going to be sued for the cost of the lost work.

You need to act effectively right now, and there are not just three options in the real-world scenario. There are a whole set of mistaken and ineffective options based upon believing the readings from some or all of the instruments. These options seem to the unwary engineer like option 2, but yield the same result as taking option 3.

There are a set of options based on being overly influenced by the tongue-lashing you received from the ultimate client's representative, the possibility of various kinds of repercussions, or otherwise unwise action founded in panic. These might lead to lagoon overtopping and/or complete plant failure.

There are a set of options grounded in despairing of the possibility of a technical fix, involving making no attempt to actually deal with the problem, but instead focusing exclusively on avoiding repercussions after the disaster. This is not even option 3. All of your effort goes into an ass-covering/blame-shifting exercise.

Then there are the information overload/analysis paralysis options. There are numerous alarms going off, both audible and visual. There is a log of what has been done by the operators, and trends can be viewed on the SCADA system to see what has been happening, or at least what the dodgy instruments say has been happening. Are these data going to help or overwhelm you? If you don't know what you are looking for, it is likely to be the second.

There are other options still, but these are enough to give a small taste of the complexity and pressure of the situation.

Luckily, the engineer's real decision-making process is largely intuitive. There is no three-part process of neatly framing a problem, considering aspect one, considering aspect two, boiling viable choices down to a manageable number, and then selecting the least bad one using philosophy, mathematics, or any other theoretical tools.

Like all professionals, engineers use a mixture of consecutive reasoned approaches and concurrent intuitive approaches to solve problems. No competent engineer would act before having satisfied themselves that they are making the best use of the information available to them to come up with the best diagnosis of a problem, and proposed solution. The best engineers will, however, see a number of good solutions in a flash

of intuition and test these options for utility against the information available. They will reject those based in panic, bullying, despair, or confusion.

Those who lack the intuition and emotional control to see the possible solutions will become lost in the data. Solutions do not emerge from the data. The data are used to test candidate solutions.

It is my opinion that the refined knack of intuitive understanding comes from pattern-matching based in personal and shared experience of practice. Educating engineers has however taught me that some of those coming into education already have more of this knack than less gifted engineers who have practiced for decades.

As I said earlier, I am not aware of any evidence that anyone makes more moral decisions after studying ethics. Is there any point in teaching ethics (or even higher mathematics) to engineers, when professional practice is so dependent on intuition?

## Common practical problems

I discussed earlier in the chapter the kinds of ethical issues which come up in professional life for engineers. There are two which seem to come up again and again: bribery and being asked to lie or shade the truth.

Bribery is a fact of life in some countries. Despite the international antibribery legislation, I have had to decide what to do about offers and invitations to bribery on several occasions.

I don't take bribes, but I will accept, for example, someone I do business with paying for a meal if everyone is clear that it will have no effect on my decision-making process. I don't offer bribes, but I might buy a bottle of wine for someone who has given me business in the last year come Christmastime.

But what about using "agents" and the like, who bribe people for you, so that you have plausible deniability? I have never engaged one, but I know people who have. I was once (long before the now-current international antibribery legislation) in the same situation as I was with the case of the industry I didn't want to work with—accept associating with an "agent" or resign.

The second most common issue in my experience after attempted or invited bribery is being asked to lie. This is quite common and is one I have walked away from a number of jobs over, including one very recently. My rule here is simple. I just won't do it. I will give my complete opinion on a matter, or no opinion at all. This is one where I am very careful to document the discussion (preferably keeping it in writing) and the version of my opinion which I am willing to stand by.

My most commonly experienced ethical issues in professional life are to my mind simple matters of conscience. Do you think it is OK to bribe people? Do you take bribes? Do you lie if offered money or some other inducement? No long thoughts are necessary. Do you?

How about if you are given a task by a manager that you know requires shortcuts to be made, or poor quality (product, workmanship, etc.) to achieve the task in the time or cost available? In such circumstances, I recommend requesting specific written instructions to do the thing implied by the instruction:

- "Are you accepting that xxx will not be followed."
- "Working like that is not the approved safe way of doing it."
- "It can't follow the approved method."

Essentially, you should aim to obtain a clear direction in writing to break rules. If you cannot, then you can state "I'll follow the established SOP, method, rule of law unless directed otherwise." If directed to do otherwise, you need to update your CV and get on LinkedIn.

I'm a believer in telling the truth. If you tell the truth you have one story to tell. If you tell a lie, you need another lie to prop it up, and after a few rounds of this you don't know if you are up, down, or sideways. Keep it simple and honest.

The examples given in the *Chemical Engineering* magazine quiz and article are subtler, and therefore questionable. In the last of these articles I read, an example is given which seems to be founded in the idea that reactive (rather than preventative) maintenance is always unethical. Reactive maintenance (if it ain't broke, don't fix it) is however more or less the norm in industrial effluent treatment. Something which would be unequivocally wrong in a nuclear reactor is widely thought OK in a plant with a far less hazardous failure mode.

The example I used earlier in this chapter was in fact caused by a radical lack of preventative maintenance. My solution to the problem would discharge water with a few ppb of PCBs into a sewer full of diluent storm water. No measurable harm would be done, and there would in any case be no one there to measure it. But, is this ethical? I think it is, as it was the least harmful option.

If you are forced to do something questionable (the least worst) once—should you look to get the situation resolved—fix the issue—so you or others don't have to face the same challenge in future?

But (again) should I have taken a sample of the water I discharged in the above scenario, have it analyzed, and report myself to the EA if any PCB was present, in the interests of "documenting everything"? Or should I not?

Some engineers, commenting on a draft of this chapter, suggested I gave you the right answer to this dilemma, but there is (as I pointed out earlier) no right answer to an ethical dilemma.

## Two useful tests

Here are two simple tests to validate that your proposed action is "ethical" or "consistent with good professional practice." Note that we work to good ethical practice,

rather than best. Best practice is (as Harvey Dearden has pointed out), the exception, not the rule.

## Test 1: "The boss test"

Imagine that you are doing what you are doing and realize your boss has been quietly at your elbow for the past 30 minutes. Will he be OK with what you are doing? (Some people suggest using your mother as the silent witness, but is she likely to be familiar with what the organization wants you to do?)

However, just in case your boss is like Tony Soprano (but without the ethical backstop), there is a stricter test.

## Test 2: "The shop window test"

Imagine you (with or without boss) are doing what you are doing in the window of a department store with a bus stop outside. You suddenly realize the bus queue are now pressed to the window observing what you are doing, taking notes, and forming an impression. Do they look happy?

This test moves us away from the detail of corporate procedure into the more general social/professional responsibility, and from a personal internal and private conversation to one where your actions are known and you will be held to account.

## Another common dilemma

When do you put your hand up to say something is wrong, generally speaking, sooner is better than later, but you can be premature.

> *Let's say you issue a report or recommendation and new information or facts show that the earlier work might have been flawed. Maybe people are now doing something less safe than was believed, or something is being built that is less safe or effective than it could be with the new information. Do you wait for someone to point it out or do you put your hands up? If I caught someone sitting on bad news I might react harshly, and at the very least I would want a really good explanation.*

The engineer who kindly gave me this example was speaking from personal experience: he had a skid design which he knew contained an access error, but the design was set aside pending final vendor information. When that information arrived, the skid had to grow by 2 m, so the access issue was resolved along with everything else. The engineer told me he would have put his hand up if the vendor information had remained unchanged and the poor access still existed—but it was fixable (as is everything in engineering) for a price. Making a fuss prematurely would have achieved nothing except making him look like a fuss-pot.

A related example comes from my own experience. When I was working for Envirowise, I used to regularly see examples of illegal bad practice at the sites I visited. Some of my fellow auditors thought that professionalism required us to report these to the authorities. I (along with the majority of my fellow auditors) thought that this would be counterproductive. We were offering confidential advice intended to improve the environmental performance of the businesses we visited. If we became in effect agents of the regulatory authorities, people would lose trust in us, and our ability to achieve our aim would be compromised. Furthermore, the authorities would almost certainly give the offender a chance to stop doing what they were doing before taking formal action against them. We could do this ourselves in a friendly way, without telling the authorities, telling the site owner that if they did not, sooner or later, the authorities would catch up with them.

# Appendix 1: Integrated design example

I often use a particular Siemens ultrasonic level instrument to measure tank fluid levels. The current model of the instrument can display just the distance from the ultrasonic transducer to liquid surface, or it can be programmed to display the fluid level or even fluid volume (even with quite complex tank shapes).

It can output the fluid level or volume as a 4–20 mA signal. It has five volt-free contacts which I can program to become active or inactive at various tank levels. It can have two transducers and be programmed to make decisions about which transducer's signal is the more reliable. It has all kinds of sophisticated signal processing onboard, and can be programmed as to which state to fail to if the signal from transducers is lost. It can produce alarm signals against many of these functions.

So, if I want to control a set of duty/standby pumps in such a way as to maintain a constant tank level, and to avoid dry running, I have choices. The way I tended to use this instrument, back when it was less sophisticated, was to use it as a field-mounted stand-alone on/off level indicator controller. I used the volt-free contacts to start and stop pumps in succession, with the lowest set point providing dry-running protection. The pumps were started under control of these contacts by online or star delta starters, and were either on or off.

I tend nowadays to use the instrument in one of two ways:

1. As a more sophisticated stand-alone modulating level indicator controller. I can wire the 4–20 mA output signal directly into a pump's inverter starter. Even motor starters have built-in computers nowadays, and an inverter drive can use the 4–20 mA signal to achieve all the same control actions as the last approach with no programmable logic controller (PLC) involvement.
2. As a dumb level indicator transmitter, with the 4–20 mA signal going out to the PLC, which then controls a number of pumps using variable-speed drives (inverters) to go faster or slower in order to maintain a fairly constant tank level. I will probably under this scenario use one of the volt-free contacts as my hard-wired (direct into the pump starter) dry-running protection.

There are many other ways to use the instrument, but to take the two I have covered, the first and second have no PLC involvement, so they may save money on PLC costs, but with the drawback that they are less flexible as they cannot be so readily controlled via the PLC or system control and data acquisition system.

There is only one 4–20 mA output on the instrument, so if we wire it into the inverter, we cannot straightforwardly supply it to the PLC, so we cannot remotely monitor tank level, or intervene to alter action levels, and so on.

(A C + I specialist comments: "4–20 mA can be routed through more than one device as current loop; better practice is to use resistor to convert to voltage and parallel connect voltage signal into as many devices as you like. Inverters might have output available that could be configured as repeat. There are repeater isolator devices available.")

As I said, "cannot be so readily controlled."

So, in this very common design scenario, which features at least once on virtually every plant I have designed, I tend to choose between these three options which I have used dozens of times before, unless I can see a strong reason not to.

There is nothing wrong with starting the detailed design of process control systems by using standard control loops, strategies, and instruments, as it is close to how experienced professionals design. We have well-tried strategies in our heads, in much the same way as chess players do. Any inappropriate elements or unforeseen interactions between stock approaches should be picked up in design reviews and Hazard and Operability studies.

At the design for construction stage, there are many interactions between the elements of design which experienced engineers will have anticipated at earlier design stages. In the example given, we are considering pumps and electromechanical components in addition to the software, controllers, and instruments which commonly fall under the heading of process control. We are informed more by broad experience than by a narrow but mathematically rigorous analysis of a few parameters.

## Integrated process control and design example

To illustrate how we balance qualitative considerations, I will take an example from the water industry which I am very familiar with.

Consider the case of pretreatment of filter feed water. We need to add a coagulant to allow for the removal of colloidal matter, measure pH (and temperature to adjust for its effect on pH), and adjust pH to the minimum solubility of the product of our coagulant addition.

In theory this is very simple, but consider the following issues affecting process design/control:

## Conceptual design issues

- The coagulant dose can be fixed, dosed proportional to flow, or dosed proportional to flow and color.
- Many coagulants are strongly acidic, so the coagulant dose will affect acid/alkali dose.
- We can choose lime or caustic for alkali addition. As lime has a greater buffering capacity, has an appreciable reaction time, and needs to be kept stirred if it is to be

reasonably homogeneous, caustic is usually more controllable, but may be less forgiving of long control loop times.
- We usually use hydrochloric or sulfuric acid for our acid addition. Adding chloride to the system may require a higher material specification.
- We usually need to control pH to within 0.1 pH units to give sufficient control over coagulant product solubility.
- We can dose chemicals using a number of pump types, or by gravity via a control valve.
- We need to have a short, sharp mix for both dosed coagulant and any required pH correction acid/alkali.
- We need to have a longer lower intensity mix for growth of the floc particles which the filter will remove.
- We can use static or dynamic mixing for either of these duties.
- Static mixers may not achieve the specified degree of mixing in the mixer body—the measurement point is usually several pipe diameters downstream.
- Static mixers for chemical addition have a hydraulic residence time (HRT) measured in seconds. Dynamic mixers can have an HRT of several minutes.
- Both static and dynamic mixers for flocculation have an HRT of several minutes.
- There is no field-mounted instrument which reliably measures the efficiency of flocculation, though we can measure it indirectly by measuring the turbidity which escapes the filter downstream, several minutes later.

## Layout/piping issues

- We may need to have a certain length of straight pipe after the static mixer before the downstream pH sensor to ensure accuracy.
- We need to make sure the flow meters will run full, which may require their installation at a low point (avoiding dead legs), to ensure accuracy.
- The pH probe needs to be regularly removed and replaced for calibration, so it needs to be installed in such a way as to make this easy for operators.
- If we are going to use a gravity chemical addition system, we have to have a certain height available to us between the storage tank and dose point.
- The output from the flocculator should be subjected to minimum shear prior to filtration to avoid breaking flocs.
- If we are going to use open-topped dynamic mixers, we will break head, so we need to arrange in the layout for them to flow to each other and then on to the filters by gravity, or (less favored) we need to add intermediate pumping stages.

## Dosing issues

- Positive-displacement pumps give a pulsating flow.
- Static mixers only mix radially.

- As a consequence of the last two issues, pulsation damping is strongly recommended if piston diaphragm (PD) pumps dose into a static mixer.
- Saturated sodium hydroxide solution freezes at 10°C.
- Precise control of chemical flow via a control valve on a line from a header tank is very hard to achieve, as head varies with tank level, so we need to measure dosed flow if we are dosing via a control valve.
- In very dirty applications it might be difficult to keep the pH probes clean.
- Many pH probes now come with onboard temperature correction.
- Cheap and reliable field-mounted dedicated pH controllers are readily available.
- PD pumps are available which allow control of motor speed by one input 4–20 mA signal and control of stroke length via another.
- Stepper motor-driven digital PD pumps are available which can control the dose directly from the above two signals.

## Cost issues

- Static mixers are far cheaper to buy and run than dynamic mixers.
- Motor-driven PD pumps are far more expensive to buy and run than solenoid pumps.
- Field-mounted pH controllers are a cheaper way to control pH than PLC control.
- Electromagnetic flow meters are more expensive to buy than the turbine type, but are cheaper to run.

## Safety issues

- Header tanks full of acids and alkalis at height carry safety concerns.
- The pressurized ring mains at height used to fill these header tanks carry safety concerns.
- We need to be sure that our main process pipework will not fill up with acid or alkali when the main plant shuts down, and that even if this did happen, this would not result in loss of containment.
- We need to be sure that positive-displacement pumps are not throttled on suction or delivery sides, and that if making this impossible is unavoidable, over pressurization of delivery pipework does not lead to loss of containment.
- We need to be sure that even if our efforts to prevent loss of containment of acid/alkali fail, we have secondary containment in place.
- We need to be sure that if loss of containment occurs, and operators are contaminated, they can wash off the chemical as quickly as possible.
- We need to be sure not to mix acid and alkali with each other.

## Robustness issues

- If the operation of our plant depends upon effective coagulation, we will need standby units for all coagulant and acid/alkali dosing systems.
- PD pumps have a much better turndown, and are far more controllable than solenoid pumps.
- Peristaltic pumps are better than piston pumps for lime dosing, but their hoses present maintenance problems.
- Chemical addition is usually done via flexible lines. These lines have a limited life in service, and consideration needs to be given to their repeated replacement in operation.
- Systems based on dynamic mixing have far longer response times due to their much higher HRT.
- Electromagnetic flow meters are far more reliable and less prone to blockage than turbine type.
- Electromagnetic flow meters are far more precise than turbine type.
- Flocculation can to some extent be optimized by measuring zeta potential, and particle size analyzers to measure filtration efficiency. However, in my opinion the kit to do this is, presently, more suited to lab than field (others disagree).
- We need to ensure dry-running protection for any dosing pumps.
- We need to be able to tell if any powered mixers are operational.
- We need to know if any control valves are actually in the position we have requested.
- We need to know that the main process stream is flowing in order to prevent dosing into an empty line.
- Some flow meters have empty pipe detection built in.

## Integrated solution

So, I would personally use a PD pump, with a 4–20 mA (or sometimes pulsed) signal from a field-mounted pH controller controlling stroke, and a 4–20 mA signal from an electromagnetic flowmeter in the main flow (with empty pipe detection) controlling speed for acid/alkali addition. A stepper motor-driven digital pump might alternatively be used, with the advantage of greater simplicity and turndown.

I would usually use caustic and sulfuric acid at around 40% (w/w) solutions for pH correction, though I sometimes use lower concentrations for operator safety reasons and to make freezing in the absence of tank heaters less likely.

The pump will deliver against a loading valve, and in between the loading valve and the pump there will be a suitably specified (especially in materials and capacity) pulsation damper vessel. Between the pump discharge and the first valve, there will be

a return line to the feed tank protected by a pressure-relief valve (PRV). This arrangement shall be arranged such that if the PRV lifts, the return flow will be visible to operators.

The pH signal into the controller comes from a probe, mounted five pipe diameters of unobstructed pipe downstream of a static mixer, specified to give a coefficient of variance (CoV) of 0.05 (or less technically a 95% degree of mixing) at that measurement point across the operating flow range.

The static mixer has separate connections for coagulant, acid, and alkali. The chemicals are dosed through injection lances (incorporating spring-loaded nonreturn valves) into the centerline of the pipe. Flexible hoses carrying dosed chemicals should be contained in trace-heated and lagged plastic pipes which provide a duct to pull though a replacement hose, as well as secondary containment.

Coagulant dose is via a PD pump (or a solenoid pump if the plant is small and price is crucial), controlled by a 4–20 mA signal direct from an electromagnetic flowmeter.

Chemicals will be stored in quantities suitable for at least a month of operation, with external connections suited to suppliers working in that area. In the United Kingdom we might need a tank heater, and will probably need trace heating and lagging of NaOH systems at a minimum. Ideally all lines which might freeze under all reasonably foreseeable conditions will be trace heated and lagged. (I have had clients talk me out of this requirement in the past, and they have had cause in time to regret the penny-pinching.)

The dosed main process flow will pass from a static mixer to a static flocculator, selected for robustness and simplicity. Line sizes and fittings from flocculator to filter shall be selected to minimize headloss and therefore shear.

So Luyben's idea of incorporating controllability into design is sound, but there is a lot more to controllability than math or generic theory. The insights of plant operators and commissioning engineers and their knowledge of the detailed characteristics of kit need to be incorporated into the design.

Some might think that some of the things in the description I give above are not control issues, but they encapsulate choices as to whether to solve a design problem with soft or hard control. For example, if I do not ensure that my pipes will not freeze through physical arrangement, soft controls will be needed.

# Appendix 2: Upset conditions table

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## Specific upset conditions

In the pages that follow, upset conditions are identified by the guidewords used in Hazard and Operability (HAZOP) studies—this is where upsets are most likely to be identified prior to plant operation. The upset condition can then be analyzed under the four phases of the project: conceptual (Con); detailed design (Det); startup (St); and operation (Op). For ease of presentation and analysis, the conditions are analyzed in block format with possible solutions and individual reference numbers. The time when the upset condition is most likely to be detected is indicated by an "X" in the project phase. In this manner, the upset condition can be read vertically in the matrix and the project timing can be read horizontally.

It should be noted that the proposed solution may not always be applicable to a specific problem, but they all have been used at one time or another. Any tabulation of this type can only give guidance. It can never hope to be comprehensive. In some instances, conflicting requirements may be identified and engineering judgment will be necessary to ensure the most appropriate solution is chosen.

A word of caution about the following. I suggest you use Appendix 4's checklist on your P + ID to check for completeness, rather than this one. Table A2.1 is not intended to support the academic "CHAZOP" which is intended to allow beginners to instrument a PFD/P + ID, nor should it be taken to imply that a HAZOP is a design review. If you find yourself adding in lots of instrumentation as a result of using this table, your design is not very well developed. This is OK, if you are a beginner, and you are not in a HAZOP. Otherwise, you are going to look like a beginner.

**Table A2.1** Specific upset conditions.

| No. | Condition | Solution | Most likely stage | | | |
|---|---|---|---|---|---|---|
| | | | Con | Det | St | Op |
| **Pressure** | | | | | | |
| P1 | More pressure | Devise a process which operates at or near atmospheric pressure and does not utilize volatile fluids or vigorous reactions | X | | | |
| P2 | More pressure | Specify the design pressure of equipment such that it cannot be overpressured by any condition other than fire | X | X | | |
| P3 | More pressure | Consider the potential for metal fatigue following pressure cycling | | X | | X |
| P4 | More pressure | Take due account of elevation changes and design for the sum of both hydraulic head and vapor pressure (see L1) | X | X | X | |
| P5 | More pressure | Install a high-integrity protective system to shut the process down before the overpressure condition is encountered | | X | | X |
| P6 | More pressure | Install a full rated safety relief system and analyze the means by which the fluids may be dispersed if they are toxic or flammable | | X | | |
| P7 | More pressure | Steam trace or purge relief valve nozzles to prevent the deposition of foulants | | X | X | X |
| P8 | More pressure | Specify the failure action of control systems so as to minimize the effect of failure (see P16) | | X | X | X |
| P9 | More pressure | Initiate control procedures such that flow-limiting devices such as orifice plates and control valves can only be changed after a safety study has been carried out (see F4 and OP2) | | X | X | |
| P10 | More pressure | Carry out routine proof tests of relief valves and test facilities for protective systems | | X | X | X |
| P11 | More pressure | Install duplicate relief valves and test facilities for protective systems | | X | | X |
| P12 | More pressure | Rod through vents to ensure that lines are clear of debris. Check flame arrestors are clear and not choked with debris (see F8, F9, and P21) | | X | X | X |
| P13 | More pressure | Install purge points on total condensers to allow the removal of inert gases like air and nitrogen | | X | X | X |
| P14 | No pressure | Choose a process which will not reach a hazardous condition if pressure falls or is lost; this may apply to oxidation processes where oxygen and hydrocarbons could enter the flammable regime should the reaction stop | X | | | |
| P15 | No pressure | Specify the metallurgy such that the metal will not enter a brittle regime when depressured. This might apply to cryogenics and refrigerants (see T13) | | X | | |
| P16 | No pressure | Specify failure action of control systems so as to minimize the effect of the failure. This may be contrary to the needs of more pressure (see P8) | | X | X | X |

(*Continued*)

**Table A2.1** (Continued)

| No. | Condition | Solution | Most likely stage | | | |
|---|---|---|---|---|---|---|
| | | | Con | Det | St | Op |
| **Pressure** | | | | | | |
| P17 | Less pressure | Consider the effects of leaks in vacuum condensers. This is a variant of no pressure | | X | X | X |
| P18 | Reverse pressure | Design equipment for full pressure and vacuum, including liquid head | | X | | |
| P19 | Reverse pressure | Specify pressures within the process such that leakage across heat exchangers produces a safe condition, for example, steam leaks into hydrocarbons and not hydrocarbon leaks into steam | | X | | X |
| P20 | Reverse pressure | Install vacuum protection where appropriate, for example, on fixed-roof storage tanks | | X | | |
| P21 | Reverse pressure | Rod out vents to prove they are clear. Check flame arrestors for debris (see P12, F8, and F9) | | X | X | X |
| P22 | Reverse pressure | Check vacuum relief valves for operation | | | X | X |
| P23 | Reverse pressure | Be mindful of the causes of vacuum: | | | | |
| | | Sucking in suction catch pots when air testing compressors | | X | X | X |
| | | Draining vessels | | | X | X |
| | | Steaming out vessels | | | | X |
| | | Adding cold fluids to hot vessels (rapid condensation) | | | X | X |
| | | Internal reactions causing volume shrinkage (e.g., polymerization or rusting) | | | X | X |
| | | Polythene sheets blowing over vents and breather lines | | | X | X |
| **Level** | | | | | | |
| L1 | More level | Specify the design temperature of equipment for the sum of hydraulic head and vapor pressure (see P4) | | X | | |
| L2 | More level | Locate vapor relief valves at the top of the equipment so that they are not "drowned" by liquid | | X | | |
| L3 | More level | Consider stressing pipelines and pipe supports for the liquid full condition (required for hydraulic pressure testing) | | X | | |
| L4 | More level | Consider the loading on foundations and structures during hydrotesting. If the vessel is totally flooded, design for the worst case | | X | | |
| L5 | More level | Changes in interface level may result in separate liquid phases passing forward along the process route, should protective systems be installed? (see L7 and OT10) | | X | X | X |
| L6 | More level | If equipment sizes are increased for any reason consider the extra loading on supports, particularly during hydrotesting | | | X | X |

(*Continued*)

**Table A2.1** (Continued)

| No. | Condition | Solution | Most likely stage | | | |
|---|---|---|---|---|---|---|
| | | | Con | Det | St | Op |
| **Level** | | | | | | |
| L7 | Less level | The light phase will pass forward as entrained fluid (see L5 and OT10) | | X | X | X |
| L8 | Less level | Electric heaters or temperature probes may be exposed. Low-level trips should be fitted to cut off the power (see L11 and T5) | | X | X | X |
| L9 | No level | Will the loss of level result in the loss of liquid flow to a vital system such as cooling water, lubricating oil, or seal oil? Should a protective system be installed? (see OT10) | | X | X | X |
| L10 | No level | Will the loss of level result in a gas "blow by" from a high- to a low-pressure system? Consider installing flow chokes and protective system or full flow pressure relief on the low-pressure system | | X | | X |
| L11 | No level | Will the loss of level result in overheating? Consider the effect of loss of level in a boiler, a reboiler, or an electrically heated vessel. Install low-level trips (see L8 and T5) | | X | X | X |
| L12 | No level | Install bunds round storage tanks sized for 1.1 times the storage tank capacity for containment in the event of tank rupture | | X | | |
| L13 | Reverse level | Consider splash filling vessels at a higher elevation as opposed to filling under liquid levels and possibly causing a siphon effect. However, consider the generation of static electricity if the fluids are flammable | | X | X | X |
| L14 | Reverse level | Consider reverse level (i.e., from high to low level) as a potential for reverse flow | | X | X | X |
| **Temperature** | | | | | | |
| T1 | More temperature | Is the reaction exothermic? Can the reactor "run away"? Consider the need for protective systems such as quenching, catalyst kill, or the equivalent | X | X | | |
| T2 | More temperature | Size the reactor cooling system with excess capacity to prevent a run away. Ensure that mixers have a reliable power supply | | X | | |
| T3 | More temperature | Consider the potential for metal fatigue due to temperature cycling | | X | | X |
| T4 | More temperature | Install low-flow trips in fired heaters | | X | | X |
| | | Install high stack temperature alarms in fired heaters | | X | | X |
| | | Install high metal temperature alarms in fired or electrically powered heaters | | X | | X |
| T5 | More temperature | Install low-flow trips in electrically heated systems | | X | | X |
| | | Install low-level trips in electrically heated vessels (see L8 and L11) | | X | | X |

(*Continued*)

**Table A2.1** (Continued)

| No. | Condition | Solution | Most likely stage | | | |
|---|---|---|---|---|---|---|
| | | | Con | Det | St | Op |
| **Temperature** | | | | | | |
| T6 | More temperature | Specify materials of construction to give adequate allowance for creep | | X | | X |
| T7 | More temperature | Inspect equipment for evidence of creep on a regular basis. Note, evidence of creep may manifest itself suddenly after a number of years of operation. Creep is a cumulative effect—a number of short deviations may lead to serious damage in the future | | | | X |
| T8 | More temperature | Specify failure action of control valves so as to minimize the effect of failure | | X | X | X |
| T9 | More temperature | Consider the potential for overheating when pumps or compressors are blocked in | | X | X | X |
| T10 | Less temperature | Consider the effects of freezing in cold environments (see C4). Water can freeze in drain lines, instrument trappings, relief valves, valve bonnets, pump casings, low point, and fire water lines. Examine the need for heat tracing, thermal insulation draining, maintaining a small flow of fluids to maintain a limited heat input | | X | X | X |
| T11 | Less temperature | Consider the possible effects of crystallization of process fluids in relief operations and emergency drain/blow down systems. Should these be heat traced? (see C2) | | X | X | X |
| T12 | Less temperature | Consider the possible effects of gels of high viscosity. Should lines be heat traced? (see C3) | | X | X | X |
| T13 | Less temperature | Specify the metallurgy such that the metals will not enter a brittle regime when depressured (see P15) | | X | | X |
| T14 | Less temperature | Specify the failure action of the control valve so as to minimize the effect of failure | | X | | X |
| **Flow** | | | | | | |
| F1 | More flow | Consider the effect of a rise or fall of levels in equipment | | X | X | X |
| F2 | More flow | Consider the potential for exciting tube vibration in heat exchangers and tube failure caused by fatigue or wear from high velocity | | X | | X |
| F3 | More flow | Consider the potential for exciting vibration in thermowells | | X | | X |
| F4 | More flow | Install flow-limiting devices | | X | X | X |
| | | Size relief systems for full flow through the flow-limiting device | | X | X | X |
| | | Register the flow-limiting device as a protective system (see P9 and OP2) | | | X | X |

(*Continued*)

**Table A2.1** (Continued)

| No. | Condition | Solution | Most likely stage | | | |
|---|---|---|---|---|---|---|
| | | | Con | Det | St | Op |
| **Flow** | | | | | | |
| F5 | More flow | Consider the potential for erosion in bends due to solids or droplets of liquids in gases | | X | | X |
| F6 | More flow | Install shallow bunded areas round pumps, fired heaters, and heat exchangers to cater for spillage and to retain foam blankets in fires | | X | | X |
| F7 | No flow | Install low-flow trips on fired heaters or electrically heated systems | | X | | X |
| F8 | No flow | Monitor flame arrestors for fouling (see P12 and P21) | | | X | X |
| F9 | No flow | Rod vents to prove they are clear (see P12 and P21) | | | X | X |
| F10 | No flow | Do not install temperature measurement points in areas of no flow | | X | | |
| F11 | Reverse flow | Install nonreturn valves in pumped systems, in potential siphons, in flexible loading/off-loading systems | | X | X | X |
| F12 | Reverse flow | Can fluids be passed from one section of the plant to another via drain or vent/blow down systems? Consider the potential hazards from flow and mixing of incompatible fluids | | X | X | X |
| F13 | Reverse flow | If a drain or vent system is choked, can fluids pass from a high- to a low-pressure vessel? | | X | X | X |
| F14 | Reverse flow | Check the size of vent headers to ensure that the pressure drop down the header does not result in overpressure or low-pressure equipment | | X | | X |
| F15 | Reverse flow | Can air be drawn into a hydrocarbon system due to condensation, process upset, or flow regimes? | | X | X | X |
| **Concentration** | | | | | | |
| C1 | More concentration | Consider what may happen if the concentration of any reactant or catalyst arises. Will the reactor produce unwanted by-products or become unstable? What warning is needed? | | X | X | X |
| C2 | More concentration | Can solids crystallize out of a liquid phase? (see T11) | | X | | X |
| C3 | More concentration | Can fluids become waxy or very viscous? (see T12) | | X | | X |
| C4 | More concentration | Consider the effects of deposits on instrument tappings, relief systems, and drain systems (see T10) | | X | X | X |
| C5 | More concentration | Consider the effects of higher or lower pH on metallurgy. It may be prudent to assume that higher concentrates may occur | | X | X | X |

(*Continued*)

**Table A2.1** (Continued)

| No. | Condition | Solution | Most likely stage | | | |
|---|---|---|---|---|---|---|
| | | | Con | Det | St | Op |
| **Concentration** | | | | | | |
| C6 | More concentration | Consider the possibility of build-up in the concentration of impurities in reactors, reboilers, and condensers. Should purge systems be installed? | | X | X | X |
| C7 | More concentration | Consider the possibility of erosion in slurry systems. Should bends be installed with extra wall thickness? Should flushing points be fitted? | | X | | X |
| C8 | More concentration | Consider the possible detrimental effects of concentrated aqueous spills or leakages into thermal insulation. Could there be an acid/alkali/salt concentration which will attack metal and cause stress corrosion cracking? | | X | | X |
| C9 | More concentration | Consider the possibility of concentration of toxics or unstable chemicals in the process, for example, acetylenes are particularly unstable in high concentrates | | X | | X |
| C10 | More concentration | Consider the adverse reactions that may take place if heat exchangers leak. Could this affect the process, the reactor chemistry or the metallurgy? | | X | | X |
| C11 | More concentration | Do control variables such as reflux or reboil require resetting if concentrations change? | | X | X | X |
| C12 | More concentration | What are the maximum ground-level concentrations from vents? Are they safe? Are they unpleasant/offensive? Should the vents lead to a flare for pyrolysis? Should the stack height be increased? | | X | | X |
| C13 | More concentration | If the effluent concentration changes can it create environmental pollution? | | X | X | X |
| C14 | Less concentration | Will the reaction stop if the concentration of reactants or catalyst falls? What warning is needed? | | X | | X |
| C15 | Less concentration | Do dilute concentrations create excessive heat loads in separation systems? | | X | X | X |
| C16 | More and less concentration | Can the process enter a flammable regime during normal or upset operation? Consider startup/shutdown and condensation | X | X | X | X |

## "Other than"

This is a variable which requires the most careful consideration as it has so many disguises. Some have already been addressed in other sections, but it should not be assumed that all have been identified.

| No. | Condition/solution | Most likely stage | | | |
|---|---|---|---|---|---|
| | | Con | Det | St | Op |
| OT1 | Creep (see T7) | | | | X |
| OT2 | Corrosion (see C5) | | | X | X |
| OT3 | Erosion (see F5) | | X | | X |
| OT4 | How will equipment age: do joints soften, harden, or crack? Will joints fail prematurely? | | X | | X |
| OT5 | Are minor components of the process incompatible with process fluids, such as copper gaskets in ammonia? | | X | | X |
| OT6 | Can fluids generate static charges under flow conditions? | | X | X | X |
| OT7 | What by-products may be expected, for example, | | | | |
| | Pyrites | X | X | X | X |
| | Polymers: unstable, explosive | X | X | X | X |
| | Polymers: unstable, hydrolysis to toxic gases | X | X | X | X |
| OT8 | Are contaminants (air and water) positive catalysts or inhibitors? | | X | X | X |
| OT9 | Is there a risk of hydrogen blistering or other unexpected corrosion effects? | | X | | X |
| OT10 | What happens if levels of liquid/liquid interface levels are lost? (see L5, L7 and L9) | X | X | X | X |
| OT11 | Is air a potential "other than" in the presence of flammables? | | X | X | X |
| **Other than—failure** | | | | | |
| FA1 | How does equipment fail? | | | | |
| | Pump seals leak—is this tolerable? | | X | X | X |
| | Heat exchangers corrode, erode, wear, and fatigue | | X | | X |
| | Vessels corrode and pit | | | | X |
| | Structures rust (and corrode in acid environments even under lagging) | X | X | | X |
| | Bearings or rotating equipment collapse—will this create an intolerable seal leak? | | X | X | X |
| FA2 | What is the effect of instrument air failure, both local or plant wide? Will the plant shutdown safely? | | X | X | X |
| FA3 | What is the effect of service failure such as cooling water or nitrogen purge? | | X | X | X |
| **Operations** | | | | | |
| OP1 | What controls are imposed to prevent staff using unsafe operational practices rather than operating procedures, for example, audits, site tours, casual enquiries? | | | X | X |

| | | | | |
|---|---|---|---|---|
| OP2 | What controls are imposed to prevent changes in design intent? Are modification control procedures in place? (see F4 and P9) | | X | X |
| OP3 | What controls are in place to prevent the override of trips/ protective systems? Is the trip test system "operator resistant"? | X | X | X |
| OP4 | What controls are in place to ensure that protective systems, for example, relief valves and trips, are tested routinely? | | X | X |
| OP5 | What controls are in place to ensure that flow-limiting devices are not removed? | | X | X |
| OP6 | Are operating instructions rewritten on a routine basis? Are all operators aware of changes? | | X | X |
| OP7 | Are maintenance procedures written and followed correctly? | | X | X |
| OP8 | Is there adequate communication between control centers and outside operators? | X | X | X |
| OP9 | Are audit procedures in place? | | X | X |

# Appendix 3: Plant separation tables

## Introduction

This appendix is taken from the second edition of *Process Plant Layout*.

Even preliminary plant layouts should provide for a very high level of protection from the spread of fire, ease of operation and maintenance, and potential future modification/expansion.

The following tables provide some rules of thumb/guidelines for typical constraints which might be applied during early design development to ensure that due consideration is given to plant safety, reliability, and ergonomics (Tables A3.1–A3.5).

**Table A3.1** Site areas and sizes (preliminary).

| | | |
|---|---|---|
| Administration | 10 $m^2$ | Per administration employee |
| Workshop | 20 $m^2$ | Per workshop employee |
| Laboratory | 20 $m^2$ | Per laboratory employee |
| Canteen | 1 $m^2$ | Per dining space |
| | 3.5 $m^2$ | Per place including kitchen and store |
| Medical center | 0.1–0.15 $m^2$, minimum 10 $m^2$ | Per employee depending on complexity of service |
| Fire station (housing one fire, one crash, one foam, one generator, and one security vehicle) | 500 $m^2$ | Per site |
| Garage (including maintenance) | 100 $m^2$ | Per vehicle |
| Main perimeter roads | 10 m | Wide |
| Primary access roads | 6 m | Wide |
| Secondary access roads | 3.5 m | Wide |
| Pump access roads | 3.0 m | Wide |
| Pathways | 1.2 m | Wide up to 10 people/min |
| | 2.0 m | Wide over 10 people/min (e.g., near offices, canteens, bus stops) |
| Stairways | 1.0 m | Wide including stringers |
| Landings (in direction of stairway) | 1.0 m | Wide including stringers |
| Platforms | 1.0 m | Wide including stringers |
| Road turning circles—90° turn and T-junctions | | Radius equal to width of road |
| Minimum railway curve | 56 m | Inside curve radius |
| Cooling towers per tower | 0.04 $m^2$/kW | Mechanical draught |
| | to 0.08 $m^2$/kW | Natural draught |
| Boiler (excluding house) | 0.002 $m^3$/kW | (height = 4 × side) |

**Table A3.2** Preliminary general spacings for plots and sites.

| Property boundary | Control room (nonpressurized) | Control room (pressurized) | Administration building | Main substation | Shippings, buildings, warehouses | Loading facilities, road, rail, water | Fire pumphouse | Cooling towers | Process fired heaters | Gas compressors | Reactors | High-pressure storage spheres, bullets | Atmospheric flammable liquid storage tanks | Aircoolers | Low- pressure storage spheres or tanks $<1$ bar G | Plot limits | Process control station | Process unit substation | Process equipment (lo flash point) | Process equipment (high flash point) | Cryogenic $O_2$[a] plant |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NA | | | | | | | | | | | | | | | | | | | | | |
| 30 | NA | | | | | | | | | | | | | | | | | | | | |
| 8 | NA | NA | | | | | | | | | | | | | | | | | | | |
| 8 | 8 | 8 | NA | | | | | | | | | | | | | | | | | | |
| 8 | 30 | 15 | 8 | NA | | | | | | | | | | | | | | | | | |
| 8 | 15 | NM | 30 | 15 | NA | | | | | | | | | | | | | | | | |
| 30 | 60 | 30 | 60 | 60 | 60 | NA | | | | | | | | | | | | | | | |
| 8 | 8 | 8 | 8 | 30 | 30 | 45 | NA | | | | | | | | | | | | | | |
| 30 | 30 | 30 | 30 | 60 | 30 | 45 | 30 | 7.5 | | | | | | | | | | | | | |
| 30 | 30 | 30 | 75 | 60 | 75 | 60 | 60 | 30 | 7.5 | | | | | | | | | | | | |
| 30 | 30 | 30 | 60 | 60 | 60 | 60 | 60 | 30 | 15 | 2 | | | | | | | | | | | |
| 60 | 30 | 30 | 60 | 60 | 60 | 60 | 60 | 30 | 15 | 10 | 2 | | | | | | | | | | |
| CP | 60 | 30 | 75 | 75 | 75 | CP | 75 | 30 | CP | 75 | 60 | CP | | | | | | | | | |
| CP | 60 | 30 | 60 | 60 | 60 | CP | 60 | 30 | CP | 60 | 60 | CP | CP | | | | | | | | |
| 60 | 30 | 30 | 60 | 60 | 60 | 60 | 60 | 30 | 15 | 7.5 | 5 | 60 | 60 | NM | | | | | | | |
| CP | 60 | 30 | 75 | 60 | 60 | CP | 60 | 30 | CP | 60 | 60 | CP | CP | 60 | CP | | | | | | |
| 60 | 60 | 60 | 60 | 60 | 60 | 45 | 60 | 30 | NA | NA | NA | CP | CP | NA | CP | 15 | | | | | |
| 30 | NA | NA | NA | 30 | NA | 60 | NA | 15 | 15 | 15 | 15 | 60 | 60 | 15 | 60 | NA | NA | | | | |
| NM | NM | NA | NA | NM | NA | 45 | NM | 15 | 15 | 15 | 15 | NM | NM | 15 | NM | NM | NM | NA | | | |
| 15 | 30 | NM | 60 | 60 | 60 | 60 | 60 | 30 | 30 | 7.5 | 5 | CP | CP | 5 | CP | NA | 15 | 15 | 2 | | |
| 15 | 30 | NM | 60 | 60 | 60 | 60 | 60 | 30 | 15 | 7.5 | 5 | CP | CP | 5 | CP | NA | 15 | 15 | 2 | 2 | |
| CP | 30 | NM | 30 | 60 | 60 | CP | 45 | 30 | CP | 45 | 60 | CP | CP | 30 | CP | CP | 60 | 50 | CP | CP | 30 |

*NA*, not applicable since no measurable distance can be determined; *NM*, no minimum spacing established—use engineering judgment; *CP*, reference must be made to relevant Codes of Practice, but see section Health and Safety Executive Recommendations.

*Notes*:

a. Flare spacing should be based on heat radiation as per American Petroleum Institute (API) Std 521/API Std 530 with a minimum space of 60 m for equipment containing hydrocarbons from base of stack.

b. The minimum spacings can be down to one-quarter these typical spacings when properly assessed.

[a]Also see section Health and Safety Executive Recommendations for minimum clearances.

**Table A3.3** Preliminary access requirements at equipment.

| Access | Item of equipment |
|---|---|
| Permanent ladder | 1. Gate and globe valves—DN 80 (in mm) and smaller at vessels when located 3.5 m above grade |
| | 2. Check valves—all sizes at vessels when located 3.5 m above grade |
| | 3. Gauge glass 2 m above access surface, or inaccessible by portable ladder or platforms |
| | 4. Pressure instrument on vessels 2 m above access surface, or inaccessible by portable ladder or platform |
| | 5. Temperature instrument on vessels 2 m above access surface, or inaccessible by portable ladder or platform |
| | 6. Handholds located 3.5 m above grade |
| Platforms | *Items located over platform* |
| | 7. Manholes |
| | 8. Heat exchange units |
| | 9. Process blinds |
| | 10. Relief valves on vertical vessels DN100 and larger |
| | 11. Control valves—all sizes |
| | 12. Cleanout points |
| | *Items located adjacent to platform* |
| | 13. Gate and globe valves—DN100 and larger at vessels |
| | 14. Motor-operated valves |
| | 15. Relief valves—DN80 and smaller |
| | 16. Relief valves on horizontal vessels DN 100 and larger |
| | 17. Level controls and gauge glass on vessels |
| | 18. Sampling valves on vessels |

Some of the typical values quoted in this appendix are taken from historical data and codes of practice which might have now been formally superseded or withdrawn, and the uncritical use of standard distances is no longer accepted as good engineering practice. However, intelligent use of these standard distances can still be considered a reasonable starting point for initial layout.

Separation distances commonly used in some parts of the world, notably the Far East, can be far lower than these recommendations. Electronics manufacturing facilities in the Far East may, for example, have eight employees in a 20 $m^2$ room. Whilst this may be acceptable locally, it does not represent best practice and is thus not recommended. Countries such as China are, in any case, increasingly updating their own separation standards to meet international standards.

It must be emphasized that none of the values in this appendix should be used for final layout without detailed checking that they apply to the circumstances of the plant or site being designed. The following data are however open, accessible, and still a sound starting point.

**Table A3.4** Preliminary minimum clearances at equipment.

| Item | Description | | Clearance (m) |
|---|---|---|---|
| Roads | 1. Headroom for primary access roads or major maintenance vehicles | | 6.0 |
| | 2. Width of primary access roads | | 6.0 |
| | 3. Headroom for secondary roads and pump access roads | | 3.0–4.5 |
| | 4. Width of secondary roads and pump access roads | | 3.0–4.5 |
| Railways | 5. Headroom over through railways from top of rail | | 6.7 |
| | 6. Headroom over dead-ends and sidings from top of rail | | 5.1 |
| | 7. Clearance from track center line to obstructions | | 3.0–4.5 |
| Access, walkways, and maintenance clearances | 8. Headroom over platforms, walkways, access ways, maintenance areas | | 2.5 |
| | 9. Width of stairways, back to back of stringers | | 0.75 |
| | 10. Width of landings in direction of stairway | | 0.9 |
| | 11. Width of walkways at grade or elevated | | 0.75 |
| | 12. Vertical rise of stairways—one flight | | 4.5 |
| | 13. Vertical rise of ladders—single run | | 7.5 |
| | 14. Clearance under furnace burner nozzles for maintenance purposes | | 2.1 |
| Platforms | Towers, vertical and horizontal vessels | 15. Distance of platform below bottom of manhole flange (side platform) | 0.3 |
| | | 16. Width of manhole platforms from manhole cover to outside edge of platform | 0.75 |
| | | 17. Platform extension beyond center line of manhole flange (side platform) | 0.75 |
| | | 18. Distance of platform below underside of flange (top platform) | 0.2 |
| | | 19. Width of platform from three sides of the manhole (top platform) | 0.75 |
| | Horizontal exchangers | 20. Clearance in front of channel or bonnet flange | 1.2 |
| | | 21. Clearance from edge of flanges | 0.3 |
| | Vertical exchangers | 22. Distance of platform below top flange of channel or bonnet | 1.5 max |
| | | 23. Width of platform from three sides of flange | 0.6 |
| | Furnaces | 24. Width of platform at sides of horizontal and vertical tube furnace | 0.75 |
| | | 25. Width of platform at ends of horizontal tube furnaces | 1.0 |
| Pipeways | | 26. Pipeways not crossing roads | 3.0 |

**Table A3.5** Handling facilities for equipment.

| Item | | Equipment and equipment part handled | | | Handling facility |
|---|---|---|---|---|---|
| Vertical vessels | 1. | Manhole covers (up to DN 600) and vessel trays | | | Davits |
| | 2. | Bottom manholes | | | Hinged |
| | 3. | Internals of fixed-bed reactors, catalyst, tower packings, etc. | | | None |
| Horizontal exchangers (at grade or in structure) | 4. | Removable tube bundles, and other removable parts except exchanger shells, shell covers, and floating head covers | | | Pulling beams or posts, for moving the bundle within the shell. Trolley beams for groups requiring up to four such beams. Trolley beams shall be provided with either (a) two trolleys, one capable of handling the entire load and the other half-capacity, or (b) two half-capacity trolleys |
| | 5. | Exchanger shells | | | None |
| | 6. | Fixed tube sheet exchangers | | | None |
| | | Shell covers and floating head covers | | | Shell davits or overhead hitching points |
| Vertical exchangers | 7. | Stationary tube sheet at lower end | | Tube bundles, channels, and channel covers | Hitching points |
| | 8. | | | Shell covers and floating head covers | Jib crane, davit, or hitching point |
| | 9. | | | Entire small-size units | Hitching point or trolley beam |
| | 10. | Stationary tube sheet at upper end | Units designed for removing tube bundle from shell | Tube bundles, channels, and channel covers | Trolley beam |
| | 11. | | | Shell covers and floating head covers | Hitching points |
| | 12. | | | Entire small-sized units | Hitching point |
| | 13. | | Units designed for removing the shell from the bundle: the entire unit or any of its component parts | | Hitching point |

(*Continued*)

**Table A3.5** (Continued)

| Item | Equipment and equipment part handled | | | Handling facility |
|---|---|---|---|---|
| | 14. | Fixed tube sheet exchangers | | Shell davits or hitching points |
| Pumps, compressors, and drivers (housed or otherwise inaccessible) | 15. | 100 kg–2 t inclusive | Parts of horizontal centrifugal pumps and steam drivers | Overhead hitching point or trolley beam |
| | 16. | | Cylinder heads and pistons only of reciprocating pumps and horizontal reciprocating compressors | |
| | 17. | Over 2 t | Parts of centrifugal pumps, compressors, and steam drivers including top halves of compressors, and turbine covers | Trolley beam or overhead traveling cable |
| | 18. | | Cylinder heads and pistons only of reciprocating compressors | |
| | 19. | | Power cylinders only of inclined type reciprocating compressors | |
| | 20. | Parts of vertical-type pumps and drivers | | Overhead hitching point |
| | 21. | Electric motors and rotors | | None |
| Piping (housed or otherwise inaccessible) | 22. | Relief valves, DN 100 × 150 and larger | | Hitching points or davits |
| | 23. | Blanks, blind flanges, fittings, and valves other than listed above and weighing more than 150 kg | | Hitching points or davits when subject to frequent removal for operation or maintenance |

## Preliminary spacings for tank farm layout

### Notes on the spacing tables (Tables A3.6–A3.8 and Fig. A3.1A and B)

1. Where space allows, greater distances than those given in the tables may be used. The incorporation of these minimum distances into a design can only be made after a proper assessment.
2. Flammable liquids are defined as those with flash points below 66°C.
3. Distances given are measured in plan from the nearest point of the vessel (or associated fittings from which an escape can occur when these are located away from the vessel).
4. A group of vessels should not exceed 10,000 $m^3$ unless a single vessel. Spacing between such groups should be a minimum of 15 m between adjacent vessels. A tank farm bund must have a net volume not less than 10% of the capacity of the largest tank in the bund after deducting volume up to bund height of all tanks in the same bund.
5. If this distance cannot be achieved, the need for suitable fire protection for cables and pipelines should be considered.
6. For bunded tanks containing water-miscible nonhydrocarbons, power cables and pipelines at ground level should be outside the bund and so protected by the bund from fire in the tanks.

**Table A3.6** Preliminary minimum distances (note 1) for liquefied oxygen (notes 5, 6).

| | Distance (m) |
|---|---|
| To site boundary | 30 |
| To site roads | 15 |
| To process units and buildings containing combustible materials and ignition sources | 30 |
| To outside fixed combustible materials | 5 |
| To buildings containing flammable fluids | 45 |
| To road and rail loading areas | 15 |
| To overhead power lines and pipe bridges | 30 |
| To other aboveground cables and important pipelines or pipelines containing flammables | 15 |
| To underground cables, trenches | 10 |
| To low-pressure gas storage | 30 |
| To compressed gas storage: flammable | 30 |
| Nonflammable | 15 |
| To liquefied pressure and refrigerated storage: flammable | 45 |
| Nonflammable | 15 |
| To liquid storage tanks: flammable (note 2) | 45 |
| Nonflammable (note 2) | 30 |

7. Spacings are measured in plan from the nearest part of the bund wall except where otherwise indicated.
8. A group of tanks should not exceed 60,000 $m^3$. Spacing of the nearest tanks in any two such groups, which may have a common bund wall, should be such that the tank in one group should be a minimum of 15 m from the inside top of the bund of any adjacent group(s).
9. The zone may be beveled across its upper corners providing all parts of the vessel are more than 3 m from the zone edge.

**Table A3.7** Preliminary minimum distances (note 1) for liquefied, flammable gases.

| Item | Material stored | | |
|---|---|---|---|
| | **Hydrocarbons** | **Nonhydrocarbons insoluble in water** | **Nonhydrocarbons soluble in water** |
| ***Pressure storage (notes 3, 4)*** | | | |
| To boundary, process units, buildings containing a source of ignition, or any other fixed sources of ignition, for example, process heaters | For example:<br>Ethylene<br>60 m<br>$C_3$ 45 m<br>$C_4$ 30 m | For example:<br>Methyl chloride<br>23 m<br>Vinyl chloride 23 m<br>Methyl-vinyl ether 23 m<br>Ethyl chloride 15 m | For example:<br>Methylamines<br>15 m |
| To building containing flammable materials, for example, filling shed | 15 m | 15 m | 15 m |
| To road or rail tank wagon-filling points | 15 m | 15 m | 15 m |
| To overhead power lines and pipe bridges | 15 m | 15 m | 15 m |
| To other aboveground power cables and important pipelines or pipelines likely to increase the hazard | (Note 5)<br>7.5 m | (Note 5) 7.5 m | See note 6 |
| Between pressure storage vessels | One-quarter of sum of diameters of adjacent tanks but not less than 1.8 m for $\leq 50$ $m^3$ or less than 15 m for 750 $m^3$ | | |
| To low-pressure refrigerated tanks | 15 m from the bund wall of the low-pressure tank, but not less than 30 m from the low-pressure tank shell | | |
| To flammable liquid (note 2) storage tanks | 15 m from the bund wall of the flammable liquid tank | | |
| To liquid oxygen storage | As defined above under "liquefied oxygen" | | |

(*Continued*)

**Table A3.7** (Continued)

| Item | Material stored | | |
|---|---|---|---|
| | **Hydrocarbons** | **Nonhydrocarbons insoluble in water** | **Nonhydrocarbons soluble in water** |
| Zone 1 extent | 1 m sphere around relief valve discharge | | |
| Zone 2 horizontal extent from edge of tank | For example:<br>Ethylene<br>30 m<br>$C_3$'s 30 m<br>$C_4$'s 20 m | For example:<br>Methyl chloride<br>15 m<br>Vinyl chloride 15 m<br>Methyl-vinyl ether<br>15 m<br>Ethyl chloride 10 m | For example:<br>Methylamines<br>10 m |
| Zone 2 height of zone | 260 × relief diameter above relief valve discharge (see note 9) | | |
| ***Low-pressure refrigerated storage (notes 7, 8)*** | | | |
| To boundary, process units, buildings containing a source of ignition, or any other fixed sources of ignition | For example:<br>Ethylene<br>90 m<br>$C_3$'s 45 m<br>$C_4$'s 15 m | | For example:<br>Ethylene oxide<br>15 m |
| To building containing flammable materials, for example, filling shed | 15 m | | 15 m |
| To road or rail tanker filling point | 15 m | | 15 m |
| To overhead power lines and pipe bridges | 15 m | | 15 m |
| Between low-pressure refrigerated tanks | One-half of sum of diameters of adjacent tanks | | |
| To flammable liquid (note 2) storage tanks | Not less than 30 m between low-pressure refrigerated LFG and flammable liquid tank shells, but LFG and flammable liquids must be in separate bunds | | |
| To pressure storage vessels | As defined above under "pressure storage" | | |
| To liquid oxygen storage | As defined above under "liquefied oxygen" | | |
| Zones 1 and 2 | As defined above under "pressure storage" | | |

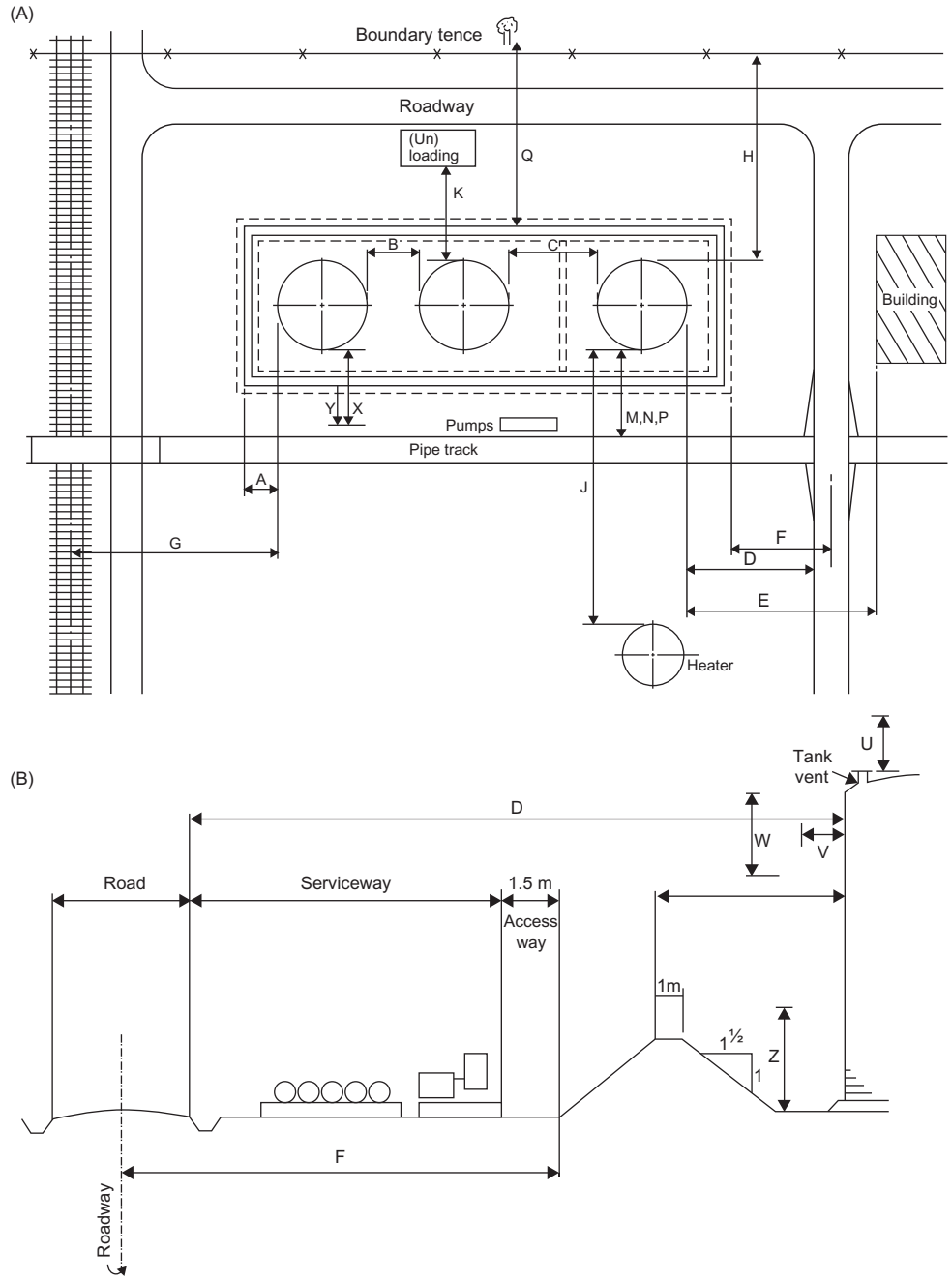



**Figure A3.1** Preliminary tank farm layout (A) plan view (B) elevation. (See Table A3.8 for key and full data).

**Table A3.8** Liquids stored at ambient temperature and pressure.

| Dim (Fig. A3.1) | Diameter of tank | Preliminary minimum clearance: Water and nonflammable liquids | Class A and B products | Class A and B products (flash point <32°C) | Class C products |
|---|---|---|---|---|---|
| | | | Fixed roof | Floating roof | |
| A: from outside of tank to outside of bund at top | Up to 6 m | – | 3 m | | 3 m |
| | 6–30 m | | Half tank diameter | | Half tank diameter |
| | Over 30 m | | 15 m | 6 m | Half tank diameter |
| B: between any 2 tanks in one tank bund | All | 1.5 m | Least of: half diameter of largest tank, diameter of smallest tank, 15 m (min 6 m) | Least of: half diameter of largest tank (6 m) | Half diameter of smallest tank (min 3 m) |
| C: between any two tanks in adjacent bunds | All | – | Diameter of largest tank (min 10 m) | Diameter of largest tank (min 6 m) | Diameter of largest tank (min 6 m) |
| D: from tanks to main plant roads | All | 6 m | 15 m | 6 m | 6 m |
| E: between tanks and buildings containing flammable fluids | All | – | 15 m | 6 m | 6 m |
| F: from toe of bund to center line of any plant roads | All | 6 m | 7.5 m | 7.5 m | 7.5 m |
| G: from tank to center of railway | All | 5 m | 30 m | 30 m | 15 m |
| H: from tank to boundary fence | All | Depends on building lines | 30 m | 30 m | 15 m |
| J: between tank and fired heaters or ignition sources | All | – | 30 m | 30 m | 15 m |
| K: from tank to road or rail filling | All | – | 15 m | 15 m | 15 m |

(*Continued*)

**Table A3.8** (Continued)

| Dim (Fig. A3.1) | Diameter of tank | Preliminary minimum clearance | | | |
|---|---|---|---|---|---|
| | | Water and nonflammable liquids | Class A and B products | Class A and B products (flash point <32°C) | Class C products |
| | | | Fixed roof | Floating roof | |
| M: from tank to ground underneath power lines and pipe bridges | All | – | 15 m | 15 m | 15 m |
| N: from tank to power cables or pipelines | All | | 7.5 m | 7.5 m | 7.5 m |
| P: from tank to ground above buried cables or pipes | All | Outside bund | Outside bund | Outside bund | Outside bund |
| Q: from tank to combustible materials | All | – | Bund width | Bund width | Bund width |
| U: from tank vent to top of zone 1 | Up to 3.5 m | – | 1.5 m | 3 m | – |
| V: from outside of tank to edge of zone 1 and zone 2 | Over 3.5 m | – | 3 m | 3 m | – |
| W: from tank rim to junction of zone 1 and zone 2 | All | – | All bund to wall height | All bund to wall height | – |
| X: from outside of tank to edge of zone 2 | Up to 3.5 m | – | 5 m | | – |
| | 3.5–5 m | – | 6 m | | – |
| | Over 5 m | – | 15 m | 15 m | – |
| Y: from center line of bund wall to edge of zone 2 | Up to 3.5 m | – | 2 m | | – |
| | 3.5–5 m | – | 2.5 m | | – |
| | Over 5 m | – | 5 m | 15 m | – |
| Z: from ground to top of zone 2 | All | – | 5 m | 5 m | – |
| Max capacity/bund | | – | 60,000 $m^3$ | 120,000 $m^3$ | – |

The spacing and arrangement of tankage can vary with each application (note 1).
Class A products have closed flash points below 23°C.
Class B products have closed flash points between 23°C and 66°C.
Class C products have closed flash points above 66°C.

## Preliminary electrical area classification distances

Note that Figs. A3.2–A3.11 and Tables A3.9–A3.10 are for preliminary layout only in well-ventilated locations. US National Electrical Code Item 500, API RP 505 (2012), or IEC/ BS EN 60079-14 should be used for more detailed analysis.

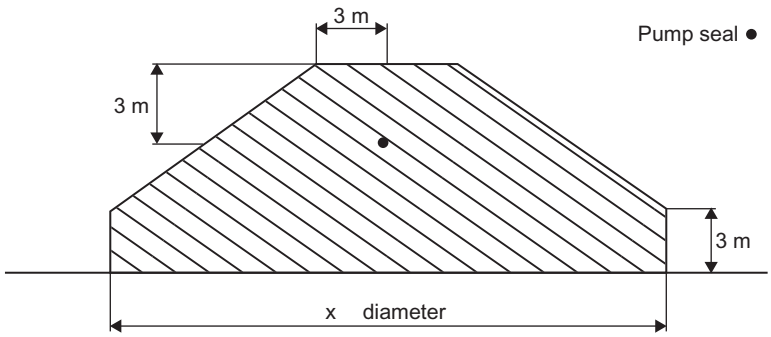
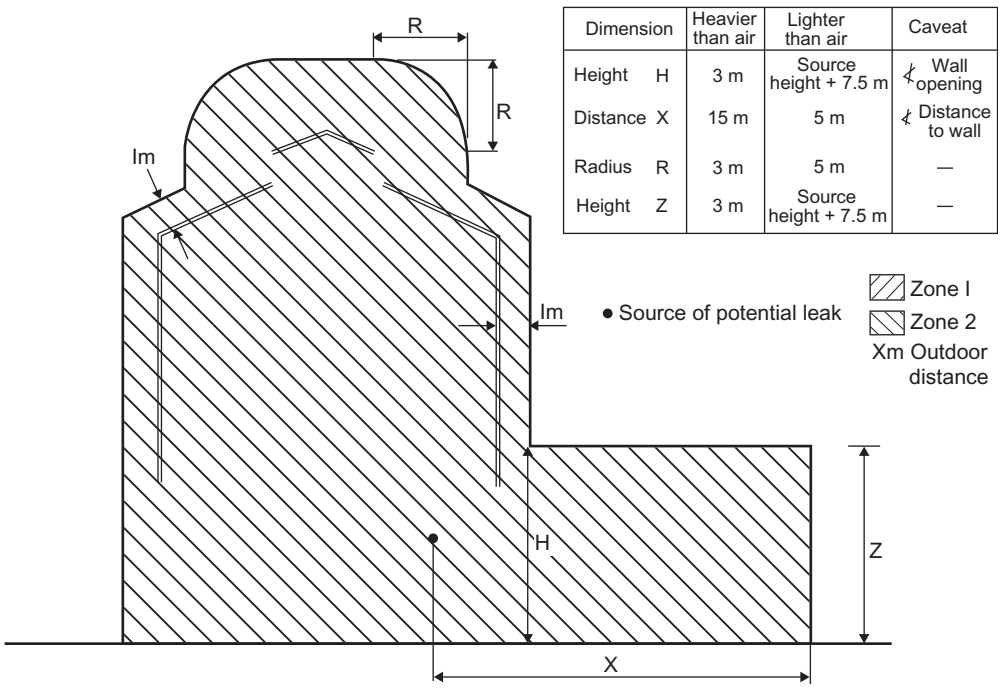
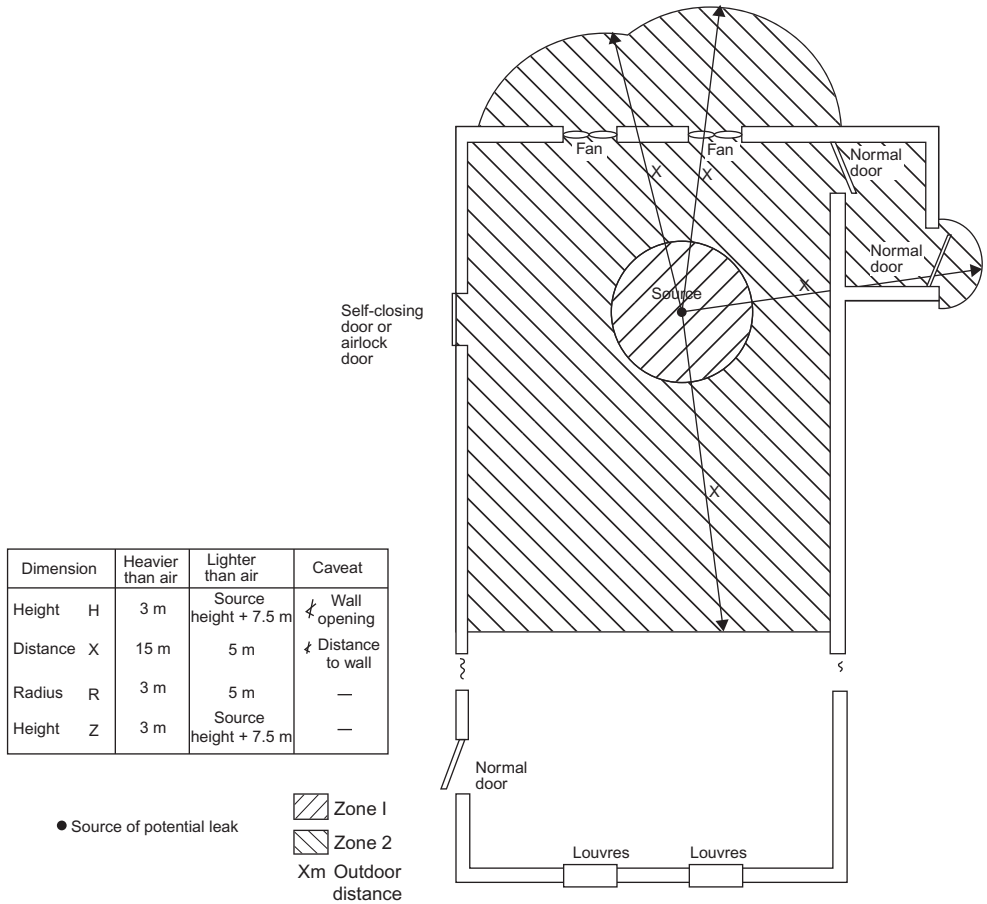



**Figure A3.2** Preliminary extent of zone 2 around a pump seal.




| Dimension | | Heavier than air | Lighter than air | Caveat |
|---|---|---|---|---|
| Height | H | 3 m | Source height + 7.5 m | Wall opening |
| Distance | X | 15 m | 5 m | Distance to wall |
| Radius | R | 3 m | 5 m | — |
| Height | Z | 3 m | Source height + 7.5 m | — |

**Figure A3.3** Preliminary extent of zone 2 in compressor house.




| Dimension | | Heavier than air | Lighter than air | Caveat |
|---|---|---|---|---|
| Height | H | 3 m | Source height + 7.5 m | Wall opening |
| Distance | X | 15 m | 5 m | Distance to wall |
| Radius | R | 3 m | 5 m | — |
| Height | Z | 3 m | Source height + 7.5 m | — |

**Figure A3.4** Preliminary extension of zones to outside building.

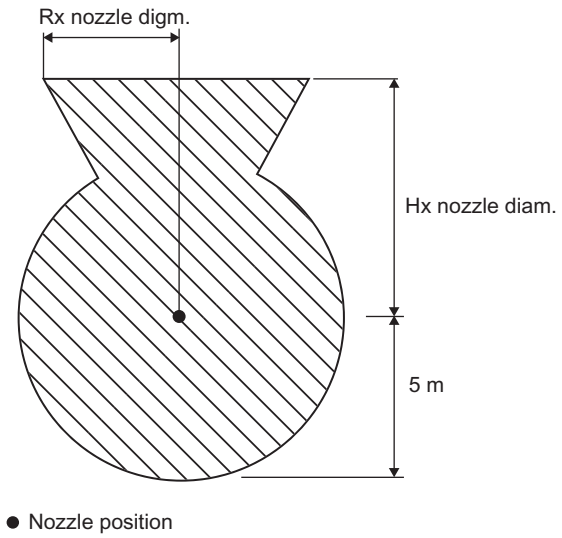



**Figure A3.5** Preliminary extent of zone 2 around a relief valve, etc.

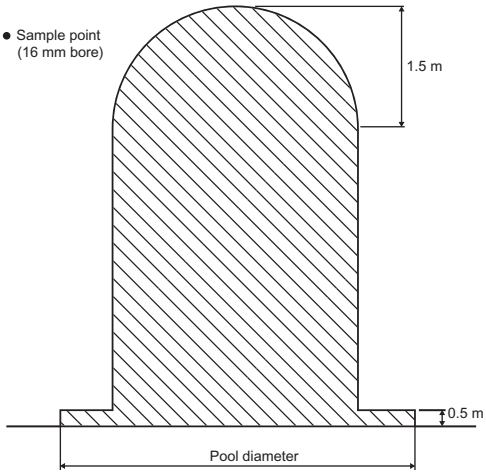



**Figure A3.6** Preliminary extent of zone 2 around a liquid sample point.

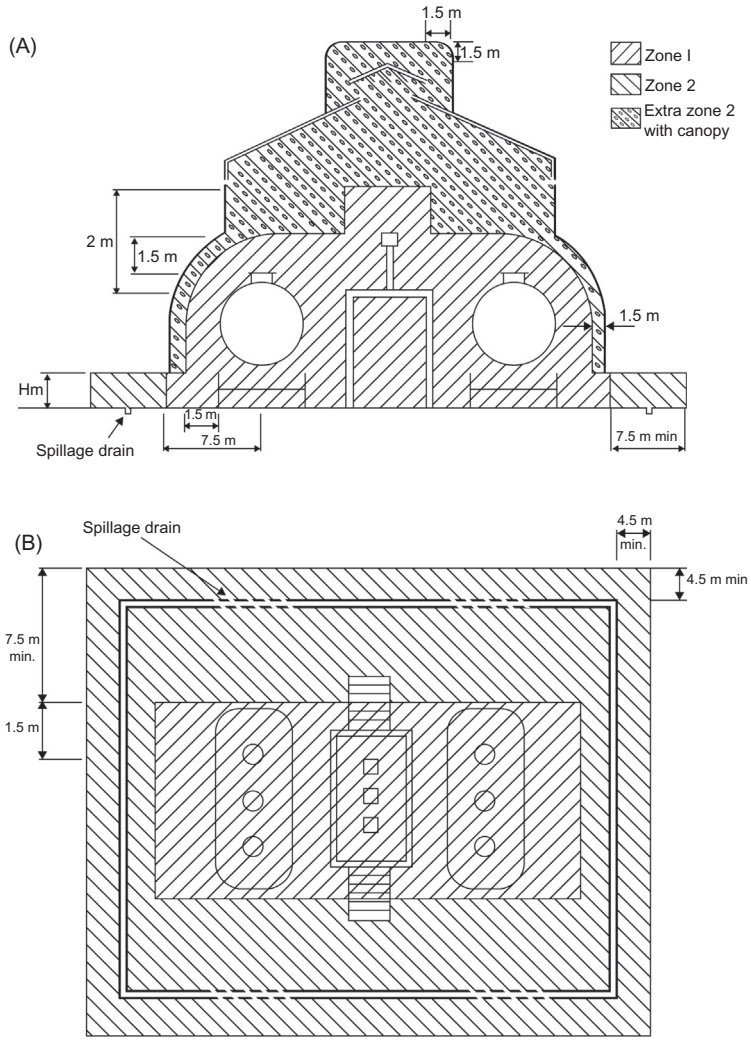
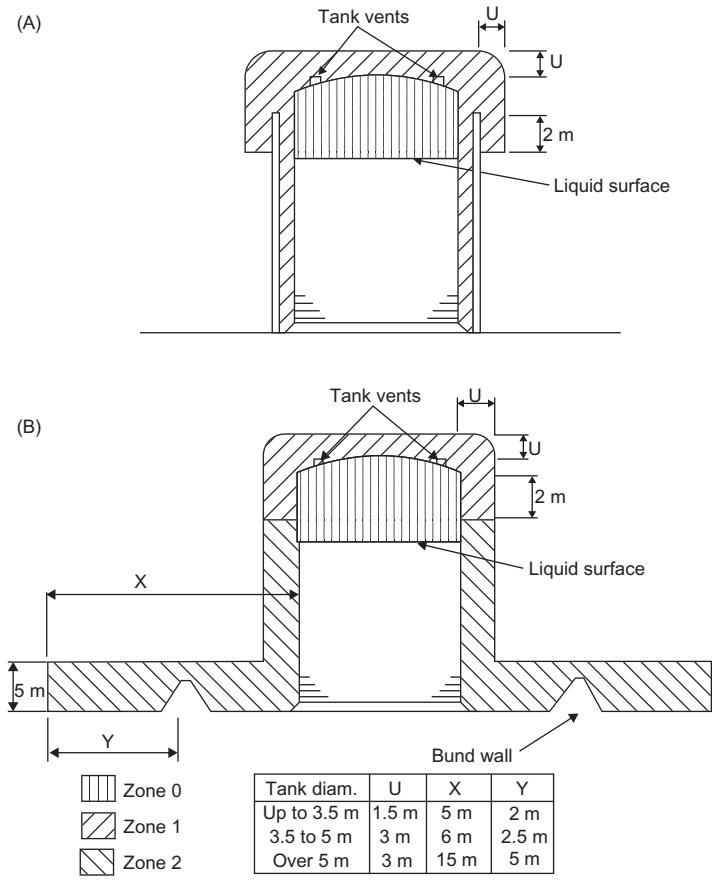



**Figure A3.7** Preliminary extent of zones 1 and 2 for road or rail (un)loading areas: (A) elevation; (B) plan view.




| Tank diam. | U | X | Y |
|---|---|---|---|
| Up to 3.5 m | 1.5 m | 5 m | 2 m |
| 3.5 to 5 m | 3 m | 6 m | 2.5 m |
| Over 5 m | 3 m | 15 m | 5 m |

**Figure A3.8** Preliminary extent of zones 0, 1, and 2 for a fixed-roof tank: (A) double-walled tank; (B) single-walled tank.

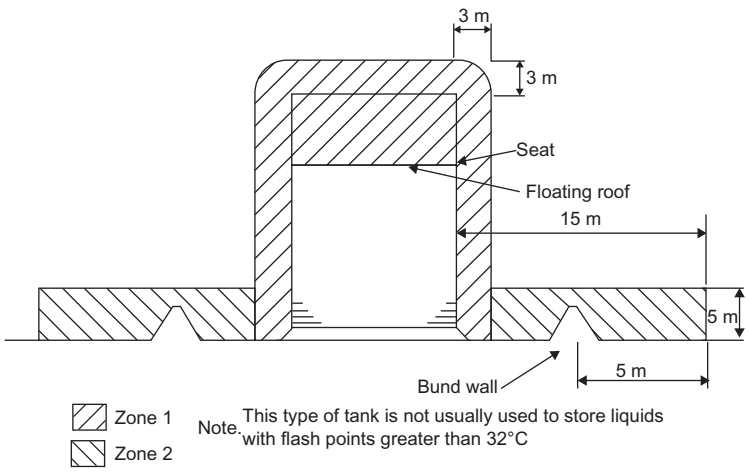



**Figure A3.9** Preliminary extent of zones 1 and 2 for a floating-roof tank.

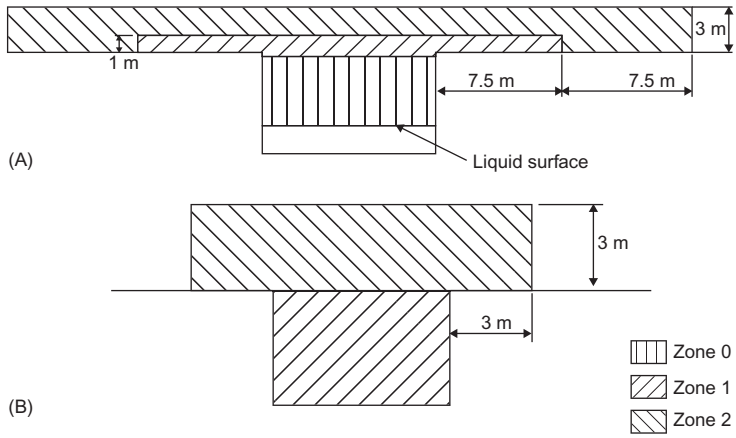



**Figure A3.10** Preliminary extent of zones 0, 1, and 2 in open-topped constructions: (A) open-topped oil/water separator; (B) quench drain channel or effluent interceptor pit.

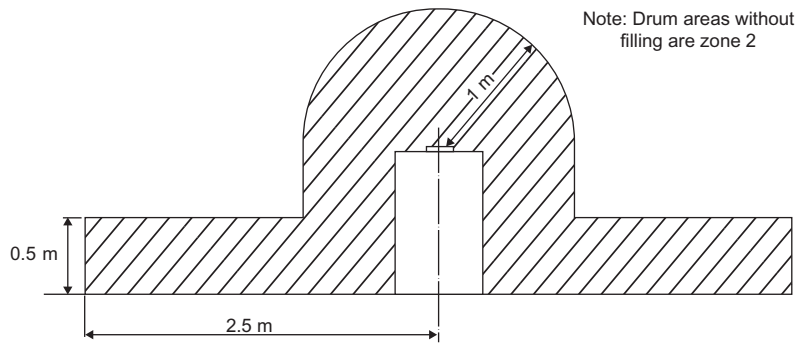



**Figure A3.11** Preliminary extent of zone 1 for drum filling in open.

**Table A3.9** Electrical area classification distances for centrifugal pumps.

| Seal | Fluid conditions | Zone 1 | Zone 2 X in Fig. A3.2 |
|---|---|---|---|
| Any (inc. reciprocating pumps) | Liquid, atm. b.p. ≥ ambient temperature | None | Diameter of pool + 6 m |
| Mechanical seal, external throttle bush, drain, atm. b.p. > ambient temperature | Class A, >atm. b.p. temp <100°C | 0.3 m sphere around seal | 20* |
| | Temp <200°C | | 40 |
| | Temp >200°C | | 60 |
| No bush need be used for cases marked * if X doubled | Class B, >atm. b.p. temp <200°C | | 20* |
| | Temp >200°C | | 50 |
| | Class C, > atm. b.p. temp <250°C | | As liquid |
| | Temp >250°C | | 20 |

(*Continued*)

**Table A3.9** (Continued)

| Seal | Fluid conditions | Zone 1 | Zone 2 X in Fig. A3.2 |
|---|---|---|---|
| Mechanical seal, external throttle bush, vent to stack, atm. b.p. ≤ ambient temperature | Liquefied $C_4$'s (i.e., atm. b.p. ≈ 0°C)<br>Liquefied $C_3$'s and lighter HC (i.e., atm. b.p. ≈ 20°C) (see note)<br>Liquefied nonhydrocarbons | 0.3 m sphere around seal | 40<br>60<br>20–30 |

*Note*: Zone 1 for $C_3$'s which may be up to 3 m depending on seal performance.

**Table A3.10** Electrical area classification distances for equipment other than pumps.

| Item | Condition | Zone 1 | Zone 2 |
|---|---|---|---|
| Compressors in open-sided houses | Gases | See note below | See Fig. A3.3 |
| *Note*: Zone 1 is 0.5 m around any gland, seal, drain parts, vents except 1 m is allowed around a seal oil lid and vent or a seal oil trap | | | |
| Equipment in normal buildings | | Outdoor distances as shown in Fig. A3.4 | |
| Joints and flanges on pipes, fittings, and process equipment | Liquid<br>Gas lighter than air<br>Gas heavier than air | None<br>None<br>None | X = diameter of pool + 6 m in Fig. A3.2<br>3 m horizontal status, 7.5 m above, 5 m below<br>7.5 m horizontal radius, 5 m above and down to floor |
| *Note*: Valve glands can be treated as pump seals | | | |
| Relief valves, vents, etc. | High velocity, gas lighter than air<br>High velocity, gas heavier than air<br>Low velocity, frequent release<br>Low velocity, infrequent release | 1 m sphere<br>1 m sphere<br>1.5 m sphere<br>None | See Fig. A3.5 H = 100, R = 60<br>See Fig. A3.5 H = 260, R = 120<br>3 m sphere |

(*Continued*)

**Table A3.10** (Continued)

| Item | Condition | Zone 1 | Zone 2 |
|---|---|---|---|
| Sample points <6 mm diameter | Liquids near ambient temperature, into open | None | See Fig. A3.6 |
| | Other liquids into closed system | None | 15 m radius, 3 m up, down to floor |
| | Gases into closed system | None | See "Joints, and flanges on pipes, etc." above |
| Process water drain point into open, at grade used regularly | Liquids | See note below | X = diameter of pool + 6 m in Fig. A3.2 |
| | C3 under pressure | See note below | 3 m high × 45 m radius |
| | C4 under pressure | | 3 m high × 30 m radius |
| | Other gases under pressure | | 3 m high × 20 m radius |
| *Note*: Zone 1 is a cylinder 1 m radius and 1.5 m high for liquids and 5 m radius and 1.5 m high for gases | | | |
| Instruments etc., near or at grade | Liquids | See note below | X = diameter of pool +6 m in Fig. A3.2 |
| | Gases | See note below | Flanges as pipe joints |
| | | | Drains as sample points |
| *Note*: Zone 1 is not needed for infrequent spills but otherwise is a cylinder 3 m high by radius of 3 m if below atm. b.p. and 5 m if above atm. b.p. | | | |
| Road or rail (un)loading | Liquids | See Fig. A3.7 for zones 1 and 2; H = 1 m | |
| | Gases | See Fig. A3.7 for zones 1 and 2; H = 3 m | |
| Ship (un)loading | | 20 m around × ∞ high | None |
| Unloading only | | None | 20 m around except seaside × 10 m high |
| Fixed roof tank | Liquids | See Fig. A3.8 for zones 0–2<br>See also section Health and Safety Executive Recommendations | |
| Floating roof tank | Liquids | See Fig. A3.9 for zones 0–2<br>See also section Health and Safety Executive Recommendations | |

(*Continued*)

**Table A3.10** (Continued)

| Item | Condition | Zone 1 | Zone 2 |
|---|---|---|---|
| Pressure storage vessel | Gases | See "Joints and flanges on pipes, etc.," "Relief valves," "Process water drain point," as appropriate | |
| Low-pressure refrigerated tank | | See also section Health and Safety Executive Recommendations | |
| Open-topped oil–water separator | Liquids | See Fig. A3.10 for zones 0–2 | |
| Open-topped drains and effluent pits | Liquids | See Fig. A3.10 for zones 1–2 | |
| Drums in open | Liquids | See Fig. A3.11 (only if being filled) | 3 m around drum area |

## Definitions

- Liquid is the fluid below atmospheric boiling point (see before for definitions of Class A, B, and C fluids).
- Gas is the fluid above atmospheric boiling point.

## Size of Storage Piles

**1.** The height ($h$, in m) of a right conical pile is given by:

$$h = \left(\frac{3V\tan^2\theta}{\pi}\right)^{1/3}$$

where $V$ is the volume ($m^3$) and $\theta$ is the angle of repose (commonly 37 degrees). If the conveyor angle is $\phi$, the horizontal length of the conveyor ($L_1$ in m) is $L_1$ is the $h$ cot $\phi$. The angle $\phi$ is commonly 18 degrees. The radius ($r$, in m) of the bottom of the pile is $r = h$ cot $\theta$. It follows that the minimum length ($L_2$ in m) required for a conveyor and pile in one straight line on plan is:

$$L_2 = L_1 + r = h(\cot\phi + \cot\theta)$$

**2.** Approximate volume ($V$, in $m^3$) of a straight conical pile is:

$$V = h^2 L_3 \cot\theta + \frac{\pi}{3} h^3 \cot^2\theta$$

where $L_3$ (in m) is the length of the top of the pile.

3. Approximate volume ($V$, in $m^3$) of a curved conical pile is:

$$V = h^2 R\alpha \cot\theta + \frac{\pi}{3} h^3 \cot^2\theta$$

where $R$ is the radius of curve (in m) and $\alpha$ = size of arc in radians.

4. Approximate volume of closed warehouse ($V$, in $m^3$) is:

$$V = h^2 L_4 \cot\theta$$

where $L_4$ (in m) is the length of the pile. This equation assumes fully triangular cross-section and no spaces around the piles for conveyors or mechanical unloading equipment. Thus the equation can be used as it is for underground conveying, but for unloading from one side, add 5 m to the width of the store. Also add 10%–20% to the length to allow for dead spaces.

## American Petroleum Institute and National Fire Protection Association recommendations

Both the API and NFPA offer key data on recommended separation distances, some of which are offered below. These will be of special interest to those working in the oil and gas sector. It should be noted that the original publications referenced contain many exceptions and caveats which are not reproduced here. Layout designers are therefore advised to consult the original sources if proposing to use these distances for anything other than preliminary design.

## Data based on American Petroleum Institute Standard 2510: minimum horizontal distances for liquefied petroleum gas tanks

### *Between the shell of a pressurized liquefied petroleum gas tank and the line of any adjoining property that may be developed (Table A3.11)*

**Table A3.11** Minimum horizontal distances between the shell of a pressurized LPG tank and the line of adjoining property that may be developed.

| Water capacity of each tanks (gallons) | Minimum distance (feet) |
|---|---|
| 2000–30,000 | 50 |
| 30,001–70,000 | 75 |
| 70,001–90,000 | 100 |
| 90,001–120,000 | 125 |
| 120,001 or greater | 200 |

### *Between the shells of pressurized liquefied petroleum gas (LPG) tanks or between the shell of a pressurized LPG tank and the shell of any other pressurized hazardous storage tank*

- Between two spheres or vertical vessels: 5 ft or half the diameter of the larger vessel, whichever is the greater;
- Between two horizontal vessels or a horizontal vessel and a sphere or vertical vessel: 5 ft or three-quarters the diameter of the larger vessel, whichever is the greater.

### *Between the shell of a pressurized (or refrigerated) liquefied petroleum gas tank and the shell of any other nonpressurized (or refrigerated) hazardous storage tank*

The minimum horizontal distance shall be the largest of the following (but the minimum horizontal distance between shells must not exceed 200 ft):

- If the other storage is refrigerated: three-quarters of the greater diameter;
- If the other storage is in atmospheric tanks and is designed to contain material with a flash point of 100°F or less: one diameter of the larger tank;
- If the other storage is in atmospheric tanks and is designed to contain material with a flash point greater than 100°F: half the diameter of the larger tank;
- 100 ft.

### *Between the shell of an liquefied petroleum gas tank and a regularly occupied building*

- If the building is used for the control of the storage facility: 50 ft;
- If the building is used solely for other purposes (unrelated to control of the storage facility): 100 ft.

  Compliance with API 752 may be used in lieu of the above requirements.

### *Between the shell of an liquefied petroleum gas tank and any other facilities or equipment*

- For process vessels: 50 ft;
- For flares or other equipment containing exposed flames:100 ft;
- For other fired equipment, including process furnaces and utility boilers: 50 ft;
- For rotating equipment, 50 ft; except for pumps taking suction from the LPG tanks: 10 ft;
- For overhead power transmission lines and electric substations: 50 ft. In addition, siting shall be such that a break in the overhead lines shall not cause the exposed ends to fall on any vessel or equipment;
- For loading and unloading facilities for trucks and railcars: 50 ft;
- For navigable waterways, docks, and piers: 100 ft;
- For stationary internal combustion engines: 50 ft;
- For the edge of a spill containment area for flammable or combustible liquid storage tanks: 10 ft.

### *Between groups of horizontal liquefied petroleum gas vessels (horizontal shell-to-shell)*

50 ft.

### *Between the shell of a refrigerated liquefied petroleum gas tank and the line of adjoining property that may be developed*

200 ft.

### *Between the shells of adjacent refrigerated liquefied petroleum gas tanks*

Half the diameter of the larger tank.

## National Fire Protection Association 30: minimum separation distance recommendations

Minimum separation distances for liquids in tanks are also set out in NFPA30, Flammable and Combustible Liquids Code. These data are freely available upon registration on the NFPA website (www.nfpa.org).

## Health and Safety Executive recommendations (health and safety guidance 176: storage of flammable liquids in tanks)[1]

### Small tanks (diameter less than 10 m)

In this guidance, "small" tanks are considered to be tanks with a diameter of less than 10 m. Table A3.12 shows the minimum recommended separation distances for single "small" tanks. The distances are based on widely accepted industry practice. The minimum separation distance is the minimum distance between any point on the tank and any building, boundary, process unit, or fixed source of ignition.

**Table A3.12** Minimum recommended separation distances for single "small" tanks from site boundaries, buildings, process areas, and fixed sources of ignition.

| Tank capacity ($m^3$) | Separation distance (m) |
|---|---|
| Less than or equal to 1 | 1[a] |
| Greater than 1 and less than or equal to 5 | 4 |
| Greater than 5 and less than or equal to 33 | 6 |
| Greater than 33 and less than or equal to 100 | 8 |
| Greater than 100 and less than or equal to 250 | 10 |
| Greater than 250 | 15 |

[a]But at least 2 m from doors, plain-glazed windows, or other openings or means of escape. Also not below any opening (including building eaves and means of escape) from an upper floor, regardless of vertical distance.

[1] Contains public sector information published by the Health and Safety Executive and licensed under the Open Government Licence.

## Groups of small tanks

Small tanks may be placed together in groups. A tank is considered as part of a group if adjacent tanks are within the separation distances given in Table A3.13. The aggregate capacity of the group should be no more than 8000 $m^3$ and the tanks should be arranged so that they are all accessible for firefighting purposes.

The recommended minimum separation distances between individual tanks in a group are given in Table A3.13. If a serious fire develops involving one tank in a group, then it is unlikely that these between-tank separation distances will prevent damage or even destruction of the adjacent tanks. However, they should allow sufficient time for emergency procedures to be implemented and for people to be evacuated from areas threatened by the incident.

For the purpose of determining separation distances from site boundaries, buildings, process areas, and fixed sources of ignition, a group of small tanks may be regarded as one tank. The minimum recommended separation distances for groups of small tanks are given in Table A3.14. The minimum recommended separation distance between adjacent groups of small tanks is 15 m.

**Table A3.13** Minimum between-tank separation distances for groups of "small" tanks.

| Tank size | Recommended separation distance between tanks |
|---|---|
| Less than or equal to 100 $m^3$ | The minimum required for safe construction and operation |
| Greater than 100 $m^3$ but less than 10 m in diameter | Equal to or greater than 2 m |

**Table A3.14** Minimum recommended separation distances for groups of "small" tanks from site boundaries, buildings, process areas, and fixed sources of ignition.

| Total capacity of the group ($m^3$) | Separation distance (m) |
|---|---|
| Less than or equal to 3 | 1[a] |
| Greater than 3 and less than or equal to 15 | 4 |
| Greater than 15 and less than or equal to 100 | 6 |
| Greater than 100 and less than or equal to 300 | 8 |
| Greater than 300 and less than or equal to 750 | 10 |
| Greater than 750 and less than or equal to 8000 | 15 |

[a]But at least 2 m from doors, plain-glazed windows, or other openings or means of escape. Also, not below any opening (including building eaves and means of escape) from an upper floor, regardless of vertical distance.

## Large tanks

The minimum recommended separation distances for "large" tanks are given in Table A3.15. The table is based on the Energy Institute's Model Code of Safe Practice Part 19: Fire precautions at petroleum refineries and bulk storage installations.

**Table A3.15** Minimum recommended separation distances for "large" tanks.

| Factor | Minimum separation from any part of the tank |
|---|---|
| Between adjacent fixed-roof tanks | Equal to the smaller of the following:<br>• the diameter of the smaller tank<br>• half the diameter of the larger tank<br>• 15 m, but not less than 10 m |
| Between adjacent floating-roof tanks | • 10 m for tanks up to and including 45 m diameter<br>• 15 m for tanks over 45 m diameter<br>The spacing is determined by the size of the larger tank |
| Between a floating-roof tank and a fixed-roof tank | Equal to the smaller of the following:<br>• the diameter of the smaller tank;<br>• half the diameter of the larger tank;<br>• not less than 10 m |
| Between a group of small tanks and any tank outside the group | 15 m |
| Between a tank and the site boundary, any designated nonhazardous area, process area, or any fixed source of ignition | 15 m |

## Separation from other dangerous substances

Separation may also be used to prevent or delay the spread of fire to and from storage or process areas where other dangerous substances may be present in quantity. Table A3.16 shows the minimum recommended separation distances from LPG storage. This may be used to estimate separation distances from other hazardous substances. If published guidance exists for the particular hazardous substance concerned, the recommended minimum separation distance is the greater of the distances given in Table A3.16 and the relevant guidance.

**Table A3.16** Minimum recommended separation distance from dangerous substances.

| | LPG cylinders (> 50 kg total capacity) | LPG vessels (up to 135 $m^3$) | LPG vessel (over 135 $m^3$) |
|---|---|---|---|
| Flammable liquid (flash point <32°C) | 3 m to bund wall | 6 m to bund wall | 15 m to bund wall |
| Flammable liquid (flash point 32°C–65°C) tank size up to 3000 L | 3 m to bund wall | 3 m to bund wall | 6 m to bund wall |
| Flammable liquid (flash point 32°C–65°C) tank size over 3000 L | 3 m to bund wall | 3 m to bund wall | 15 m to bund wall |

## Storage of flammable liquids in buildings

Storage of flammable liquids in bulk tanks within buildings should be avoided if possible. If storage is required in buildings then only the minimum amount should be stored and for the minimum time, preferably no more than that needed for one day or one shift.

Additional safety measures may be needed for the building. These include:

- A single-storey and generally noncombustible construction;
- A lightweight roof or other means of explosion relief. Where this is not reasonably practicable, an acceptable alternative is to provide sufficient mechanical ventilation to remove flammable vapor released in the event of an incident;
- A high standard of natural ventilation, using high- and low-level openings in the walls (typically 2.5% of the total wall and roof leading directly to the open air). Alternatively, if natural ventilation is not possible, permanent mechanical ventilation can be used, equivalent to at least five air changes per hour;
- Fire separation (by means of a partition of at least 30 minutes' fire resistance) between the part of the building housing the tank and other parts of the building, or other buildings within 4 m; and
- Adequate means of escape.

The tank should have the following features:

- Effective means of preventing the spread of leakage. Where appropriate the building walls may form part of the bund, providing they are impervious, have sufficient strength and doorways are fitted with kerbs, ramps, or sills;
- Vents which discharge to a safe place in the open air.

## Underground tanks

The minimum recommended separation distance from any underground tank to any building line is at least 2 m, to avoid undermining the building foundations. It is advisable to increase this distance to 6 m for a basement or pit, to minimize the risk of vapor accumulation.

# Appendix 4: Checklists for engineering flow diagrams

This appendix is reproduced and adapted from Sandler, H. J., & Luckiewicz, E. T. (1987). *Practical process engineering: A working approach to plant design*.

The placement and identification of the required equipment and necessary connecting piping on an engineering flow diagram such as a process flow diagram or piping and instrumentation diagram (P&ID) are only the initial phase of the work required to make the diagram complete. A great many details must be added so that the process being described on the diagram fulfills its function in an economical and safe manner and complies with environmental requirements. While the details entered vary considerably from project to project, many items are common to most projects. The following checklists regarding major components found on many engineering diagrams should be kept in mind while preparing the diagrams. The lists concern the appurtenances on equipment and piping and also review primary instrumentation as well as important safety considerations.

Although the lists are not fully comprehensive, the items in them relate to situations most likely to be encountered and alert the process engineer to the type of common details to be considered for inclusion on engineering flow diagrams.

Short elaborations of the various items in the following checklists give guidance for their representation on an engineering flow diagram (Table A4.1).

**Table A4.1** Checklists for engineering flow diagrams.

| Type of equipment | Item | Notes |
|---|---|---|
| Vessels | Nozzle types | • Connections: Couplings, generally for connections of 32 mm nominal bore (NB) diameter or smaller.<br>• Flanged nozzles, for any size of connection. Nozzles with a diameter smaller than 50 mm NB on low-pressure vessels are fragile, and connections should be made by means of reducing fittings or flanges.<br>• Nonmetallic connections are often of limited size. Manufacturer catalogues should be consulted. |
| | Vents | • Closed vessels are generally vented.<br>• Vents with only air or low amounts of water vapor terminate above the top of the vessel.<br>• Vents with vapors that may be harmful but are not toxic or lethal (i.e., hot gases or hot vapors) may terminate outdoors above adjacent structures in accordance with pertinent regulations. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | | • Dangerous vapors or gases pass to a flare system or to a collection system for further treatment.<br>• An invert or "rain hat" protects vessel contents from precipitation.<br>• The diameter of the vent line is generally made equal at least to that of the largest liquid line entering the vessel. |
| | Drains | • Vessels are to be provided with drains.<br>• Drain connections can originate from a discharge line or from the vessel itself.<br>• The destination of a drain should be indicated. |
| | Vortex breakers | • A vessel with a low liquid level may require a vortex breaker to prevent gases from entering a pump suction. |
| | Overflow pipes | • Open or low-pressure vessels handling liquids require an overflow connection.<br>• The top invert of the overflow nozzle must be sufficiently below the top tangent line to accommodate the constriction head at the maximum flow rate through the nozzle.<br>• Overflow lines for closed, blanketed vessels or those under a slight negative pressure must be sealed in a suitable liquid loop seal or by means of a mechanical sealing trap.<br>• Seal-leg heights should be included on the engineering flow diagram if required to prevent overpressuring or collapse of the vessel.<br>• A high-level switch can be used to close valves in inlet lines or to stop supply pumps. |
| | Sample connections | • Sample connections may be placed on a vessel, on a discharge line at the bottom of the vessel, or on a continuously flowing line from a pump taking suction from the vessel.<br>• Samples may be taken from the top of a vessel through a suitable sampling mechanism.<br>• A series of connections is required for vessels which may have stratified layers. |
| | Dip legs | • Dip legs are required to diminish the generation of static-electricity effects with flammable liquids, reduce foaming, introduce reactants into an agitated vessel, return heated, viscous fluids to the suction nozzle of a circulating pump, create a barometric leg in a vacuum system, or prevent corrosive effects due to aeration.<br>• A weep hole or a siphon break is frequently required in dip legs other than those acting as barometric legs. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | | • Weep holes in lines with vapor–liquid flow should be of minimum size and located in the neck of the nozzle. |
| | Gooseneck inlets | • A gooseneck inlet is an alternative to a dip leg in a metallic vessel to reduce static-electricity effects.<br>• A weep hole is not required with a gooseneck inlet. |
| | Baffles | • Baffles are frequently required to improve agitation.<br>• The vendor of agitation equipment usually recommends the baffle sizing and configuration best suited for the respective vessel dimensions. |
| | Manholes | • Manholes are required for inspections, cleanout, and maintenance.<br>• For ventilation and as an escape or rescue port, one manhole should be in the head or top of a vessel with another on the side or bottom.<br>• Manholes are normally of 600 mm diameter but never smaller than a 400 mm × 600 mm ellipsoid for use in special instances.<br>• Unwanted dead space in a manhole can be avoided by use of an internal "hat" or a curved flush cover.<br>• Number, sizes, and special configurations are to be shown on engineering flow diagrams. |
| | Handholds | • Handholds are used on small vessels for inspecting limited areas, feeling for the integrity of a vessel, and charging or removing catalysts, desiccants, or packing from columns or vessels.<br>• Number, sizes, and special configurations are to be called out on flow diagrams. |
| | Air locks | • An air lock is a small vessel mounted at the top or directly beneath a bin or reactor to introduce or remove solids or liquid intermittently.<br>• Suitable valves are placed upstream and downstream on the air lock. One or both valves are always closed to isolate the bin or reactor from its surroundings.<br>• An inert purge may be used to preclude air or water vapor from a bin or reactor or to prevent the atmosphere in the vessel from escaping to the surroundings. |
| | Rotary feeders | • A rotary or star feeder permits a continuous, controlled, adjustable flow of solids into or from a vessel while isolating it from its surroundings.<br>• An inert purge may be used to preclude air or water vapor from a vessel or to prevent the atmosphere in the vessel from escaping to the surroundings. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | Live bottoms | • The containing vessel should have a coned bottom whose angle is greater than the angle of repose of the solids.<br>• An internal pair of small cones, one inverted from the other, facilitates the outflow of solids.<br>• An air lance is frequently used to prevent or disrupt bridging.<br>• One or more mechanical vibrators attached to the outside of the cone bottom helps to induce the flow of solids.<br>• A "live bottom," or pulsating section, is often inserted between the cone section and the discharge valve for difficult solids-flow problems. |
| | Vessel jackets | • Carbon steel vessel jackets offer a low-cost means of transferring heat to glass-lined or high-alloy vessels.<br>• Liquid media enter the bottom of a jacket and follow a tortuous path through the baffled or dimpled annulus to exit at the top.<br>• Condensing media enter at the top, and the condensate leaves at the bottom; baffling is not needed. A vent should be provided.<br>• Steam and water may be used alternately, but vents and drains must be provided in utility piping so that the two media do not contact one another. Controls should be provided in utility piping to glass-lined tanks to prevent high-temperature differentials between the vessel and the jacket contents. |
| | Heat transfer panels | • The panels are used to transfer modest amounts of heat or in retrofitting a vessel. They are frequently used to maintain the temperature of vessel contents against heat loss or gain.<br>• External panels may be constructed of carbon steel or galvanized sheet regardless of the vessel material.<br>• They are available in a variety of shapes to fit various contours. They may be supplied with different internal paths, serpentine configurations, and positions for inlet and discharge connections.<br>• Usually they are given item numbers separate from that of the vessel. |
| | Internal coils | • These coils are placed inside agitated vessels for improved heat transfer. They may be used by themselves or in addition to a jacket.<br>• They may consist of more than one concentric set of coils provided there is adequate space for circulation between coils and rows. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | | • The materials of construction must be compatible with the contents of the vessel at the extremes of temperature expected within the coil. |
| | Vessel tracing | • Heat needed to hold a storage vessel at a required temperature or to provide freeze protection is sometimes supplied by tracing the vessel with electrical tape. Heat transfer is enhanced by the use of a special grout or mastic.<br>• Sheets of metallic foil can be used to cover vessels constructed of plastic, resinous, or other nonmetallic materials before the application of electric-tracing tape to prevent the generation of localized hot spots.<br>• The presence of electric tracing on a vessel is normally not indicated in the body of an engineering flow diagram but is noted with the item number, name, and description. |
| | Insulation | • Some design groups indicate insulation by portraying a section of it on a vessel in the body of the flow diagram; others include a notation "Insulate" or the purpose of the insulation in the section with the item description. |
| | Removable spool pieces | • Vessels which personnel can enter should be provided with removable spool pieces at liquid inlet nozzles servicing the vessel.<br>• Spool pieces are removed and piping or valves blanked off whenever a person is in the vessel. |
| | Vessel position | • Engineering flow diagrams should show whether vessels are in a vertical, horizontal, or inclined position. |
| | Vessel supports | • Representations of vessel supports should be included in flow diagrams. |
| Agitators or mixers | Location of agitators | • Most agitators enter at the top, and the shaft extends straight down or at an angle.<br>• A side-entering agitator is mounted through a nozzle below the liquid level.<br>• In some instances, the shaft may enter through the bottom head. |
| | Types of agitators | • The type of agitator (propeller, turbine, anchor, etc.) should be depicted on the flow diagram.<br>• Multiple sets of blades are sometimes required and should be shown.<br>• Auxiliary internals such as vessel baffles or draft tubes are often associated with agitators.<br>• In the absence of prior similar or pilot-plant experience, a reputable agitator or mixer manufacturer should be consulted to determine the type of agitator or auxiliaries. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | Steady bearings | • A steady bearing should be denoted on a flow diagram if one is included to reduce the size of the shaft diameter. |
| | Seals | • Packing or a mechanical seal is used to prevent leakage of air into or vapor out of a closed vessel.<br>• Shaft packing or a mechanical seal is required for a side- or bottom-entering agitator.<br>• While shaft packing or mechanical seals generally are not noted on engineering flow diagrams, special lubrication or cooling systems are depicted. |
| Pumps | Types of pumps | • A large variety of pumps is available for use in a processing plant [e.g., centrifugal pump, reciprocal pump, gear pump, metering pump, diaphragm pump (air-operated), in-line pump]. |
| | Types of drivers | • Since most pumps are driven by electric motors, many design groups usually omit a driver symbol if the driver is an electric motor.<br>• An air motor may be employed if the power requirement is low or for safety considerations in electrically hazardous areas.<br>• Hydraulic motors are used for high-torque requirements in special applications.<br>• Steam turbines are used as an economy measure when exhaust steam is available. They are also used for critical pumps or compressors when flow is to be maintained during a power failure.<br>• Diesel and gasoline engines are used as alternatives to steam for critical services. They are also used as prime movers in remote locations. |
| | Valved vents and drains | • Vents and drains can be provided on a pump casing rather than on the discharge or suction piping.<br>• The type and size of valve are to be shown at the appropriate location on the pump symbol.<br>• T-bar handles can be welded to casing plugs. They should be indicated on the flow diagram. |
| | Quench system | • Pump packings or seals must be protected from high-temperature fluids by a suitable cooling-water quench.<br>• Some types of seals require special jacketing.<br>• Water piping to and from pump quench or seal jackets is shown on the flow diagram. |
| | Flushing and seal fluid systems | • Water or other compatible fluid is sometimes required to flush slurries, crystallizing solutions, or corrosive liquids from shaft packings.<br>• Liquids may be needed to flush a mechanical seal to remove frictional heat or to prevent a slurry from reaching a seal face. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | Jacketed pumps | • Jacketed casings are used to maintain the fluid in the pump at an elevated or chilled temperature.<br>• Jacketing is also used to protect the pump casing from excessive temperatures. |
| | Tracing and insulation | • Heat tracing may be required to prevent residual fluid in a pump from freezing when the pump is not operating.<br>• Insulation may be required over tracing or jackets to conserve heat or energy. It may also be needed for personnel protection or antisweat purposes.<br>• Tracing and insulation requirements are included with the equipment description. |
| | Pump recycle lines | • A continuous recycle line is sometimes installed to maintain minimum flow through a pump<br>• A restriction orifice is normally placed in the recycle line. |
| Heat exchangers | Types and configurations | • The representation of the heat exchanger on the flow diagram should reflect as much as possible its particular type and configuration.<br>• The location of the nozzles should approximate those on the exchanger as it is to be placed in service. |
| | Sloping exchangers | • Single-tube-pass horizontal exchangers in condensing service are frequently sloped in the direction of the condensate outlet. |
| | Position of nozzles | • Liquids being heated should enter exchangers at the low point and leave at a high point to prevent buildup of air or other gases which may come out of solution.<br>• If suspended solids are present, the flow should be from the top down to prevent a buildup of solids.<br>• Gases may be removed from a two-shell-pass exchanger by an external restricted vent or from the channel of a vertical U-tube exchanger by an internal weep hole. The orifices are sized to preclude excessive bypassing of fluid. |
| | Backflushing exchangers | • Periodic backflushing is needed if a fluid contains suspended matter and there is a wide variation in its velocity as it passes through the exchanger.<br>• Cross piping and valving are provided to direct normal inlet fluid to the discharge nozzle while effluent leaves the inlet nozzle carrying dislodged suspended material to the discharge piping. |
| | Impingement protection | • In many exchangers, it is necessary to protect the tubes or internals from erosion by high-velocity fluids entering the shell. The exchanger manufacturer should be consulted to determine whether or not such protection is required and what form it should have. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | | • Protection is afforded by an impingement baffle beyond the fluid inlet nozzle, a dome at the inlet nozzle, or an oversized nozzle. |
| | Vents and drains | • Vents and drains, when removed, are usually placed in the inlet or discharge piping to an exchanger; however, they can be made to connections on the inlet and outlet discharge nozzles or to a boring through the tubesheet |
| | Tracing and insulation | • Tracing and insulation are required to prevent one or both sides from freezing unless a small continuous flow is sufficient to prevent freezing or it is permissible to drain the affected side of the exchanger when it is not in use.<br>• Insulation may be required for heat or energy conservation, personnel protection, or antisweat reasons.<br>• Requirements for insulation and tracing are indicated on a flow diagram as part of the equipment description.<br>• It is not feasible to trace or insulate some exchangers such as plate-type units. Shrouds must be indicated for them for personnel protection, and they must be drained when not in use to prevent freezing. |
| Fans, blowers, and compressors | Gas movers | • An appropriate symbol should be entered on the flow diagram. |
| | Types of drivers | • Gas movers are usually driven by electric motors.<br>• Compressors sometimes are operated by steam turbines if excess steam is available or for emergency use during an electrical interruption.<br>• Gasoline or diesel engines are employed for emergency conditions or at remote locations. |
| | Coolers | • The heat developed in a compressor must be removed if the discharge temperature exceeds the unit's maximum allowable value, usually about 177°C.<br>• Some compressors are designed to circulate cooling water in jackets or internal passages. Filtration is often required to prevent clogging if municipal water is not used as the cooling medium.<br>• Intercoolers are frequently used between compressor stages with an aftercooler following the unit; provision is made to remove condensate.<br>• Large compressors usually have separate lubrication systems including external lubricating-oil coolers which require municipal and filtered cooling water. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | Knockout pots | • These are required in the suction line to a blower or compressor if there is liquid carryover from the preceding step of the process or if condensate can form in the suction piping. |
| | Valved drains | • Despite the use of knockout pots, moisture may enter a blower or compressor and coalesce.<br>• Drains also are needed to remove wash fluid that may be injected intermittently to clean the blower or compressor blades. |
| | Accumulators | • Accumulators are needed to smooth suction gas flow if the upstream volume is relatively small or if there are upstream pressure variations.<br>• They are needed to smooth pulsations from a reciprocating compressor and reduce downstream pressure variation. |
| | Screens, filters, and silencers | • A screen may be needed in the inlet line of an air blower or compressor to prevent foreign objects from entering the unit.<br>• A filter may be required if suction gas contains small solid particles which would cause excessive wear or a buildup of deposits. Nonlubricating reciprocating compressors are particularly subject to the abrasion of piston rings.<br>• Filters are used after oil knockout pots on lubricated compressors to remove fine oil mists.<br>• Silencers are sometimes needed on the suction or discharge sides of blowers or compressors to reduce noise to an acceptable level. Some high-speed centrifugal types must be provided with a noise-abatement envelope. |
| | Controls and interlocks | • Primary sensors and control valves are shown on engineering flow diagrams to ensure economical and satisfactory operation of blowers and compressors and proper functioning of auxiliary cooling and lubrication systems. |
| Vacuum equipment | Types of vacuum equipment | • The particular type of vacuum equipment should be represented by an appropriate symbol. |
| | Drives and motive forces | • Mechanical types of vacuum equipment are usually operated by electric motors.<br>• Vacuum equipment with nonmoving parts is powered by a high-pressure fluid, usually steam, air, or water. Piping for the motivating fluid is shown on the flow diagram. |
| | Cooling vacuum equipment | • The heat of compression is removed from nonwetted mechanical equipment by circulating water through jackets or internal passages. Interstage cooling is required if there is more than one pumping stage. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | | • Liquid-ring vacuum pumps are cooled by a modest flow of fresh water or a cooled recycle and compatible sealant fluid. There is usually a sufficient pressure differential between the discharge and suction sides to accomplish the recycle through an exchanger.<br>• Steam-jet ejector systems are supplied with interstage condensers once the interstage dew-point temperature is above that of the cooling medium. Condensation may take place either by direct contact with the cooling medium or indirectly in a heat exchanger.<br>• Condensate from an interstage condenser is subatmospheric and is collected through a closed dip leg in a hot well or is pumped to disposal. The flow diagram should include a note regarding the minimum height of the interstage condenser above the hot well, taking into account the specific gravity of the continuous phase of the condensate. |
| | Knockout pots and traps | • Inlet knockout pots are provided to prevent entrained liquids from entering rotary, screw, or reciprocating-type vacuum pumps.<br>• Oil-lubricated units are followed by a knockout pot to recover and recycle oil. Knockout pots follow liquid-ring vacuum pumps to separate the sealant from the discharge gas.<br>• Motive-steam lines to jet ejectors should contain a condensate separator and be well trapped to prevent intermittent condensate particles from damaging the orifices in the jets. |
| Filters and centrifuges | Types of filters and centrifuges | • Representations of filters and centrifuges in an engineering flow diagram should be typical of their configuration. |
| | Types of drivers | • Centrifuges and rotating filters usually are powered by electric motors; some centrifuges use hydraulic motors to drive solids-removing plows.<br>• Compressed air or nitrogen is frequently used to dislodge solids from filter socks in a baghouse or to inflate flexible members in some plate-and-frame filters for the compression of the cake or to assist in its discharge. |
| | Additives and precoating | • Some liquid–solids separations require the addition of surfactants or coagulants before filtration.<br>• It is often necessary to precoat a filter or to mix filter aid with the filter feed. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | | • All mix tanks, agitators, pumps, and controls are to be shown on the flow diagrams as auxiliaries to the filtration. |
| | Recycle and sampling | • A recycle line is included in batch operations to ensure sufficient buildup of cake or filter medium to give the desired clarity.<br>• A sampling point should be provided in a filtrate discharge line if sampling ports are not provided on the filter. |
| | Auxiliary lines and equipment | • A wash system is frequently required for filters and centrifuges.<br>• A means to contain and transfer segregated solids is needed.<br>• Provision must be made to collect and transfer mother liquor from a centrifuge.<br>• Drum filters require vacuum equipment as an auxiliary.<br>• Piping and equipment for all auxiliaries are shown on the flow diagrams. |
| Piping | A considerable amount of the work represented on engineering flow diagrams is concerned with piping. The following are several important aspects which should be kept in mind when preparing the diagrams. | |
| | Valves | • Valves are used to isolate piping or equipment from other portions of the process and to throttle or divert flows; thus they are an essential part of any piping system. Valves should be designated on engineering flow diagrams by a symbol which not only shows where a valve is required but also indicates the type of valve. |
| | Bypasses for control valves | • On–off valves, that is, blocking valves, are usually placed immediately upstream and downstream of an automated control valve in continuous or critical service along with a bypass line containing a manual throttling valve about the group. Such configuration permits continued operation or orderly and safe shutdown of a process in the event of a controller or control-valve malfunction.<br>• The block valves and bypass line and valve are usually of line size for main lines up to 75 mm NB in diameter. For 75 mm NB main lines and larger, it is good practice to have the bypass line and valve one line-size smaller.<br>• Some self-regulating valves in clean service, such as air-pressure regulators, are seldom provided with a bypass line. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | Vent and drain sizes | • Vent lines on a vessel should be of at least the size of the largest incoming recycled line. |
| | Condensate traps | • Vent lines or relief-valve discharge lines which carry steam or condensable water vapor and have a horizontal section that can form a seal leg should be provided with a drain hole, if permissible, or with a suitable condensate trap at low points to prevent excessive pressure drops or the development of excessive and dangerous velocities of trapped liquids.<br>• A manual drain is usually suitable for intermittent operations. |
| | Protective screens | • Atmospheric lines to the suction of a blower or compressor as well as pump intake lines from natural bodies of water or from sumps should be protected by screens from the entrance of foreign bodies. |
| | Jacketing and bundling | • An outer pipe, known as a jacket, is sometimes placed around a process line. An appropriate heating or cooling utility stream flows in the annulus to maintain the process fluid at a desired temperature.<br>• Jacketing is shown on the body of the flow diagram, and the word "jacketed" is entered in the tracing column on the line tabulation.<br>• A line is "bundled" when it is placed next to a hot or refrigerated line, and both lines are then insulated together. The word "bundled" is placed in the tracing column of the line tabulation. |
| | Boundary definitions | • While building outlines per se are seldom defined on engineering flow diagrams, it may be necessary to locate a change point through which a pipeline passes for tracing, insulation, piping classification, or safety reasons.<br>• The transition between classifications is marked by a short indicator perpendicular to the piping line. The boundary definitions are delineated. |
| Instrumentation and safety | The process engineer enters all sensing instrumentation, control valves, and safety devices on the P&ID or engineering flow diagram and designates whether instrument measurements are to local, or remotely indicated, or as recorded points. The instrument engineer completes the control loops in the P&ID or on a separate instrumentation flow diagram. The following subsections discuss some of the more common instruments and safety devices to be considered for application on a flow diagram. Other specialized items should be provided as required. | |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | Relief valves | • A relief valve, also known as a pressure safety valve, protects equipment or piping from pressures beyond its design maximum allowable working pressure.<br>• Typical situations for relief-valve application are:<br>• Any vessel, exchanger, column or other equipment that can be completely isolated by valving must be protected from an external fire or runaway exothermic heats of reaction.<br>• Vessels with an open vent or overflow that is of such size or length that excessive pressure could be generated in the event of fire or reaction excursion must be protected.<br>• Protection is also needed when the maximum discharge pressure of a pump or compressor feeding a piece of equipment or piping is greater than its MWAP and the pump or compressor can be deadheaded through the equipment or piping.<br>• Exchangers need protection when a liquid "cold" side is isolated and expanded owing to the continued flow of the "hot" side.<br>• A relief valve is usually placed after a pressure-reduction valve to ensure that subsequent equipment is protected in the event of a malfunction of the reduction valve.<br>• If a relief valve may not reseat completely owing to fouling by solids or gummy materials, a pair of relief valves is used in parallel and two ganged three-way valves are incorporated in the piping so that there is always one relief valve functioning with the equipment while the other is being cleaned.<br>• The sizes of relief-valve inlet and discharge lines are shown on the flow diagrams. The discharge side of most vapor safety valves is usually larger than that of the inlet, while those in liquid service usually have equal inlet and discharge connections. |
| | Rupture disks | • A rupture disk is an alternative to a relief valve when it is acceptable to allow pressure in equipment or piping to fall and to lose material until atmospheric pressure is reached.<br>• It consists of a frangible wafer of composite materials or a thin metallic element which is shattered or ripped apart at a predetermined pressure. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | | • The material of the wafer and the metallic element must be compatible with the fluid in the equipment or piping. A thin membrane of Teflon or other polymeric material is used to prevent chemical attack of the disk and results in an economical construction.<br>• A rupture disk can be placed ahead of a relief valve to protect the relief valve from plugging or to permit the valve to be constructed of more economical materials. A pressure gauge is usually placed between the relief valve and the rupture disk to indicate the integrity of the disk. |
| | Vacuum breakers | • A vacuum breaker permits atmospheric air or a compatible gas or vapor to enter a vessel at a determined vacuum level to prevent collapse of the unit at its maximum design pressure.<br>• Typical situations that require a vacuum breaker are the withdrawal of liquid with insufficient replacement of gas or vapor, the condensation of vapors in an isolated piece of equipment whereby the pressure in the vessel is reduced, and the connection of vessels to a powered vent system. |
| | Conservation vents | • A conservation vent is a combination of a relief valve and a vacuum breaker.<br>• It normally allows storage vessels containing volatile fluids to float within a limited pressure range so that the loss of vapors is reduced. |
| | Flame arresters | • The vent on any unit containing an inflammable fluid should be provided with a flame arrester to prevent backflushing if the discharge vapors become ignited.<br>• Conservation vents may be purchased with integral flame arresters. |
| | Pressure sensors | • Pressure connections to equipment should be made, where possible, in the gas or vapor space to eliminate corrections for hydraulic head.<br>• Units such as filters, baghouses, heat exchangers, or distillation columns which induce considerable pressure drops often have a differential-pressure measurement across the unit in addition to an absolute- or gauge-pressure sensor at the inlet or discharge.<br>• A pressure gauge on the discharge of a pump provides information regarding the operation of the pump; a permanent gauge (PI) may be installed, or a valved provisional tap (PP) may be used instead. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | | • Pressure gauges should be isolated from equipment or piping with a suitable valve or chemical seal. The latter is used with corrosive fluids, toxic fluids, slurries, or fluids that would solidify in the gauge. All isolating valves and chemical seals are shown on the flow diagrams. |
| | Temperature sensors | • Whenever applicable, thermowells are located in the liquid portion of a two-phase system to give quicker responses.<br>• Thermowells, with or without indicators, are frequently provided upstream and downstream of a heat exchanger.<br>• It is good practice to provide a redundant temperature measurement to activate an alarm function in addition to the normal temperature measurement used to control an exothermic reaction. |
| | Sight glasses and lights | • A viewing port is often included in agitated vessels or on distillation columns, especially if there may be foaming problems.<br>• If caustic or hydrogen fluoride is present, glass ports must be protected by a suitable transparent insert between them and the fluid.<br>• Sight glasses are available in multiple sizes and configurations for use in piping. They are employed to indicate the presence of liquid or an interface, whether the liquid is stationary or flowing (the turning of a wheel), and the approximate flow rate (the lifting of a flapper).<br>• A sight glass is often accompanied by a sight light; all sight glasses and lights are shown on the flow diagrams. |
| | Level indicators | • All process vessels containing liquids require level measurements.<br>• The simplest indicators are a shadowed liquid level through the translucent wall of a plastic tank with a calibration on the outside of the tank or a calibrated dipstick for use as an intermittent indicator in noncritical, nonhazardous service.<br>• A simple continuous-indicating device is a window or a series of windows in the straight side or a vertical cylindrical glass tube along the side of a vessel. A series of tubes is required to determine an interfacial level.<br>• A series of hollow external metal columns provided with translucent reflux faces is used when the application of glass windows or cylinders is limited by the design pressure of the vessel. This system is not suitable for showing interfaces. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | | • Means must be provided to drain, flush, and clean external gauges.<br>• A pressure-sensing device may be used at or near the bottom of the vessel as an indication of level. A differential-pressure unit with one leg connected to the vapor space is required if the tank is not open or if its pressure in the vapor space is greater than a few inches of water column.<br>• A chemical seal is used to isolate the pressure sensor from liquids which are corrosive or toxic, could freeze at ambient temperatures, or are slurries.<br>• A common level indicator uses a top-entering dip tube through which a small metered flow of compressed air, nitrogen, or other compatible gas is metered and bubbles through the liquid. The pressure of the gas, corrected for liquid density, indicates the height of the liquid above the end of the dip tube. A differential-type pressure indicator is required for pressurized vessels.<br>• Bubble-type indicators should not be used with saturated or nearly saturated solutions since evaporation may leave deposits at the end of the tube and lead to obstructions, causing erroneous level readings.<br>• A guided float sensor gives a continuous level reading of the surface of a liquid or a pile of solids. It is also used to indicate a narrow-gauge "either—or" local condition.<br>• Paddles, flappers, capacitance and sonic probes, and radiation units are some of the devices employed for specialized level indication. Strain gauges are used to determine weight. Notes on the flow diagrams are used to denote these special level indicators. |
| | Flexible connections | • Equipment or piping made of ceramics, glass, and certain resinous materials is isolated by flexible connections or hoses from damaging vibrations caused by mechanical equipment, especially reciprocating or high-speed types of gas movers.<br>• Flexible connectors are frequently used to ensure that liquid lines of 200 mm NB diameter or larger do not overstress inlet or discharge nozzles on pumps, filters, or similar equipment.<br>• Flexible connections serve to isolate a weigh tank from its fixed entrance, discharge, or vent lines to permit unimpeded movement of the vessel. |
| | Expansion joints | • An expansion joint is used in piping in lieu of bends and loops to account for linear growth due to changes in temperature. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | | • Differential linear growth between the two sides of a heat exchanger is usually relieved by placing an expansion joint in the shell unless the tubes are coils or U tubes or the unit has a floating, pull-through, or packed-head configuration.<br>• Consideration should be given to the extremes of start-up or emergency conditions as well as normal operating temperature in determining whether or not an expansion joint is required. |
| | Fire valves | • These are ball or plug valves which maintain their closure by a built-in spring mechanism but are held open in normal operation by a link mechanism containing a fusible section.<br>• They are recommended for installation at draw-off nozzles on vessels with flammable contents. |
| | Spring-closure valves | • These valves are used when it is important that a manually operated valve returns to a closed, open, or partially open position after being used.<br>• They are often used instead of a restriction orifice in services which tend to clog openings. If the valve begins to clog, it can be opened fully and then returned to a stop for its partially open position. |
| | Locked valves | • Certain valves should remain in an open or locked position until a change is authorized.<br>• The abbreviation LO or LC next to a valve on a flow diagram notes that a valve is to be locked open or locked closed. |
| | Limit switches | • Limit switches are required when the position of a process or instrument valve must be known before a particular operational step can be taken or as part of an interlocked permissive sequence.<br>• Information is provided by small limit switches on the valve housing. This is signified by using a Y as the final identification letter in an instrument bubble.<br>• Only one switch is required to know whether a valve is fully open or fully closed. Two switches are needed to know if the valve is either fully open or fully closed. |
| | Automatic switchover of pumps | • Automatic switchover is required in critical services when a pumping operation must be maintained despite mechanical or electrical problems with the pump currently running.<br>• Isolating valves about the spare pump are kept open and check valves provided in the discharge line from each pump.<br>• A pressure-sensing device or flow switch in a common discharge line detects a pump failure, |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | | sounds an alarm, and automatically starts the reserve pump.<br>• Pumps with severe but intermittent duties are frequently placed on alternate start-up, whereby the pump started automatically is the one that had not previously been operating. |
| | Failure alarms | • Current to motors of critical pumps, compressors, agitators, or similar equipment is sometimes monitored to indicate the status of the process or of the equipment itself.<br>• Engineering flow diagrams should reflect the presence of current indicators and accompanying low or high alarms. |
| | Interlocks | • Often the operation of a piece of equipment depends on another function in the process before it can begin, continue, or terminate its operation.<br>• The permissive conditions are covered by the appropriate instrumentation or notes on the engineering flow diagrams. Complex interlocks are indicated by an appropriate symbol to show that a separate logic diagram prepared by the instrument engineer covers the instrumentation and sequence of operations. |
| Miscellaneous | Flow diagrams show many miscellaneous and specialty items to complete a project. Some of the more frequently encountered features are reviewed here. | |
| | Expansion tanks | • Expansion tanks are required to relieve thermal expansion when liquid-filled sections of piping runs can be isolated and subsequently heated.<br>• They may not be needed with water, as developed pressure is relieved by minor distortions of piping plus a small leakage at gaskets or by the use of a thermal relief valve.<br>• They can be used to reduce water hammer or induced shock waves for any fluid.<br>• Units are shown on a flow diagram with their dimensions or as a note giving a make and model number if they are to be purchased units. |
| | Backflow preventers and air gaps | • Backflow preventers are required by authorities supplying municipal water to prevent contamination of the water supply.<br>• Backflow preventers or air gaps are used within a plant to ensure that contaminants do not enter the potable, locker room, or safety-shower water systems. |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | | • A backflow preventer is a commercial item consisting of a series of special check valves and pressure-differential chambers to ensure the absence of backflow. An air gap is an arrangement whereby the line bringing incipient process or plant water from the municipal supply is terminated several inches above the tank that is to supply the process of plant water. |
| | Safety showers, eyewashes | • These are required whenever hazardous liquids or solids are being unloaded or handled.<br>• They are usually purchased as a single combination unit.<br>• Units are sized to give about 8 $m^3$/h to the shower portion and 1.5 $m^3$/h to the eyewash for a water pressure of 2 Bar. If the pressure is less, it must be boosted, and it if is too great, units must be supplied with the requisite restriction orifices.<br>• The units should be connected directly to the potable water supply. If they are taken from a pumped process- or plant-water supply, their feed lines should be taken immediately after the discharge of the process-water pump. A backflow preventer isolates the shower−eyewash−water takeoff point from any process or plant users.<br>• Units located outdoors must be protected from freezing. This is accomplished by having an underground water-supply assembly designed so that water remains below the freezing level until the unit is activated and residual water at the end of use passes into a prepared drain at the base. Aboveground supply piping is usually protected by electric self-limiting tracing or electric induction heating. The shower or eyewash unit itself is then supplied with tracing or induction heating.<br>• Safety-shower and eyewash units are shown on engineering flow diagrams near the equipment with which they are needed with a reference to the utility flow diagram containing the distribution header.<br>• Symbolic containers showing dilute acetic acid or carbonate solutions are often shown next to an eyewash to denote their presence for swabbing purposes. |
| | Utility service stations | • It is good engineering practice to place utility hose stations at convenient locations throughout a plant. There should be air for such tasks as blowing dirt or water from equipment, unplugging or cleaning outlines, and operating pneumatically driven |

(*Continued*)

**Table A4.1** (Continued)

| Type of equipment | Item | Notes |
|---|---|---|
| | | mechanical equipment or tools; water for housekeeping and emergency cooling; and steam to thaw or clean lines and equipment. Steam and water can be brought together to form a separate hot-water station.<br>• Stations are sited on equipment-arrangement drawings and given identifying numbers. Each station is shown on the respective utility flow diagram and identified by the assigned number.<br>• Air, steam, and water pressure for normal usage is limited to 2 Bar by pressure reducers to prevent a pressure hazard caused by high-velocity fluid impinging on the skin or by the whipping action of hoses. High-pressure air required to drive pneumatic motors or tools should have special connectors.<br>• Hoses are typically 10 m long. If a series of hose stations is required, they can be located approximately 20 m apart. |
| | Fire protection | • Fire protection is required in operating and storage areas if flammable ingredients are used in the process or if gaseous or liquid fuels are present.<br>• It is provided for control rooms, laboratories, maintenance shops, and office areas.<br>• Although chemical canister units are provided, fire hydrants with fire-water pumps and underground fire-water mains are frequently included. The number and location of fire hydrants are set in accordance with local ordinances.<br>• A method to reduce danger from a fire within a large oil storage tank is to sparge steam into the vapor space to displace air and snuff out the fire by smothering it. |
| | Seal fluid systems | • Reference is made at appropriate seal or packing locations on engineering flow diagrams to the seal or flushing fluid system required at the respective application point.<br>• A notation lists the flow diagram which presents the distribution header and the line-identification codes of lines bringing and returning the fluid.<br>• A separate section on a utility flow diagram should illustrate a schematic of the typical instrumentation and piping required at each application point for the various systems, list the various instruments and line numbers, and show the distribution systems with pertinent information in the line table. |

# Appendix 5: Teaching practical process plant design

This appendix explains why I wrote this book, and how and why I teach plant design in the way I do for the benefit of anyone who wishes to follow my approach. I also offer many of my design exercises to assist anyone who does not have ready access to real design problems.

My approach is pragmatic, atheoretical, and firmly grounded in professional practice, but not uninformed by pedagogic literature. I have read the relevant literature, and I offer references for that which I consider most useful in a field which is mostly still arguing about whether rational investigation of its subject is even possible.

This part of the book may to some extent betray its origins as the extended abstract of my PhD by publication by having a residue of the horrible, stilted third-person style of academic discourse, though repeated rejections by academic journals have made it clear that this style has made the content no more acceptable to academics.

## Part A: academic context: PhD abstract

### Introduction

Since at least the 1960s, both thoughtful professional designers and social science researchers in the field of design have observed a significant divergence between professional and academic practice in engineering design (Crawley, Malmqvist, Östlund, & Brodeur, 2007; Fielden, 1963; Pugh, 1991; Trevelyan, 2014; Wilde, 1983). The reasons for this are structural, and largely beyond the scope of this appendix, but are explored in *An Applied Guide*. However, this has had limited impact on the inclusion of professionally led approaches to engineering education.

Taken at its extreme, the purpose of engineering education nowadays is arguably no longer that understood by Dym et al. (2005), "to produce graduates who can design useful things." It is to provide a more generic academic grounding in science, technology, engineering and mathematics (STEM), rather than engineering (or even chemical engineering), best tailored to the needs of future PhD candidates, despite the fact that only 4% of UK engineering graduates undertake PhDs (Goodhew, 2017).

#### *Consequences*

This divergence has impacted on the ability of universities to offer a realistic design education, resulting in a highly unrealistic approach to design teaching (Douglas, 1988). To meet the needs of universities, real-world engineering problems must be transformed into a collection of tasks which will meet learning objectives; comply with

administrative requirements; prove straightforward to teach and assess by academic staff who are almost never engineering practitioners (Excell, 2014); and garner high levels of student satisfaction (Santini, Ladeira, Sampaio, & Da Silva Costa, 2017). However, these requirements restrict educators' ability to foster a realistic total system-level approach to design, as Pugh (1991) has explained. Furthermore, academic culture tends to consider that the best teaching is "research-led" (Bak & Kim, 2015; Prince, Felder, & Brent, 2007) although pedagogic research suggests that this idea does not necessarily work in practice. This ethos can lead to an overemphasis on design approaches related to areas of research interest, of which modeling and simulation are the key examples. The research ethos also favors design novelty, as opposed to the constrained creativity which is a key characteristic of professional practice (Sinnott & Towler, 2009).

### Lack of system-level thinking

In a typical student engineering design exercise, a great deal of data is provided to students, problems are tightly framed and, in a "successful" example (as judged by student satisfaction), it is clear to students that they are being assessed on carrying out a number of the subtasks which would have been covered in recent lectures (Pugh, 1991). Whilst such exercises are frequently undertaken at least in part in groups, they are structured such that the group can readily split them into a number of stand-alone elements to be undertaken as individual exercises. This is contrary to the way teams operate in a professional setting, as described by Trevelyan (2007, 2010).

The typical approach to the student design exercise in chemical engineering education correlates strongly with texts such as Biegler et al.'s *Systematic methods of chemical process design* (1997), Turton et al.'s *Analysis, synthesis and design of chemical processes* (2012), and Smith's *Chemical process: design and integration* (2016), all of which refer to "chemical process design," rather than to "process plant design," its real-world counterpart. Despite their widespread use in academia, these books have limited application in demonstrating how process plants (as opposed to chemical processes) are designed in practice.

Personal experience of examining several cohorts of students who carried out this type of design exercise (see Appendix 4: Checklists for engineering flow diagrams) suggests that only the most able have any understanding of the "big picture"—the majority are following the textbook method (or operating the simulation program) for the subtask which they have been assigned and their appreciation of the complexity of the substructures of a process plant tends to be limited. Thus, the typical student design exercise produces neither a total design approach, nor a grasp of detailed considerations.

Pugh (1991) (whilst commentating specifically on product design as opposed to process plant design) labels the approach taught in universities "partial design," resulting from the necessity to dismantle a complex and holistic discipline into distinct parts

which can be taught in an academic setting by nonpractitioners, an example of assessment drift. Or, as Kahneman (2013) puts it: "when faced with a difficult question, we often answer an easier one instead, usually without noticing the substitution."

Pugh discusses the importance of placing this simplified version of design in context to students in order to emphasize that it represents just a small part of the real-world total design activity, and of clarifying that what is being taught is not really design itself.

The greatest problems with the simplified approach occur when the bricks are mistaken for the building itself: if process design is taught in a partial way, without explicit recognition that processes happen in process plants, then the full range of challenges associated with total design are not considered. Instead, design becomes a variant of applied mathematics in which selected elements of partial design are combined to make what is considered to be an integrated model, even though it lacks many required aspects (Crawley et al, 2007; Pugh, 1991).

In such approaches, the three most important measures of a design's quality in real-world practice (cost, safety, and robustness) are given significantly less emphasis than the optimization of a small number of parameters in a greatly simplified model of just part of the plant.

### Overemphasis of research interests

Research quality is a major contributor to financially important wider indices of quality in university education such as the *times higher education supplement* (THES) and Quacquarelli Symonds (QS) rankings. In addition, the majority of staff in UK engineering departments have academic backgrounds and research interests in the physical sciences and mathematics as opposed to the practice of engineering (Excell, 2014). Taken with the Institution of Chemical Engineer (IChemE)'s requirement for exposure to research in the final year of the typical undergraduate chemical engineering degree (IChemE, 2017) this leads to an increase in curriculum time being allocated to the types of science and mathematics preferred by scientific researchers, which lack applicability in professional practice.

There has also been an increased generalized promotion within academia of modeling and simulation methodologies used as research tools, the ramifications of which are explored in some detail in *An Applied Guide*. The products of such an engineering education have been labeled "Hysys monkeys" by experienced engineers (Trotter, 2018), implying that such graduates have merely been taught to operate the most commonly used program, Aspen Hysys.

### Overemphasis on computer modeling

Computers can handle complex but essentially rote tasks better than people (Pahl, Beitz, Feldhusen, & Grote, 2006) but computers are not creative, and engineering is a creative activity. Therefore, computers cannot engineer.

Even the most sophisticated computer simulation in engineering is still a model, based on applied mathematics and science, which does not fully describe what is being modeled. Moreover, commercial software normally has a 1% chance of containing significant errors. (Kletz, 2001). Overreliance on computer models instead of collective professional judgment, acquired through extensive experience, has the potential to be dangerous, as the IChemE point out in their guidance on the use of computers (IChemE, 1999).

Pugh explains that teaching design as it is practiced by professionals is harder than teaching science and mathematics. It may be too complex ever to be practically replaceable with software. Not alerting students to the limitations as well as the benefits of software leads to a narrower understanding of the process. Simulation programs may generate very precise answers, but within the software are many assumptions which no-one (perhaps not even the programmer) fully understands (IChemE, 1999).

The key skill of the process engineer, which cannot be supplanted by simulation technologies, is an intuitive grasp of the ways in which a complex system fits and works together. If process design were to be handed over to software, process plants would be generated that nobody really understood, which would be of great concern from a safety point of view. For example, the key risk assessment tool in process engineering, the Hazard and Operability Study, requires participants to dissect and analyze every reasonably foreseeable aspect of a plant's operational life, a procedure which cannot be undertaken without detailed understanding.

Academic research reflects the precision of mathematics, and the certainty of pure science. By contrast, professional engineers look beyond that which can be explained with complete certainty in order to serve the needs of society, using heuristics and mind's eye approaches (Ferguson, 1994).

Whilst Mecklenburgh (1985) amongst others speculated that computer programs would eventually be laying out plants or even completing process design, they are not routinely used for these purposes by practitioners. In the toolbox of professional engineers, software will not replace professional judgment because it is at best only as good as its programmers, who are rarely professional process engineers.

### Lack of constraint on creativity

A second consequence of the research-led ethos in engineering education is related to creativity. In the research arena, novel concepts are considered favorably. Whilst creativity is an important element in professional process design, excessive novelty is not. Engineers thus exercise a limited form of creativity bounded by considerations of cost, safety, and robustness.

At an individual level, the process designer must nonetheless forge a personal style, as advocated by Gibbs (1988), which bears specific distinct hallmarks. The constrained

creativity of professional designers is often grounded in a particular method of recombination of elements they have used before or have seen others use.

For example, when designing systems for dosing acids and alkalis into water under control of a pH probe, an engineer will use a particular combination of static mixers, piston-diaphragm pumps, loading and pressure-relief valves to provide a robust, economical, and reliable solution. Professional designers can reliably develop such designs based on limited data: virtually never will there be sufficient sampling data even to generate a statistically significant estimate of the values of key parameters. Furthermore, for this type of design, the buffering capacity of the water is a key determinant of how much acid or alkali will be required, but scientifically valid estimates of a representative range of buffering capacities are not available to the professional designer.

The professional designer's methodology may be based in part on mathematical analysis, and in part on long-standing scientific papers, but will also incorporate an intuitive feel for the data and certain qualitative measures. The choice of technology is based on a personal style, grounded in repeated experience, and to some extent influenced by the personal style and preferences of professional mentors and teachers.

The ultimate fine detail of a design is thus conceived from a range of inputs, of which the application of science and mathematics are just one.

### Loss of the professional process design philosophy

Process design is learned by the application of intuition and judgment, which originate in practice (Sinnott & Towler, 2009), and by developing a reliable understanding of both complex system-level issues (Meadows, 2008) and finer details. The professional designer will develop and progressively refine individual approaches to problems, developing an intuitive feel for optimum combinations and subassemblies of components, appropriate margins of error, etc.

My own approach has been to teach process design in this more intuitive fashion. Formal approaches to creativity were attempted, but ultimately it was found that engineering creativity reliably followed once teaching was based on professional experience.

My early discussions with fellow chemical engineering academics suggested that there was a widely held belief in those parts of academic chemical engineering interested in the area that process plant design practice had changed radically since the 1980s (see Appendix 2: Upset conditions table). However, this suggestion was at odds with my ongoing professional experience as a plant designer and as an expert witness, which indicated that the core activities and interrelationship of parts of the design process had remained largely the same over this period.

Supporting scientific research in this area is unavailable, because the professional process plant design process is not an area of modern research interest. However, the divergence between academic engineering and professional practice would appear to have been caused by gradual ongoing change in engineering education, rather than in

the profession. The ultimate consequence of this divergence has been the loss of the professional design philosophy from the engineering curriculum and its replacement with a simulated incomplete version of design. The teacher of engineering in academia will thus find a range of textbooks to support what might be considered "researcher-led process design," but limited resources which describe and support the teaching of a professional design philosophy.

## "Literature search" and the search for engineering design literature

Upon entering academia, I searched for publications which would support the teaching of a professional design philosophy. However, it proved difficult to identify a textbook whose methodologies were fully consistent with consensus professional practice. Furthermore, there was limited research to validate professional experience, whether on engineering practice generally, the design process specifically, or on engineering design education.

### *Engineering design textbooks*

A wide range of potentially relevant engineering textbooks published between 1970 and the time of writing was considered. Those which contained any systematic design methodology were as follows:

- Erwin's *Industrial chemical process Design* (2013);
- Luyben's *Principles and case studies of simultaneous design* (2011);
- Sinnott and Towler's *Chemical engineering design* (2009);
- Pahl et al.'s *Engineering design: A systematic approach* (2006);
- Peters, Timmerhaus, and West's *Plant design and economics for chemical engineers* (2003);
- Koolen's *Design of simple and robust process plants* (2001);
- Baasel's *Preliminary chemical engineering plant design* (1989);
- Douglas's *Conceptual design of chemical processes* (1988);
- Sandler and Luckiewicz's *Practical process engineering* (1986);
- Wells and Rose's *The art of chemical process design* (1986);
- Backhurst and Harker's *Process plant design* (1973).

The context and content of each of these was explored. All gave at best partial descriptions of process plant design methodology, in line with standard academic engineering curricula which Pugh (1991) discusses. To offer brief comment in reverse chronological order:

Erwin's *Industrial chemical process design* (2013) explains how to use MS Visual Basic to support engineering design (rather than solve engineering problems). The book's focus is narrow and statements such as: "The great majority of the process engineer's work is strictly with organic chemicals," may reflect Erwin's subjective experience, but it does not my own.

However, as a practitioner, Erwin's approach is practical. It is acknowledged that even the programs supplied with the book on disc "have not been put through an exhaustive beta test." Erwin states, without implying that we should forget the IChemE's Guidance on Use of Computers (1999), that the "quest of this book... [is] to correct the program through your good ability."

This book will be valuable to those who wish to use MS Visual Basic to carry out design tasks (especially those in the petrochemical industry), with the caveat that the time taken to write and test a program might compare poorly with that of other methodologies, unless the program is to be reused many times.

Luyben's *Principles and case studies of simultaneous design* (2011) also takes a partial approach, considering only steady-state economics and dynamic controllability aspects of a process. Design for controllability is strongly emphasized, supported by computer modeling; an approach which may be too partial to represent a realistic design methodology. In meeting the stated aim of producing something more compact than *Perry's handbook* (Green & Perry, 2007), Luyben has focused on two elements. Whilst these are undoubtedly important partial design elements, optimizing only two of the variables in a design will not produce an optimal solution. The text thus offers a methodology for *process* design, not *process plant* design; *partial* rather than *total* design, and the substitution of modeling for design.

Sinnott and Towler (2009) attempt to provide a design methodology and the book is used widely in universities. However, the explanation of professional design is not explicit, which may contribute to the usual situation where student plant design outputs are unrealistic from the perspective of the practitioner. The book provides "turn-the-handle" methods to "design" various unit operations. Many current academic "process design projects" combine a group of tasks of this nature with using a simulation program like Hysys, or working through pinch analyses.

In contrast, Pahl et al.'s *Engineering design: A systematic approach* (2006) captures the essence of engineering design practice (Anderson, Courter, McGlamery, Nathans-Kelly, & Nicometo, 2010; Eckert et al., 2004). Though it is a mechanical engineering text, it comes far closer to professional practice in chemical engineering than Sinnott. Pahl et al. suggest that German design teaching is far more closely aligned with professional practice than in the English-speaking world. They describe realistic design methodologies and provide a clear analysis of the engineering design process, including aspects often overlooked in an academic setting. The book proved useful in my design teaching prior to the publication of *An Applied Guide*. Pahl et al. provide a useful counter to the oversimplification of problems, by differentiating between a task and a problem. When there is a well-established methodology which produces unambiguous guidance on how to choose between design options, following such an approach is not a problem-solving activity, but is merely a task. Where data are gathered, entered into a computer program or design

methodology, and a reasonably straightforward answer is produced, this is not engineering.

As the title suggests, Peters, Timmerhaus, and West's *Plant design and economics for chemical engineers* (2003) focuses on economics, but also contains valuable guidance on technical report writing and delivery. Whilst the design content is incomplete, the book has particular relevance for engineering educators as a ready source of many cost curves for use in costing exercises.

Koolen's *Design of simple and robust process plants* (2001) contains practical summaries of the implications of 10 approaches to process or process plant design. Koolen's own approach emphasizes the importance of simplicity, although this is not a key metric in professional design. Simplicity can be an indicator of expert design [as expressed by Kelly Johnson in the KISS principle *Keep it simple, stupid* (Rich, 1995)] but, like any other single metric, should not be overemphasized. Koolen quantifies complexity, which is an intriguing and potentially fruitful approach, but his discussion of partial approaches, combined with a theorist's attempt to substitute modeling and simulation for design, are indicative of a normative rather than positive design methodology.

Baasel's *Preliminary chemical engineering plant design* (1989) was authored by an academic with industrial experience. Baasel acknowledges that process design is essentially plant design and the importance of issues frequently overlooked in academia. However, whilst the text reflects a clear appreciation of professional practice, it does not contain a realistic modern design methodology.

The approach to researcher-led "process design" elaborated in academia can be traced back to Douglas's seminal book *Conceptual design of chemical processes* (1988). As the title suggests, it attempts to design chemical processes, rather than process plants. Its author understands that the expert designer proceeds by intuition and analogy, aided by "back of the envelope" calculations, but identifies the need for a method which helps students and academics to manage the extra calculations they have to perform before their formation is complete. The arguments underlying the academic approach since built on it are set out explicitly. It assumes that the purpose of conceptual design is to determine process chemistry and parameters such as reaction yield. Choices between technologies are not considered. Pumps are explicitly assumed to be a negligible proportion of the capital (capex) and running cost (opex) of a plant, whilst heat exchangers are a major proportion of capex and opex. It is implicit in the chain of assumptions used to create the simplified design methodology that a particular sort of process is being designed. Like all design heuristics, it has a limited range of applicability. Whilst Douglas mentions other industries, the text is based throughout upon an example taken from the petrochemical industry, and the approach is clearly also most suited to that industry, overlooking items of great importance in other industries, but including commentary on pinch analysis (irrelevant in most industries), which was relatively new when the book was written.

Whilst this may have been an appropriate approach for a student or a junior process designer in the petrochemical industries of the 1980s, it may have less relevance today. For example, nowadays there are many process plant designs which do not contain a single heat exchanger; whilst petrochemical plants of the sort used as the example by Douglas are no longer being constructed in the developed world.

Douglas attempts to offer a beginner a way to choose between potential process chemistries and specify the performance of certain unit operations in a somewhat dated area of chemical engineering. However, the problem for which a methodology is offered is one which many professional engineers do not encounter. When asked to offer a conceptual design, engineers must address different questions, on plants with a different balance of cost of plant components. That said, the approach in the book retains a coherence that more recent developments based on it do not. For example, emphasis is placed on obtaining as rigorous a costing as possible at early design stages (setting aside the issue of those items which are left out).

In summary, Douglas provides a plausible and pragmatic approach to the limited problem it articulates. However, successive oversimplifications of the approach outlined may have led engineering education away from a professional design philosophy and towards the researcher-led approaches which prevail in subsequent engineering teaching and textbooks.

Sandler and Luckiewicz's *Practical process engineering* (1986) is potentially far more useful to a new designer, although it has regrettably become obsolete in some respects. The book represents the joint endeavor by an academic and a practitioner to remedy the shortcomings of academic engineering courses. It emphasizes the importance of drawing and practical hydraulics, and contains useful practical knowledge on trace heating, lagging, electrical power, and motors. By contrast, it is less substantial on the matter of unit operation design—the term "vessels," for example, covers everything from reactors to storage tanks. Nonetheless, it contains useful material that none of the other books cover, and certainly informed the development of *An Applied Guide*.

Wells and Rose's *The art of chemical process design* (1986) was authored by an academic and a software company representative. Its premise is that design begins in the laboratory and proceeds via simulation and modeling. Whilst it recognizes the iterative nature of design, the methodology described is scientific, rather than artful.

While its authors are academics, Backhurst and Harker's *Process plant design* (1973) reflects clearly the concept that what engineers do differs from what is taught in universities. Certain areas (described by the authors as arbitrarily chosen) are however given unusual emphasis, which results in another partial methodology, and limits the utility of the text as a realistic design methodology.

With the exception of Pahl et al., none of the books summarized above embodies the concepts of professional practice articulated by observers such as Trevelyan (2014); rather they appeared to reflect the misconceptions which Trevelyan has also described.

By contrast, the approach which was most representative of teaching in the area had much in common with the work of Douglas (1988) which, it is explicitly stated, was intended to address the difficulty in teaching process design in an academic environment free of experienced process designers.

## *Engineering design research*

A search of the relevant research literature identified three distinct types of study: those which explored the nature of engineers and engineering; those which investigated the engineering design process; and those which discussed engineering education.

### Research into the nature of engineers and engineering

**The true nature of engineering** Shortly after submitting the manuscript of *An Applied Guide*, Trevelyan's (2014) book *The making of an expert engineer* was published. Trevelyan groups the key issues in promoting engineering expertise in beginners to the field into "Misconceptions": received ideas about the nature of engineering which are heard in academia and are subtly promoted during the student experience; and "Practice Concepts": over 80 separate characteristics which describe the landscape of professional engineering. Trevelyan describes the importance of relationships and communication and performances in engineering; the way in which engineers must work with incomplete information, and how they rely on past precedent, codes, and standards. He emphasizes the constraints, most notably economic, which underpin all engineering decisions.

Trevelyan's conclusions were reached from a different starting point to the author's, and by means of a different methodology. Moreover, Trevelyan's work serves a different purpose to *An Applied Guide*. However, the alignment between the common misconceptions and threshold concepts which Trevelyan identifies and those described in *An Applied Guide* would appear to corroborate the description of the nature of engineering outlined in this appendix.

**Intuitive approaches and visual representations** A characteristic of the engineer's mindset, frequently overlooked in academia, is the innate intuitive ability to visualize design. Design still starts "in the mind's eye" (Ferguson, 1994), just as it has for thousands of years. That starting concept comes not from science or mathematics, but from the designer's ingenuity, experience, and ability to see analogies.

Technology progresses as the designer's mind's eye envisages concepts based on a more sophisticated state of the art; more powerful tools are devised to allow the best options to be selected; and more powerful information storage devices are developed which facilitate learning from past mistakes.

Engineering is in essence the same activity as it was before it was known by that name. Unlike the professional researcher who will tend to seek the most recent references, designers go back to the ancients, as Petroski (2012) discusses.

Professional engineers still place greater emphasis on analysis by drawing, by analogy, and using experience-based intuition than on mathematical and scientific approaches. As Whyte et al. (2008) discusses, drawings are tools for thinking as well as records of past thinking. Meadows (2008) demonstrates this by making great use of diagrams in her work on system-level design. This is effective because the systems she discusses, like drawings, happen all at once, and are connected in many directions simultaneously, whilst words can only come one at a time in linear logical order.

Ferguson (1994), as well as Henderson (1999), have observed that visual and drawing skills are poorly represented in the engineering curriculum. They describe how the engineering curriculum emphasizes mathematics above all else, next science, then language, whilst visual reasoning and intuition tend to be overlooked. Ferguson states: "the art of engineering has been pushed aside in favor of the analytical 'engineering sciences' which are higher in status and easier to teach. . .an engineering education that ignores its rich heritage of nonverbal learning will produce graduates who are dangerously ignorant of the myriad subtle ways in which the real world differs from the mathematical world their professors teach them."

Ferguson further observes that "It is usually a shock to [engineering] students to discover what a small percentage of decisions made by a designer are made on the basis of the kind of calculation he has spent so much time learning in school." Leonardi, Jackson, and Diwan (2009) and Trevelyan explain this further, reporting that students enter engineering education with misconceptions about the nature of engineering which are often reinforced rather than dispelled by the education they receive.

**Relationship between research and practice** Vincenti (1993) explores how engineering research and engineering practice should properly fit together. His essential theory is that engineering has six categories of knowledge, of which he considers the last five are proper subjects for engineering research, as follows:

1. *Fundamental design concepts*

   These are not scientific fundamentals, but instead the design engineer's axioms—a common idea of what the thing being designed is for, its operating principle, and its normal configuration.

2. *Criteria and specifications*

   Engineers may design artifacts to meet a need defined by others in nontechnical terms, but in order to do so they need to transform the general, qualitative specification into concrete, quantifiable performance characteristics.

**3.** *Theoretical tools*

The theoretical tools of the engineer may be based in mathematics, science, or be peculiar to engineering. They provide ways of thinking about and analyzing design problems.

**3a.** *Mathematical methods and theories*

The mathematical tools least peculiar to the engineer may be based in pure mathematics, or sciences, but they have been simplified for application to a particular situation by introducing a set of approximations and assumptions which apply to only that specific set of circumstances. More particular still are the phenomenological theories which practitioners share about things too complex for scientific analysis, even if they have little scientific standing. At the far end of the spectrum are commonly held approaches to design of specific systems, used only because they seem to work, and no better method is known.

**3b.** *Intellectual concepts*

Engineers are less like philosophers than they are like scientists. They do not discriminate between the sources of their ways of thinking about a design problem—anything which works is good.

**4.** *Quantitative data*

Engineers need physical data to design things. They need descriptive knowledge of how things are. They need prescriptive knowledge of how things should be, to ensure that the designed item meets the specified need.

**5.** *Practical considerations*

One can have perfect knowledge in all previous categories and still be unable to design an artifact that works. One also needs know-how, usually obtained from long practice in the profession, and interaction with those who produce, commission, and operate the artifact.

**6.** *Design instrumentalities*

Or less opaquely, structured procedures for going about the design of an artifact, ways of thinking about design problems, and judgmental skills. Some of these can be taught directly, but professional competence in these areas comes only from practice.

Vincenti then differentiates between seven ways in which engineering knowledge is generated:

**1.** Transfer from science;
**2.** Invention;
**3.** Theoretical engineering research;
**4.** Experimental engineering research;
**5.** Design practice;
**6.** Production;
**7.** Direct trial.

Research can generate new engineering knowledge in all categories other than practical considerations. Researchers know *about*, whilst practitioners know *how*.

### Research into the engineering design process

Engineering design is not researched with a view to teaching it positively (as it *is* done), as opposed to normatively (how it *should be* done), since universities engineering departments do not teach professional design methodology (Dym et al., 2005).

As with academic textbooks, there have been few publications in peer-reviewed journals since the 1970s which describe a realistic process plant design methodology. The most realistic papers tended to be published in nonpeer-reviewed publications by practitioners. The most notable example of this was Kern's series on plant layout in *Chemical Engineering* (Kern, 1977a, 1977b, 1977c, 1977d, 1977e, 1978a, 1978b, 1978c, 1978d, 1978e) as well as more recent articles in the same publication by Meissner and Shelton (1992), Brandt, George, Hathaway, and McClintock (1992), Russo and Tortorella (1993), and me (Moran, 2016c). Whilst the earlier of these provided the ultimate basis of the plant layout methodologies found in the standard texts by Mecklenburgh (1985) and Sinnott and Towler (2009), they are rarely referenced by academics working in the area of plant layout.

Since the 1970s, the body of research on engineering and architectural design practices has been provided in the main by sociologists, HR, and business management researchers, usually using an ethnographic methodology. Other methodologies are used such as action research, grounded theory, participant observation, and phenomenography, etc. These methodologies, when employed from the perspective of the sociologist, have resulted in papers which critique the culture of engineering in general, and design in particular from, variously, antimasculinist (Faulkner, 2009a, 2009b, 2009c), antitechnicist (Faulkner, 2007), and antirationalist (Sandberg, 2000) viewpoints. HR and management researchers such as Druskat and Wheeler (2003) tend to focus on the practical challenges associated with managing design teams, rather than philosophical considerations.

The most common technique used by sociologists for studying engineering practice is ethnography, where the researcher attempts to understand a culture they are not part of by participation in it. Ethnographers attempt to tread the line between "Martian" and "convert" according to Davis (1973), but sociologists will always be Martians in the design office, whether or not they notice or assimilate the group's shared axioms and attitudes. Engineering is not a job, it is a way of being, as Koen (2003) explains. Thus, when the investigator is not an engineer, the embedding of the investigator in a design team becomes a somewhat artificial exercise.

Whilst evidence from observers trained as engineers, who are reflecting upon practice as practitioners, teachers, and researchers (such as the author), might be considered stronger, there is limited research literature of this nature. Trevelyan's work synthesizes

the best research on the subject and concurs with the views expressed in *An Applied Guide*.

In addition, there is a smaller body of research by professional engineers who employed sociological research methods. Minneman (1991) and Bea (2002) conclude that the profession of engineering is far more "people-focused" and far less about "nuts and bolts" than they had assumed before they started their investigation. To put it another way, much of the day-to-day work of most professional engineers is to do with interpersonal rather than technical issues.

However, despite the contribution of these perspectives within their own frame of reference, they neither support nor dismantle the author's thesis—that explicit realistic guidance on professional design practice has not previously been published.

Trevelyan and Tilli (2007) report that, across disciplines, "almost all the papers in the literature that refer to engineering practice aim to provide evidence for changing engineering education or evidence to support a particular set of engineering competencies. From these narrow objectives we can learn a little about engineering work. More empirical evidence is needed before we can work towards a comprehensive understanding, let alone improvement of engineering working methods and practices."

### Research into engineering education

The body of research on engineering education in general (and chemical engineering education in particular) was considered, to explore how and why it has drifted so far from professional practice.

Before the Second World War, engineering education was led by professional engineers, who provided mentoring, modeling, and professional knowledge. After 1945, the model moved toward a system intended to replicate the posited success of science in winning the war. Goldberg (1996) describes "the fundamental myth of engineering education that asserts the supremacy of basic research over all other engineering academic activities. . .the myth resulted largely from an overestimation of the role of science and an underestimation of the role of engineering in World War II. . .."

Thus, the role and importance of research in engineering education grew, and history adopted this narrative retrospectively (Macfarlane, 2015). This was in line with a more general trend in Higher Education (HE), though Macfarlane reports that, as late as 1979, those who worked in HE considered teaching far more important than research.

Practical suggestions have since been offered on how to address the current state of engineering education. Notable amongst these is Crawley et al.'s *Rethinking engineering education* (2007), which advocates two changes to the structure of engineering education.

Crawley et al.'s first recommendation is to improve contextualization of engineering education, as a preparation for professional life, by implementing what is referred to as CDIO: conceptualization, design, implementation, and operation. This is a useful recommendation: engineering is not merely the application of mathematics and science, though engineers must have a firm grasp of this fundamental knowledge (as well as other, non-STEM knowledge) to achieve specific goals, which Crawley et al. define as "Conceive-Design-Implement-Operate complex value-added engineering products, processes, and systems in a modern, team-based environment."

The second recommendation consists of a combination of the CDIO change outlined above with a progression towards a highly problem-based learning (PBL) approach, inspired by "constructivism," a "theory of learning" with limited empirical evidence to support it (Osborne, 2015).

The popularity of PBL and its related approaches in education tends to be cyclical. The approaches sound seductive, and are popular with students when well executed, but tend to be abandoned by educationalists once it is acknowledged that they are an ineffective way to teach fundamentals (Hattie, 2008).

To the extent that approaches such as PBL show any positive effect on learning outcomes, it is in teaching professional skills (Hattie, 2008). Such techniques are both popular and effective; particularly where the objective is to encourage students to integrate what they have learned elsewhere.

Process plant design is an art, whose practitioners use science and mathematics, models and simulations, drawings and spreadsheets, but only to support their professional judgment. It cannot be supplanted by these things, just as people cannot be replaced by computers. Imagination, mental imagery, intuition, analogies and metaphors, ability to negotiate and communicate with others, knowledge of custom and practice and of past disasters, personalities and experience are what designers bring to the table.

Academia should thus be better equipped—through practitioner staff and appropriate supporting materials—to understand the total nature of design which is at the heart of professional practice.

## Resistance to understanding design from engineering academics

I have encountered strong resistance to the professional design philosophy from academic colleagues, the overwhelming majority of whom were scientists by training, and preferred "scientific" research-led approaches. This resonates with the reports of Goldberg and Somerville (2014) that the emphasis on research, and "glorification" of scientific research methodology has led to a certain scientism amongst the staff in "engineering departments," who seek scientific rigor both in the subjects they teach, and in the evaluation of potential new approaches to teaching. They look to senior

figures in the research community, rather than the profession, to provide leadership; and they require suggestions for change to meet standards for scientific evidence.

Taken with the lack of experience of engineering practice amongst academic staff (Excell, 2014), and their lack of knowledge of the social science research on engineering practice, academics may find it challenging to develop a wider appreciation of professional engineering. Instead, there may be an insistence that engineering practice is closely related to the subjects they research and teach, an example of "motivated reasoning"—"a form of implicit emotion regulation in which the brain converges on judgments that minimize negative and maximize positive affect states associated with threat to or attainment of motives" (Westen, Blagov, Harenski, Kilts, & Hamann, 2006).

There are a number of problems with this. First, the most commonly used hierarchies of evidence [which originate in medicine (Burns, Rohrich, & Chung, 2011)] give greatest weight to reviews of the literature by academics, followed by peer-reviewed research papers, and lastly expert opinion; a hierarchy which contrasts with the status of expert testimony in the civil and criminal justice systems.

Consequently, researchers may give less credence to the opinion of professional engineers, who are neither research-active nor in a position to carry out rigorous controlled scientific studies for commercial reasons. However, given that the divergence from professional practice lies within academia, it could be argued that the onus should be on researchers to prove that their approaches are superior to established professional practice rather than the other way round.

Pedagogical research is of variable quality; and subjecting it to formal systematic review may well establish that some is of the lowest possible category of evidence: "not even wrong," as Pauli would have it (Peierls, 1960). Gorard has published extensively on so-called "pseudo research" (Gorard & Cook, 2007; Gorard & Smith, 2006; Gorard, 2015a, 2015b).

Thus, a scientific researcher evaluating papers on engineering education as if they were scientific literature may not find them persuasive. On the other hand, scientific researchers may also find the opinion of professional engineers on their own area of practice difficult to accept.

Trevelyan (2017) observed that "It can be emotionally challenging for an established engineering educator to realize that there are complex aspects of practice knowledge of which he or she is almost completely unaware. I have personally witnessed the resulting insecurity among my colleagues on numerous occasions."

By way of illustration, I submitted an account of teaching to a peer-reviewed journal. The paper (Moran, 2017a) was rejected following comments from reviewers which focused on a lack of peer-reviewed evidence and research including:

> *"…, the argument never develops into a solid, evidence-based contribution to knowledge."; "… Dismissing an alternate perspective is no substitute for the deep thought required to understand a different perspective and successfully argue for an alternate framework."*

Arguably, a requirement in academic debate to give full credence to opposing viewpoints, where credible evidence for such opposing viewpoints is entirely lacking, amounts to an insistence on false balance. Okrent's law states, "The pursuit of balance can create imbalance because sometimes something is true." In this case, my carefully validated views on the nature of the profession I have practiced for more than 25 years are true, despite the lack of a peer-reviewed evidence base.

I have consequently found it very difficult to obtain engagement with academics, though my approach was cited by Ventura-Medina and Hapgood (2013) and my critique of engineering education was published in the American Society for Engineering Education's *Prism Magazine* (Moran, 2016e). In addition, a presentation was given to the IChemE Education Subject Interest Group and a poster presentation given at an Institution of Engineering and Technology (IET) conference (Moran, 2017b).

In fact, my repeated attempts to engage academia have been considered by some to be so controversial as to result in official complaints to the author's former professional body—all since dismissed—on the grounds that the expression of such opinions was "injurious to academics." For many in academia and professional engineering bodies, the issues raised remain taboo and a true scholarly debate may never be possible. As Lord Uff said in his 2017 report on our profession in the United Kingdom, "the existing educational system in the United Kingdom is highly entrenched and not easily dislodged by logic or evidence."

## Consequences for early-career engineers

### *Employability*

As previously discussed, the typical undergraduate engineering degree (whilst no doubt arguably technically compliant with the requirements for accreditation), is nowadays less about the formation of a chartered engineer and more of a generic STEM education. In addition, the much-publicized notion of a "STEM shortage" persists, together with a commonly held belief that such graduates will be in great demand in the wider professions (Royal Academy of Engineering, 2017).

However, the rhetoric around employability is contradicted by reporters such as Wakeham (2016) who found "high unemployment, especially for high tariff institutions" among chemical, process, and energy engineering graduates. The author's own survey of alumni of the University of Nottingham suggested that only around 50% of graduates secure a graduate role in engineering.

### *The leap from design project to professional design*

A degree which is characterized by researcher-led approaches may be an ideal preparation for postgraduate research but is far less so for industry. Uff (2017) has reported "a disconnect between HE providers and industry in terms of capturing employers'

requirements, willingness to satisfy those requirements and competence to satisfy them. This was especially so in research-intensive universities whose academics are armed with a particular set of skills. . .. The view is expressed that too many universities focus on research outputs as a success measure, rather than on their primary role to produce the graduates that industry and the economy need."

Today's students consistently report surprise at how little of their jobs after university are the "proper engineering" (Faulkner, 2009a) they learned at university, whilst Uff has further observed that "engineering requires a combination of theoretical knowledge and its practical application, coupled with many other skills," which are often lacking from the curriculum.

### Lack of understanding of professional design techniques

Aside from a lack of specialist technical knowledge, early-career engineers are unlikely to have gained any insight into the culture and key tools of the professional design engineer during their undergraduate education. The lack of system-level understanding, even during student design exercises, has been discussed elsewhere in this appendix. The consequence of this deficit is that graduates are unfamiliar with de Figueirdo (2008)'s "design dimension": "The design dimension sees engineering as the art of design. It values systems thinking much more than the analytical thinking that characterizes traditional science. Its practice is founded on holistic, contextual, and integrated visions of the world, rather than on partial visions. Typical values of this dimension include exploring alternatives and compromising. In this dimension, which resorts frequently to non-scientific forms of thinking, the key decisions are often based on incomplete knowledge and intuition, as well as on personal and collective experiences."

"Reading" an engineering drawing does not just imply knowing what the symbols mean. It means having an accurate model of the plant the drawing represents in your mind's eye. Whilst many graduates will have seen professional CAD-rendered engineering drawings during their degrees, only a minority will have the technical ability to read one, and still fewer will be able to draft one. Thus, graduates are often "visually illiterate" when it comes to the single most important communication and collaboration tool between engineers and engineering disciplines.

Graduates will also have a limited understanding of the needs of other engineering disciplines, or of the necessity for professional collaboration. Their student design projects will have been undertaken in a group with their peers—usually friends. They will have no experience of working with other disciplines, or with a diverse and unfamiliar team, missing the opportunity to learn that "teams work because of diverse interpretations" (Trevelyan, 2014).

### Overconfidence in simulation and modeling techniques

In contrast to the lack of confidence which junior design engineers tend to display over the fundamentals, many—paradoxically—arrive in industry with an overconfidence in research-led "process design" techniques. In professional engineering, design virtually never proceeds from first principles, and modeling/simulation technologies have a highly specific and limited application in the design process. Fresh graduates, however, may have excessive faith in the solidity of their design when based on such approaches, due to the emphasis placed on these techniques in academia, as observed by the author when acting as an expert witness (Moran, 2017c).

In that particular case, the consequences were expensive, but not dangerous. However, a worst-case scenario might involve margins of safety on a plant being pared back based on the outputs of a modeling exercise.

Moreover, given the migration of engineering graduates into other sectors, this overconfidence may have wider ramifications. For example, automated trading programs contributed to the depth of the most recent stock market crash; programs which were devised by highly numerate physical science graduates, applying the formulae of physics to financial modeling (Foley, 2013). The consequences of an excessive reliance on modeling could thus be felt beyond the process plant.

## Conclusion

The conclusion drawn by the author from exposure to engineering education, its research and reference literature, its practitioners, and products was that engineering education had moved away from professional practice and, moreover, that this had been identified and reported in the past.

This divergence, the hallmark of which is an emphasis on researcher-led approaches in the undergraduate engineering curriculum, compromises one of the key objectives of engineering education, namely the provision of the first stage in the formation of a professional engineer.

There were no modern textbooks before *An Applied Guide* was written which effectively support the professional consensus design philosophy, as opposed to the research-led approach. Furthermore, there is a limited body of peer-reviewed research in the field, very little of which has been undertaken by practitioners, and some of which might be characterized as "pseudo" research.

Having concluded that no modern textbook or scientific literature could be identified either to underpin the author's own design teaching approach or to support the dissemination of its ethos amongst teaching colleagues, the author resolved to write the textbook which was missing.

*An Applied Guide* is the result of this resolution, intended to communicate the author's understanding from over more than 25 years of attempting to become an

expert engineer. It is, as far as I am aware, presently the only publication which offers an explicit, realistic plant design methodology. *An Applied Guide* thus attempts to address the deficits in modern engineering education and explain what new graduates need to know to become engineers. *An Applied Guide* represents a distillation of both the professional consensus on the engineering design combined with a more philosophical commentary of what makes a design engineer. It is deliberately image-heavy, using drawings and diagrams wherever possible to convey the complex nature of design.

## Update since publication of *An Applied Guide*

In the course of writing the book, it became clear that Mecklenburgh's *Process plant layout* (1985), a text which had historically been at the forefront of UK layout teaching, required updating. By losing currency, it had perhaps contributed to the loss of layout from UK chemical engineering curricula. Thus, the second edition of *Process Plant Layout* was published in 2016 (Moran, 2016b). The update was influenced by the work of Petroski (2012) and resulted in the inclusion of over 100 case studies of layout-related accidents, some well-known, others confided by colleagues, to allow a new generation of reader to learn from historical design mistakes.

After this project, the principles of *An Applied Guide* were applied to a new textbook focusing on the author's own area of professional specialism, water treatment (Moran, 2018).

A revised second edition of *An Applied Guide* has now also been produced (in which this abstract features as an appendix). Whilst the book is now an undergraduate engineering text at the University of Nottingham and beyond, its key market has proved to be among new graduate engineers. The focus of this second edition, in common with more recent publications (Moran, 2015a, 2016c, 2016d, 2017c; see also Appendix 2: Upset conditions table), will be on continuing to provide the bridge. Until the need for fundamental change within engineering education is more widely acknowledged it will remain necessary to support graduate engineers, in ways that academia cannot currently envisage, on the road to professional design expertise.

## Improving engineering education

Whilst at the University of Nottingham, I led changes in curriculum and teaching methodologies which were associated with enhanced student employability, employer reputation, student satisfaction, and THES rankings (Moran, 2017b).

This might be as much as can be achieved in the current climate. Whilst there are various initiatives based on CDIO, or more radically on the work done at Olin College in the United States [for example, the UK's New Model in Technology & Engineering

(NMiTE)], even the most radical of these does not challenge the status of research in the curriculum.

A more radical approach still would be to staff engineering departments with a combination of engineering practitioners and professional teachers, and to set aside the concept of research-led teaching entirely, an approach which would be highly controversial but would represent a significant step toward converging engineering education and practice.

## References


Anderson, K., Courter, S. S., McGlamery, T., Nathans-Kelly, T. M., & Nicometo, C. G. (2010). Understanding engineering work and identity: A cross-case analysis of engineers within six firms. *Engineering Studies*, *2*(3), 153–174.

Baasel, W. D. (1989). *Preliminary chemical engineering plant design* (2nd ed.). New York: Springer.

Backhurst, J. R., & Harker, J. H. (1973). *Process plant design*. Oxford: Butterworth-Heinemann.

Bak, H. J., & Kim, D. H. (2015). Too much emphasis on research? An empirical examination of the relationship between research and teaching in multitasking environments. *Research in Higher Education*, *56*, 843.

Bea, R. G. (2002). Human and organisational factors in the design and reliability of offshore structures. *Risk Analysis*, *22*(1), 29–45.

Biegler, L. T., Grossman, I. E., & Westenberg, A. W. (1997). *Systematic methods of chemical process design*. Upper Saddle River, NJ: Prentice Hall.

Brandt, D., George, W., Hathaway, C., & McClintock, N. (1992). Plant layout: Part 2 The impact of codes, standards and regulations, Davy-McKee Corp. *Chemical Engineering.*, *99*(4), p89.

Burns, P. B., Rohrich, R. J., & Chung, K. C. (2011). The levels of evidence and their role in evidence-based medicine. *Plastic and Reconstructive Surgery*, *128*(1).

Crawley, E. F., Malmqvist, J., Östlund, S., & Brodeur, D. R. (2007). *Rethinking engineering education: The CDIO approach*. New York, NY: Springer US.

Davis, F. (1973). The Martian and the Convert: Ontological polarities in social research. *Journal of Contemporary Ethnography*, *2*(3), 333–343.

de Figueirdo, A.D. (2008). Toward an Epistemology of Engineering, Royal Academy of Engineering Workshop on Philosophy and Engineering, London, November 10–12, 2008.

Douglas, J. M. (1988). *Conceptual design of chemical processes*. New York, NY: McGraw-Hill.

Druskat, V. U., & Wheeler, J. V. (2003). Managing from the boundary: The effective leadership of self-managing work teams. *Academy of Management Journal*, *46*(4), 435–457.

Dym, C. L., Agogino, A. M., Ozgur, E., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education*, *94*(1), 103–120.

Eckert, C., Blackwell, B.D., Buccarelli, L.L., John Clarkson, P., Earl, C., Knight, T.W. (2004). What designers think we need to know about their processes: Early results from a comparative study. In: International design conference—DESIGN 2004, Dubrovnik, Croatia, 18–21 May 2004.

Erwin, D. (2013). *Industrial chemical process design* (2nd ed.). New York, NY: McGraw-Hill.

Excell, J. (2014). Academia's engineering skills shortage. *The Engineer*. Available from <https://www.theengineer.co.uk/issues/december-2013-online/academias-engineering-skills-shortage/> Accessed 27.03.18.

Faulkner, W. (2007). Nuts and bolts and people. *Social Studies of Science*, *37*(3), 331–356.

Faulkner, W. (2009a). *Everyday practices: Heterogeneity in building design engineering*. Unpublished.

Faulkner, W. (2009b). Doing gender in engineering workplace cultures I: Observations from the field. *Engineering Studies*, *1*(1), 3–18.

Faulkner, W. (2009c). Doing gender in engineering workplace cultures II: Gender in/authenticity and the in/visibility paradox. *Engineering Studies*, *1*(3), 169–189.

Ferguson, E. S. (1994). *Engineering and the mind's eye*. Cambridge, MA: MIT Press.
Fielden, G. B. R. (1963). (Chair) *Engineering design report of DSIR Committee on mechanical engineering design*. London: HMSO.
Foley, S. (2013). Physicists and the financial markets. *Financial Times*, 18 October 2013. Available from <https://www.ft.com/content/8461f5e6-35f5-11e3-952b-00144feab7de> Accessed 29.03.18.
Gibbs, G. (1988). *Learning by doing: A guide to teaching and learning methods*. Oxford: Oxford Polytechnic Further Education Unit.
Goldberg, D. E. (1996). Change in engineering education: One myth, two scenarios, and three foci. *Journal of Engineering Education*, *85*, 107–116.
Goldberg, D. E., & Somerville, M. (2014). *A whole new engineer: The coming revolution in engineering education*. Douglas, MI: Threejoy Associates.
Goodhew, P. (2017). *What is the VP scheme and why*. Royal Academy of Engineering Visiting Professors Conference, Aston University.
Gorard, S. (2015a). A proposal for judging the trustworthiness of research findings. researchED Magazine (pdf). Available from <http://scholar.google.co.uk/scholar_url?url = http://dro.dur.ac.uk/16207/1/16207.pdf&hl = en&sa = X&scisig = AAGBfm2NUeJ4y5mjefbu6VvCL6Dgusyq-g&nossl = 1&oi = scholarr&ved = 0ahUKEwjv7bucxY7aAhWBBsAKHZakCQQQgAMIKCgAMAA> Accessed 28.03.18.
Gorard, S. (2015b). Rethinking 'quantitative' methods and the development of new researchers. *Review of Education*, *3*, 72–96.
Gorard, S., & Cook, T. (2007). Where does good evidence come from? *International Journal of Research & Method in Education*, *30*, 3.
Gorard, S., & Smith, E. (2006). Beyond the 'learning society': What have we learnt from widening participation research? *International Journal of Lifelong Education*, *25*, 6.
Green, D. W., & Perry, R. H. (2007). *Perry's chemical rngineers' handbook* (8th ed.). New York, NY: McGraw-Hill.
Hattie, J. (2008). *Visible learning: A synthesis of over 800 meta-analyses relating to achievement*. New York, NY: Routledge.
Henderson, K. (1999). *On line and on paper: Visual representations, visual culture and computer graphics in design engineering. Inside Technology Series*. Cambridge, MA: MIT Press.
IChemE. (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 (pdf). Rugby: Institution of Chemical Engineers. Available from <http://www.icheme.org/communities/special-interest-groups/cape/resources/publications.aspx> Accessed 27.03.18.
IChemE. (2017). Accreditation of chemical engineering programmes: A guide for higher education providers and assessors (pdf). Rugby: Institution of Chemical Engineers. Available from <http://www.icheme.org/accreditation/university-accreditation/guidance.aspx> Accessed 27.03.18.
Kahneman, D. (2013). *Thinking, fast and slow*. New York: Macmillan.
Kern, R. (1977a). Arrangements of process and storage vessels. *Chemical Engineering*, *84*, 93.
Kern, R. (1977b). How to manage plant design to obtain minimum cost. *Chemical Engineering*, *84*, 130.
Kern, R. (1977c). How to get the best process plant layouts for pumps and compressors. *Chemical Engineering*, *84*, 131.
Kern, R. (1977d). Layout arrangements for distillation columns. *Chemical Engineering*, *84*, 153.
Kern, R. (1977e). How to find the optimum layout for heat exchangers. *Chemical Engineering*, *84*, 169.
Kern, R. (1978a). Space requirements and layout for process furnaces. *Chemical Engineering*, *85*, 117.
Kern, R. (1978b). Arranging the housed chemical process plant. *Chemical Engineering*, *85*, 123.
Kern, R. (1978c). Instrument arrangements for ease of maintenance and convenient operation. *Chemical Engineering*, *85*, 127.
Kern, R. (1978d). Controlling the cost factors in plant design. *Chemical Engineering*, *85*, 141.
Kern, R. (1978e). How to arrange the plot plan for process plants. *Chemical Engineering*, *85*, 191.
Kletz, T. (2001). *An engineer's view of human error* (3rd ed.). Rugby: IChemE.
Koen, B. V. (2003). *Discussion of the method: Conducting the engineer's approach to problem solving*. Oxford: Oxford University Press.

Koolen, J. L. A. (2001). *Design of simple and robust process plants*. Weinheim: Wiley-VCH GmbH.
Leonardi, P. M., Jackson, M. H., & Diwan, A. (2009). The enactment-externalization dialectic: Rationalization and the persistence of counterproductive technology design practices in student engineering. *Academy of Management Journal*, *52*(2), 400–420.
Luyben, W. L. (2011). *Principles and case studies of simultaneous design*. Hoboken: Wiley-AIChE.
Macfarlane, B. (2015). The invention of tradition: How 'researchers' replaced teachers. *Times Higher Education*, 25 June 2015.
Meadows, D. H. (2008). *Thinking in systems—A primer*. London: Routledge.
Mecklenburgh, J. C. (1985). *Process plant layout*. London: George Godwin Ltd.
Meissner, R. E., III, & Shelton, D. C. (1992). Plant layout: Part 1 Minimizing problems in plant layout, The Ralph M. Parsons Co. *Chemical Enginerring*, *99*(4), 81.
Minneman, S. L. (1991). The social construction of a technical reality: Empirical studies of group engineering design practice. PhD Thesis, Department of Mechanical Engineering, Stanford University, Stanford, CA.
Moran, S. (2015a). Competitive pricing of process plants. *Chemical Engineering*, *122*(12), 38–42.
Moran, S. (2016b). *Process plant layout* (2nd ed.). Oxford: Butterworth-Heinemann.
Moran, S. (2016c). Process plant layout—Becoming a lost art? *Chemical Engineering*, *123*(12), 71–76.
Moran, S. (2016d). Pump sizing: Bridging the gap between theory and practice. *Chemical Engineering Progress*, *112*(12), 38–44.
Moran, S. (2016e). Research is overemphasised. ASEE Prism, *25*, 6. Available from <http://www.asee-prism.org/last-word-6/ Accessed 28.03.18.
Moran, S. (2017a). *A case study of coordinated design and employability teaching Chemical engineering education*. Unpublished.
Moran, S. (2017b). Case Study: Coordinated design and employability teaching. In: *IET/EPC new approaches to engineering higher education conference*, London, 22 May 2017. Available from <https://www.theiet.org/policy/panels/education/proceedings.cfm> Accessed 28.03.18.
Moran, S. (2017c). Troubleshooting wastewater treatment plants. *Chemical Engineering Progress*, *113*(9), 62–65.
Moran, S. (2018). *An applied guide to water and effluent treatment plant design*. Oxford: Butterworth-Heinemann.
Osborne, J. (2015). Constructivism: Criticism. In R. Gunstone (Ed.), *Encyclopedia of science education*. Dordrecht: Springer.
Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. H. (2006). *Engineering design: A systematic approach*. New York: Springer.
Peierls, R. (1960). Wolfgang Ernst Pauli, 1900–1958. *Biographical Memoirs of Fellows of the Royal Society*, *5*, 186.
Peters, M., Timmerhaus, K., & West, R. (2003). *Plant design and economics for chemical engineers*. New York: McGraw-Hill.
Petroski, H. (2012). *To forgive design: Understanding failure*. Cambridge, MA: Harvard University Press.
Prince, M. J., Felder, R. M., & Brent, R. (2007). Does faculty research improve undergraduate teaching? An analysis of existing and potential synergies. *Journal of Engineering Education*, *96*(4), 283–294.
Pugh, S. (1991). *Total design: Integrated methods for successful product engineering*. Boston: Addison-Wesley.
Rich, B. R. (1995). *Clarence Leonard (Kelly) Johnson 1910—1990: A biographical memoir*. Washington D.C.: National Academies Press.
Royal Academy of Engineering. (2017). *Closing the STEM skills gap: A response to the House of Commons Science and Technology Committee inquiry into closing the STEM skills*. Available from <https://www.raeng.org.uk/publications/responses/closing-the-stem-skills-gap> Accessed 08.04.19.
Russo, T. J., & Tortorella, A. J. (1993). Plant layout, Part 3: The contribution of CAD. *Chemical Engineering*, *99*(4), 97.
Sandberg, J. (2000). Understanding human competence at work: An interpretive approach. *Academy of Management Journal*, *43*(1), 9–25.
Sandler, H. J., & Luckiewicz, E. T. (1986). *Practical process engineering*. New York, NY: McGraw-Hill.
Santini, F., Ladeira, W., Sampaio, C., & Da Silva Costa, G. (2017). Student satisfaction in higher education: A meta-analytic study. *Journal of Marketing for Higher Education*, *27*(1), 1–18.

Sinnott, R., & Towler, G. (2009). (5th ed.). *Chemical engineering: Chemical engineering design*, (6). Oxford: Butterworth-Heinemann/Elsevier.
Smith, R. (2016). *Chemical process: Design and integration* (2nd ed.). Hoboken: Wiley.
Trevelyan, J. (2007). Technical coordination in engineering practice. *Journal of Engineering Education*, *96* (3), 191–204.
Trevelyan, J. (2010). Reconstructing engineering from practice. *Engineering Studies*, *2*(3), 175–195.
Trevelyan, J. (2014). *The making of an expert engineer*. Boca Raton, FL: CRC Press.
Trevelyan, J. (2017). *Engineering education and practice*. Unpublished Letter.
Trevelyan, J., & Tilli, S. (2007). Published research on engineering work. *Journal of Professional Issues in Engineering Education and Practice*, *133*(4), 300–307.
Trotter, G. (2018). LinkedIn comment. Available from <https://www.linkedin.com/feed/update/urn:li:activity:6395210236126380032>.
Turton, R., Bailie, R. C., Whiting, W. B., Shaeiwitz, J. A., & Bhattacharyya, D. (2012). *Analysis, synthesis and design of chemical processes* (4th ed.). Upper Saddle River, NJ: Prentice Hall.
Uff, J. (2017). *UK Engineering 2016: An independent review*. Institution of Mechanical Engineers/Institution of Engineering & Technology/Institution of Civil Engineers (pdf). Available from <https://www.engc.org.uk/news/news/review-of-uk-engineering-profession-published/> Accessed 28.03.18.
Ventura-Medina, E., & Hapgood, K. (2013). Embedding engineering practice in the chemical engineering curricula through industrial expert lecturers. In: *Conference proceedings of the 2013 Australasian chemical engineering conference (CHEMECA 2013)*, Brisbane, QLD, Australia, pp. 1–5, Accessed 29.09.13.
Vincenti, W. G. (1993). *What engineers know and how they know it: Analytical studies from aeronautical history*. Baltimore, MD: Johns Hopkins University Press.
Wakeham, W. (2016). *Wakeham review of STEM degree provision and graduate employability*. UK Department for Business, Innovation & Skills/Higher Education Funding Council for England (pdf). Available from <https://www.gov.uk/government/publications/stem-degree-provision-and-graduate-employability-wakeham-review> Accessed 28.03.18.
Wells, G. L., & Rose, L. M. (1986). *The art of chemical process design*. Amsterdam: Elsevier Science Publishers B.V.
Westen, D., Blagov, P. S., Harenski, K., Kilts, C., & Hamann, S. (2006). Neural bases of motivated reasoning: An fMRI study of emotional constraints on partisan political judgment in the 2004 U.S. Presidential Election. *Journal of Cognitive Neuroscience*, *18*(11), 1947–1958.
Whyte, J., Ewenstein, B., Hales, M., & Tidd, J. (2008). Visualizing knowledge in project-based work. *Long Range Planning*, *41*(1), 74–92.
Wilde, G. L. (1983). The skills and practices of engineering designers now and in the future. *Design Studies*, *4*(1), 21–34.

## Part B: methodology

My design teaching essentially supports a series of group courseworks of increasing difficulty. Working on these courseworks takes up the great majority of my students' time. I don't do much traditional lecturing.

I used to have a teaching fellow with a lot of professional drafting experience whilst I was at Nottingham who taught the students how to use AutoCAD and to some extent Excel in computer lab sessions. Between the two of us there was a lot of contact time, around 6 hours per week, and I used to also see groups who were having difficulty in my office for another half an hour a week.

I used to teach classes of around 150, and I set three courseworks per module with maybe six deliverables each. Group work allowed me to reduce the amount of

marking I had to do to practical levels. Splitting the class into 20 groups reduced my marking load by a factor of seven.

I set the coursework with tight deadlines, and I did not negotiate on workload, group composition, deadlines, or marks. This allowed me to get marks and feedback back to students in a day or two, so that they did not repeat their mistakes on the new coursework they received.

The UK's Higher Education Academy produced a very useful and robust tool for peer assessment called WebPA which I prefer to use to prevent free-riding in the group work exercises. I have also tried the National University of Singapore's "Teammates"[1] application for this purpose. Whilst in my opinion inferior to WebPA, it is adequate to the task, and it has the advantage of not requiring software to be installed on university servers, which always seems to cause problems with the IT department in my experience.

I have a number of collaborating process plant designers who help to deliver lectures, set assessments, and conduct design reviews with students in years 1–4. Nottingham's year 3 design project incorporated two group design reviews supervised by highly experienced chartered engineers with decades of professional experience. The output from all of my design courses is professional front-end engineering design study documentation; and design reviews aim to produce professional quality documents (albeit early-career version).

There are a number of modules which have to be integrated with the process design module for best results, most notably process control, materials, fluid mechanics, and separation processes modules.

I persuaded Nottingham to stop teaching students how to use modeling and simulation programs before year 3, and even then not to allow their use in year 3 projects. I believe strongly that early access to simulation programs has a similar effect on process design ability as access to calculators has on mental arithmetic.

As I said in the last section, this is not a time-efficient approach. It has taken up a lot of my time and a lot of the students' time. But, as I am making them into engineers, I think it is worthwhile for all of us.

## Exercises

I have included in this section the exercises I use in my design teaching. All the courseworks are real plants I (or in one case an associate) have actually designed.

I have not included model solutions, as I recommend this text to my students, and in any case there are no right answers. Even my own design solutions to these problems are not "right answers," as they were based on the state of the art at the time. I would do them differently (and better) today.

[1] https://teammatesv4.appspot.com/ (accessed November 18, 2018).

I have, however, included along with the courseworks my marking criteria (which I give to students along with the question when setting coursework) which explain to both students and lecturers what I am after from the exercises.

1. *Class exercise*—The marshmallow challenge;
2. *Class exercise*—A 5 $m^3$ tank;
3. *Coursework 1*—Ortoire water treatment plant;
4. *Coursework 2*—Alnwick Castle water feature;
5. *Coursework 3*—Upgrading Jellyholm water treatment plant;
6. *Class exercise*—Fun size creativity;
7. *Coursework 4*—Groundwater pilot plant;
8. *Coursework 5*—Supercritical water oxidation plant;
9. *Class exercise*—Pharmaceutical intermediate bulk container (IBC);
10. *Coursework 6*—Pharmaceutical aerosol manufacture.

## Class exercise: The marshmallow challenge

"The task is simple: in eighteen minutes, teams must build the tallest free-standing structure out of 20 sticks of spaghetti, one yard of tape, one yard of string, and one marshmallow. The marshmallow needs to be on top."

See the TED Talk online[2] for details and a supporting video.

A 40″ tower is thought to be the world record, 20″ is average. Use a tape measure calibrated in inches to allow ready comparison with the supporting video.

## Class exercise: a 5 $m^3$ tank

Very early in the course, I used to ask students to give the optimal height to diameter ratio for a tank for liquid with a 5 $m^3$ capacity made of 3 mm thick stainless steel.

Though they knew all the necessary mathematics to solve the problem, they struggled to make the necessary assumptions, and to frame the problem in a way which allows it to be solved using mathematics.

The instructor should not give them clues, or even tell them whether it has an open top or bottom unless asked.

There are very different solutions based on which assumptions are made, and some sets of assumptions, while themselves reasonable, yield no useful mathematical solutions.

Students who complete the exercise should be asked to comment on how many significant figures are meaningful in the answer if 3 mm stainless steel costs £2/$m^2$.

The problem is very useful for demonstrating the difference between engineering and math, and for introducing sensitivity analysis to an audience of mathematically competent engineering incompetents like freshers (or university lecturers).

[2] https://www.ted.com/talks/tom_wujec_build_a_tower?language = en (accessed November 18, 2018).

## Coursework: Ortoire water treatment plant

### *Task*

- Produce, as individuals, a single-tab Excel spreadsheet which shows a rough initial design for a water treatment plant taking 15 megaliters per day (MLD) of water from a river (see Fig. A5.1) at 750 mAOD, passing it through settlement tanks on to pressure sand filters, and from there into a chlorine contact tank to TR60 of 30 min hydraulic residence time (HRT) and 1 m water depth at 575 m above ordnance datum (AOD). Distance from lake to chlorine contact tank (CCT) is 1500 m. Fall on ground is constant along this 1500 m.
- Numbers and diameters for circular settlement tanks and sand filters, external and internal dimensions of CCT, and theoretical and actual pipe diameter sizes will be needed to be calculated as a minimum.
- Produce a single MS Excel file for your group which combines all of your individual submissions, with the submission you have as a group agreed is the best at the front.
- Use your calculated sizes of units to produce a group scale drawing showing as much detail as you can in both plan and elevation.
- Peer assess each other using WebPA.

### *Rules of thumb for design*

- Surface loading settlement tanks 1 m/h;
- HRT settlement tanks 2 hours;
- Maximum diameter settlement tanks 30 m;

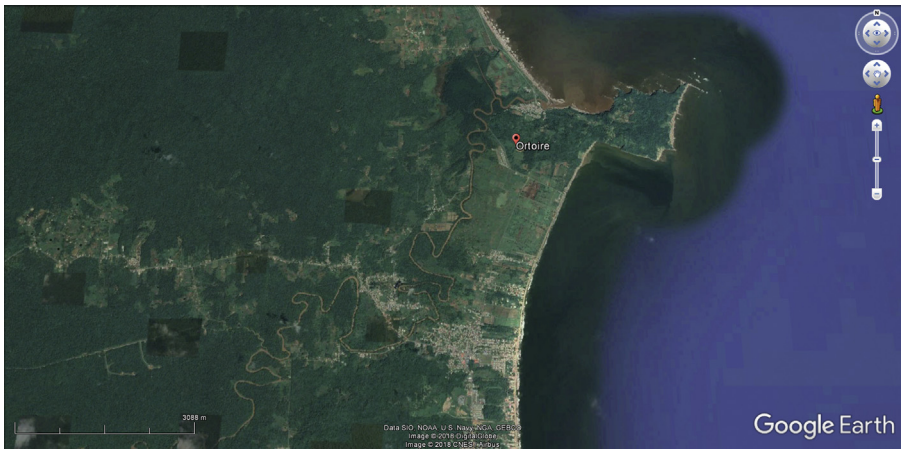



**Figure A5.1** Overhead view of Ortoire area. *Courtesy: Google (2018); Digital Globe (2018); CNS Airbus (2018).*

- Surface loading sand filters 15 m/h;
- Sand filter depth 2 m;
- Maximum diameter sand filters 3 m;
- Static head required for sand filter operation 10 m;
- Superficial velocity pipework 1.5 m/s.

### *TLAs (Three-Letter Acronyms(!)*

- *AOD*—above ordnance datum;
- *HRT*—hydraulic residence time;
- *CCT*—chlorine contact tank;
- *MLD*—megaliters per day.

### *Learning outcomes*

- D1: Define a problem and identify constraints.
- D2: Design solutions according to customer and user needs.
- S1: Knowledge and understanding of commercial and economic context of chemical/environmental engineering processes.
- P1: Understanding of and ability to use relevant materials, equipment, tools, processes, or products.
- P5: Ability to use appropriate codes of practice and industry standards.
- P8: Ability to work with technical uncertainty.

### *Assessment criteria*

- Apply British Standards;
- Size unit operations via rules of thumb;
- Undertake hydraulic calculations;
- Produce appropriate plant layout drawing (plan and elevation).

### *Grading criteria*

| **ALL assessment criteria passed to a satisfactory level** | **3RD** |
|---|---|
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of some analysis. Integrate into system design and produce a drawing to BS that clearly shows design intent. | 2:2 |
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of detailed analysis. Integrate into system design and produce a drawing to BS that clearly shows design intent. Cost, safety, and robustness are considered. | 2:1 |
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of critical analysis. Integrate into system design and produce a detailed drawing to BS that clearly shows design intent. Cost, safety, and robustness are analyzed. | 1ST |

### *Teaching notes*

You can make the exercise harder by specifying the quantity of water produced rather than the quantity input, requiring an iterative solution to the mass balance.

## Coursework: Alnwick Castle water feature

You have been engaged to provide hydraulic and process design of a new water feature at Alnwick Castle by Expertise Limited, on behalf of the Duchess of Northumbria.

Your responsibility is to make sure that the water in the feature is suitably treated, and that the required effects are achieved.

The drawing provided (Fig. A5.2) shows the Grande Cascade, which is the centerpiece of the gardens. Hidden underneath the cascade are the plant rooms containing the pumps and treatment plant which make the feature work. Your job is to design the required plant and pumps, and fit them into the plant rooms.

You need to submit your calculations as an Excel spreadsheet, a piping and instrumentation diagram (P&ID), and a modified version of the GA provided [note that all working water levels are to be marked on the general arrangement (GA)], along with manufacturers' datasheets for any equipment used.

The Water Features Design Manual provided should facilitate your design, but additional marks are valuable for a more sophisticated approach. (I wrote the design guide to allow plumbers to design water features—I expect more from you.)

### *Learning outcomes*

- D1: Define a problem and identify constraints.
- D2: Design solutions according to customer and user needs.
- S1: Knowledge and understanding of commercial and economic context of chemical/environmental engineering processes.

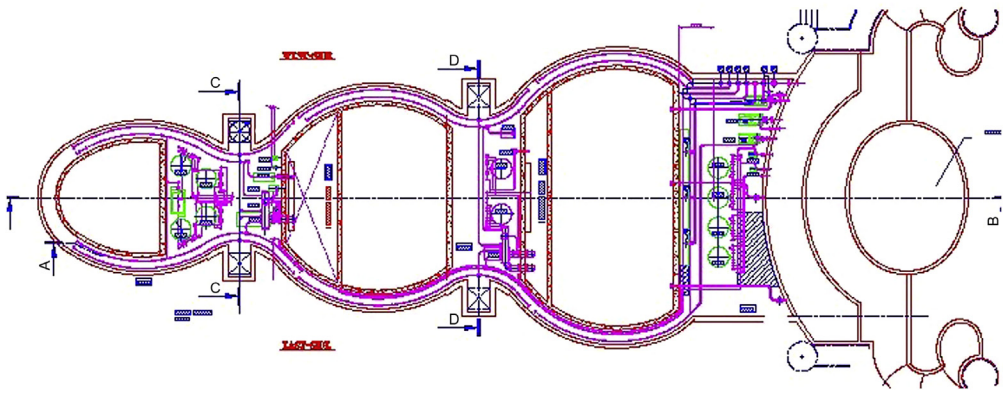



**Figure A5.2** Alnwick Castle: Grande Cascade. *Courtesy: Expertise Limited.*

- P1: Understanding of and ability to use relevant materials, equipment, tools, processes, or products.
- P5: Ability to use appropriate codes of practice and industry standards.
- P8: Ability to work with technical uncertainty.

### *Assessment criteria*

- Apply British Standards;
- Size unit operations via rules of thumb;
- Undertake hydraulic calculations;
- Produce appropriate plant layout drawing (plan and elevation);
- Produce P&ID.

### *Grading criteria*

| ALL assessment criteria passed to a satisfactory level | 3RD |
|---|---|
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of some analysis. Integrate into system design and produce drawings to BS that clearly show design intent. | 2:2 |
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of detailed analysis. Integrate into system design and produce a drawing to BS that clearly shows design intent. Cost, safety, and robustness are considered. | 2:1 |
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of critical analysis. Integrate into system design and produce detailed drawings to BS that clearly show design intent. Cost, safety, and robustness are analyzed. | 1ST |

### *Teaching notes*

Students will be able to find out quite a lot of data on this real project on the internet. A good solution will involve taking publicly available data on flows and appearance and flowrates calculated in a number of ways to size the pumps and treatment plant.

## Coursework: upgrading Jellyholm water treatment plant

### *Scenario: Jellyholm water treatment works*

The Jellyholm water treatment plant (Fig. A5.3) in Sauchie (FK10 3AZ; Fig. A5.4) is fed with water from the nearby Gartmorn reservoir (Grid Ref NS 92000 94200). The reservoir is subject to periodic algal blooms, and you have been commissioned to upgrade the plant to handle these.

The plant feeds housing which has lead piping, and orthophosphate dosing is to be provided to prevent lead dissolving into the drinking water on its way to supply.

The assignment is to carry out as detailed a design as you can of an upgrade to the treatment works. You can if you wish follow what was done as shown on the case study document, or you can offer an alternative approach.

**Figure A5.3** Jellyholm water treatment works. *Courtesy: Doosan Enpure.*

**Figure A5.4** Sauchie area. *Courtesy: Google (2018); Getmapping plc (2018).*

### *Deliverables*

- P&ID;
- GA;
- Hydraulic calculations, from dam to treated water tank;
- Process design calculations including mass balance;
- Control philosophy;
- Approximately 2000-word proposal for your plant upgrade including capital and running cost estimate, and justification of design choices;
- WebPA assessment of yourself and fellow group members.

For avoidance of doubt:

All drawings are to be in AutoCAD format. All spreadsheets are to be in MS Excel. Report in MSWord. Your drawings should be to British Standards. They should be neat, clear, and accurate. Your report should also be neat, clear, concise, and accurate.

If you don't understand any part of this assignment, ask me to explain. If you cannot see how to do some or all of the task set, ideally you would ask among your group first, then see if you can find the answer by research, then ask me.

Learning outcomes

D1: Define a problem and identify constraints.

D2: Design solutions according to customer and user needs.

S1: Knowledge and understanding of commercial and economic context of chemical/environmental engineering processes.

P1: Understanding of and ability to use relevant materials, equipment, tools, processes, or products.

P5: Ability to use appropriate codes of practice and industry standards.

P8: Ability to work with technical uncertainty.

### *Assessment criteria*

- Apply British Standards;
- Size unit operations via rules of thumb;
- Undertake mass balance and hydraulic calculations;
- Produce appropriate plant layout drawing (plan and elevation);
- Produce P&ID;
- Produce proposal;
- Produce control philosophy.

### *Grading criteria*

| **ALL assessment criteria passed to a satisfactory level** | **3RD** |
|---|---|
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of some analysis. Integrate into system design and produce drawings to BS that clearly show design intent. Produce control philosophy which explains control system design intent. Produce proposal document which explains all proposed refurbishments. | 2:2 |
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of detailed analysis. Integrate into system design and produce a drawing to BS that clearly shows design intent. Produce control philosophy which clearly explains control system design intent, and adequately considers most common system disturbances. Produce proposal document which clearly explains all proposed refurbishments. Cost, safety, and robustness are considered. | 2:1 |
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of critical analysis. Integrate into system design and produce detailed drawings to BS that clearly show design intent. Produce control philosophy which clearly explains control system design intent and adequately considers many system disturbances. Produce proposal document which clearly explains all proposed refurbishments. Cost, safety, and robustness are analyzed. | 1ST |

## Coursework: groundwater pilot plant

A temporary groundwater treatment plant has been running for some time at a railway location (Fig. A5.5), and it is time to propose a permanent replacement. A pilot trial has been undertaken to see if alternative technologies to that used for the temporary plant are viable.

Using the temporary and pilot plant data provided, choose a suitable mixture of technologies, and produce a conceptual design with GA and P&ID appropriate to the site shown on the drawing provided.

It should be noted that the approach used on the real plant may not be the optimal one based on the data provided to you.

### *Deliverables*

- Excel spreadsheet with as a minimum mass balance, unit operation sizing, and hydraulic calculations.
- AutoCAD general arrangement drawing.
- AutoCAD P&ID.

### *Learning outcomes*

- D1: Define a problem and identify constraints.
- D2: Design solutions according to customer and user needs.
- S1: Knowledge and understanding of commercial and economic context of chemical/environmental engineering processes.
- P1: Understanding of and ability to use relevant materials, equipment, tools, processes, or products.

**Figure A5.5** Site of temporary groundwater treatment plant. *Courtesy: Google (2018); Infoterra and& Bluesky (2018).*

- P5: Ability to use appropriate codes of practice and industry standards.
- P8: Ability to work with technical uncertainty.

### *Assessment criteria*

- Apply British Standards;
- Analyze data provided to choose technologies;
- Size unit operations via rules of thumb;
- Undertake hydraulic calculations;
- Produce appropriate plant layout drawing (plan and elevation);
- Produce P&ID.

### *Grading criteria*

| ALL assessment criteria passed to a satisfactory level | 3RD |
|---|---|
| Produce Excel spreadsheet which analyzes data, sizes unit operations and pipework with evidence of some analysis. Integrate into system design and produce drawings to BS that clearly show design intent. | 2:2 |
| Produce Excel spreadsheet which analyses data, sizes unit operations and pipework with evidence of detailed analysis. Integrate into system design and produce drawings to BS that clearly show design intent. Show how cost, safety, and robustness have been considered. | 2:1 |
| Produce Excel spreadsheet which analyzes data, sizes unit operations and pipework with evidence of critical analysis. Integrate into system design and produce detailed drawings to BS that clearly show design intent. Show how cost, safety, and robustness have been analyzed. | 1ST |

## Class exercise: fun-size creativity

After a short lecture on creative systems including the McMaster 5-point strategy, students are invited to solve a problem which proved very difficult in practice—producing "fun size" Mars bars. The problem is that the Mars bar filling sticks to the blades used to cut up the large sheet it is made from into "fun-size" pieces.

## Coursework: supercritical water oxidation plant

### *Task*

Produce, as individuals, multitab MS Excel spreadsheets which show a rough initial design for a supercritical water oxidation nanoparticle production plant (Fig. A5.6) comprising as a minimum the following elements, as shown on the process flow diagram (PFD) supplied:

- 1 No. DI water stock tank, dosing pump, and valves delivering up to 3 $m^3$/h;
- 1 No. hydrogen peroxide stock tank, dosing pump(s), and valves delivering up to 1 $m^3$/h;

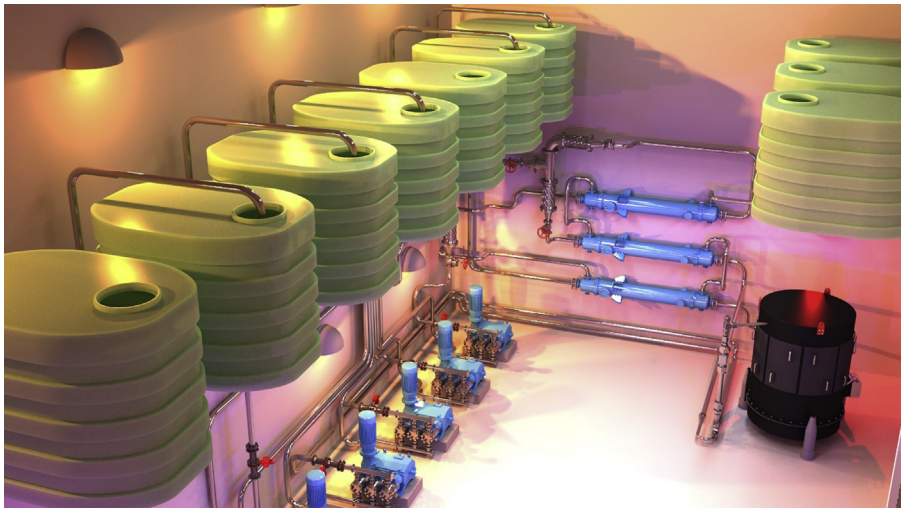


**Figure A5.6** 3D CAD-rendered image of a supercritical water oxidation plant[3]. *Courtesy: Thomas Huddle, Shyman Project.*

- 1 No. metal salt 1 stock tank, dosing pump(s), and valves delivering up to 1.5 $m^3$/h;
- 1 No. metal salt 2 stock tank, dosing pump(s), and valves delivering up to 1 $m^3$/h;
- 1 No. capping agent stock tank, dosing pump(s), and valves delivering up to 1 $m^3$/h;
- 1 No. electrical process heater;
- 1 No. preheat heat exchanger;
- 1 No. reactor;
- 1 No. energy recovery heat exchanger;
- 1 No. postfilter;
- 2 No. cooling water pumps each delivering 6.5 $m^3$/h;
- Cooling tower;
- Cooling water filter.

### *Notes to the deliverables*

- The sizes of these elements and actual pipe diameters will be needed to be calculated as a minimum.
- Produce a single Excel file for your group which combines all of your individual submissions, with the submission you have as a group agreed is the best at the front.
- Use your calculated sizes of units to produce individual scale drawings (GA) showing as much detail as you can in both plan and elevation, choose one to represent the group, and submit all as a single file with the chosen submission clearly marked.

[3] www.shyman.eu (accessed November 18, 2018).

- Produce an individual P&ID showing as much detail as you can, choose one to represent the group, and submit all as a single file with the chosen submission clearly marked.
- Peer assess each other using WebPA.

### *Learning outcomes*

- D1: Define a problem and identify constraints.
- D2: Design solutions according to customer and user needs.
- S1: Knowledge and understanding of commercial and economic context of chemical/environmental engineering processes.
- P1: Understanding of and ability to use relevant materials, equipment, tools, processes, or products.
- P5: Ability to use appropriate codes of practice and industry standards.
- P8: Ability to work with technical uncertainty.

### *Assessment criteria*

- Apply British Standards;
- Size unit operations via rules of thumb;
- Undertake mass and energy balance and hydraulic calculations;
- Produce appropriate plant layout drawing (plan and elevation);
- Produce P&ID.

### *Grading criteria*

| ALL assessment criteria passed to a satisfactory level | 3RD |
|---|---|
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of some analysis. Integrate into system design and produce drawings to BS that clearly show design intent. | 2:2 |
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of detailed analysis. Integrate into system design and produce a drawing to BS that clearly shows design intent. Cost, safety, and robustness are considered. | 2:1 |
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of critical analysis. Integrate into system design and produce detailed drawings to BS that clearly show design intent. Cost, safety, and robustness are analyzed. | 1ST |

## Class exercise: pharmaceutical intermediate bulk container

You are considering the design of a new dispensary for a solid dose facility. Table A5.1 gives the formulation to be dispensed into IBCs within the dispensary.

Fig. A5.7 gives the typical dimensions of the IBC that the client wishes to use. The dimensions shown are fixed and cannot be changed. This configuration is based

**Table A5.1** Formulation data.

| Material | Quantity to be added (kg) | Bulk density (kg/L) | Occupation exposure limit |
|---|---|---|---|
| Lactose mono SDS | 45.0 | 0.625 | 10 mg/m$^3$ |
| Lactose | 220.0 | 0.625 | 10 mg/m$^3$ |
| Hydroxy cellulose | 15.0 | 0.500 | 10 mg/m$^3$ |
| Carboxy methyl cellulose | 23.0 | 0.500 | 10 mg/m$^3$ |
| Micronized active ingredient | 30.0 | 0.150 | 5 μg/m$^3$ |

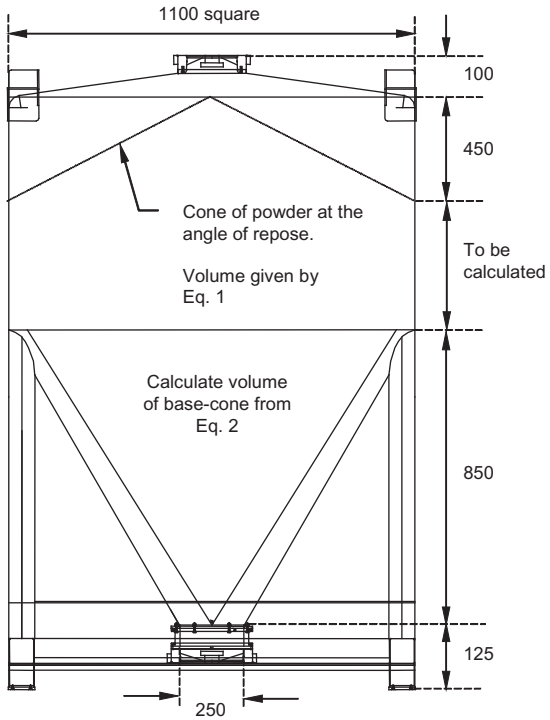



**Figure A5.7** IBC dimensions.

on filling the IBC so that the top of the repose-cone of powder does not go any higher than the top of the straight section of the IBC. Calculate the length of straight side shown and hence the overall height of the IBC. Show your working and assumptions.

### *Teaching notes*

This is like a more sophisticated version of the 5 m$^3$ tank exercise, which I give to second-year and MSc students as a preparation for coursework 6. Even if you give

them the formulae and simplifying assumptions below, they tend to make quite heavy weather of it.

It can be interesting to use figures rounded to 2–3 significant figures at the start of the exercise, to illustrate the problems of premature rounding.

The volume of the repose-cone can be calculated from:

$$\text{Volume} = 1/3(\text{Base Area} \times \text{Height}) \tag{A5.1}$$

The volume of the base-cone of the IBC can be calculated from:

$$\text{Volume} = 1/3(A_1 + A_2 + \sqrt{(A_1 \times A_2)} \times \text{Height}) \tag{A5.2}$$

where $A_1$ is the cross-sectional area of the top of the base-cone and $A_2$ is the cross-sectional area of the bottom of the base-cone. Assume that the bottom of the base-cone has a square cross-section and ignore the transition to the circular outlet. Also assume that this square has the same length and breadth as the outlet valve diameter.

## Coursework: pharmaceutical aerosol manufacture

### *General requirements*

| No. | Description | Acceptance criteria |
|---|---|---|
| 1. | Product contact surfaces—metallic materials of construction | Stainless steel type EN 1.4435 |
| 2. | Product contact surfaces—polymeric materials | PTFE or PVDF compliant with ASME BPE 2012 Part PM |
| 3. | Product contact surfaces—elastomeric materials | Perfluorelastomer, silicone, or PTFE encapsulated EPDM compliant with ASME BPE 2012 Part PM |
| 4. | Product contact surfaces—metallic materials surface condition | Compliant with ASME BPE 2012 Table SF-2.2-1 |
| 5. | Product contact surfaces—metallic materials surface finish | Electro-polished to 0.38 μm. Compliant with ASME BPE Table SF-2.4-1 |
| 6. | Product contact surfaces—nonmetallic materials surface condition | Compliant with ASME BPE 2012 Table SF-3.3-1 |
| 7. | Material certificate of compliance | EN 10204 Type 3.1 |
| 8. | Product contact piping | OD hygienic tubing—True imperial dimensions |
| 9. | Product piping couplings | Hygienic union couplings compliant with EN 11864 |
| 10. | Product contact liquids and clean steam—valves | Weir-type diaphragm compliant with ASME BPE SG-2.3.1.2 |

*Note*: Product contact surfaces include all clean utilities downstream of the final sterilizing grade filter, propellant downstream of the final sterilizing grade filter, and clean in place systems.

### *Dispensary operations*

| No. | Description | Acceptance criteria |
|---|---|---|
| 1. | Active ingredient maximum water content | 2% w/w |
| 2. | Active ingredient maximum ethanol content | 1% w/w |
| 3. | Active ingredient drying time | 15 h maximum |
| 4. | Active ingredient dryer end point | 80°C at 20 mbar abs |
| 5. | Active ingredient dryer yield | >98% mass basis |
| 6. | Active ingredient median particle size | 2 μm mass basis |
| 7. | Active ingredient milling yield | >98% mass basis |
| 8. | Active ingredient CIP fluid | Purified water BP |
| 9. | Active ingredient CIP fluid flow | 35 L/min/m of vessel circumference with a static spray device |
| 10. | Active ingredient CIP final rinse liquid. | Purified water BP |
| 11. | Active ingredient dispensing accuracy | ± 0.1% mass basis |
| 12. | Excipient dispensing accuracy | ± 0.5% mass basis |
| 13. | Lubricant maximum water content | 1% w/w |
| 14. | Sweetener maximum water content | 0.5% w/w |
| 15. | Flavor maximum water content | 0.5% w/w |

### *Propellant storage and distribution*

| No. | Description | Acceptance criteria |
|---|---|---|
| 1. | Design pressure—maximum | Vapor pressure at maximum design temperature plus 1 bar g |
| 2. | Design pressure—minimum | Full vacuum |
| 3. | Design temperature—maximum | 50°C |
| 4. | Design temperature—minimum | −20°C |
| 5. | Tank capacity | Tanker load plus 5000 L |
| 6. | Temperature of propellant transferred to manufacturing | 20°C ± 1°C |
| 7. | Transfer rate to manufacturing | To take no more than 20 min |
| 8. | Level indication accuracy | ± 1% |
| 9. | Pressure relief requirements | Duplex pressure relief valve |
| 10. | Pump head | Static head 10 m<br>Piping equivalent length 300 m<br>Heat exchanger pressure drop max 0.5 bar |
| 11. | Pump NPSH | To avoid cavitation at all times |

| | | |
|---|---|---|
| 12. | Piping upstream of sterilizing filter—metallic material | Stainless steel type EN 1.4404 |
| 13. | Pump mechanical seal | Sealless magnetic seal |
| 14. | Piping upstream of sterilizing filter—nonmetallic material | PTFE or EPDM |
| 15. | Piping upstream of sterilizing filter—piping standard | Flanged to BS 4504 |
| 16. | Piping upstream of sterilizing filter—valves | Flanged ball valves |
| 17. | Propellant filtration | Prefilter 5 μm, final filter 0.2 μm sterilizing grade filter |

### *Formulation*

| No. | Description | Acceptance criteria |
|---|---|---|
| 1. | Design pressure maximum | Vapor pressure at maximum design temperature plus 1 bar g |
| 2. | Design pressure minimum | Full vacuum |
| 3. | Design temperature maximum | 100°C |
| 4. | Design temperature minimum | −20°C |
| 5. | Maximum batch size | 1000 L |
| 6. | Minimum batch size | 500 L |
| 7. | Vessel nominal volume | To the top of the heat transfer surface |
| 8. | Vessel minimum stirred volume | 50 L maximum. Batch shall remain homogeneous at minimum stirred volume |
| 9. | Formulation temperature | 20°C ± 1°C |
| 10. | Dispersion time | 10 min at 400 rpm |
| 11. | Mixing requirement | To achieve full suspension<br>To achieve efficient heat transfer |
| 12. | Heating requirement | Hold at 20°C during formulation and can filling<br>Hold at 80°C during CIP and drying |
| 13. | Cooling requirement | Cool to 20°C after drying in 30 min |
| 14. | In-place cleaning fluid | 2% w/w NaOH in purified water BP |
| 15. | In-place cleaning final rinse | Purified water BP |
| 16. | In-place cleaning temperature | 80°C ± 1°C |
| 17. | In-place cleaning fluid flow | 35 L/min/m of vessel circumference with a static spray device |
| 18. | Heat transfer method | External dimpled jacket covering shell and bottom head |
| 19. | Maximum pressure drop through heat transfer jacket | 0.5 bar g |
| 20. | Maximum variation of propellant concentration during can filling | ± 1% of propellant concentration |

| | | |
|---|---|---|
| 21. | Maximum water concentration in final formulation | 0.5% w/w |
| 22. | Maximum oxygen concentration in final formulation | 0.1% w/w |
| 23. | Maximum nitrogen concentration in final formulation | 0.1% w/w |
| 24. | Vessel drainability | Fully drainable with no pools greater than 5 mm diameter after draining |
| 25. | Mixing dead spots | No mixing dead spots, vessel surface shall be flush below the liquid level including the bottom outlet |

### *Can filling*

| No. | Description | Acceptance criteria |
|---|---|---|
| 1. | Can purge | 2 can volumes minimum |
| 2. | Filling temperature | 20°C ± 1°C |
| 3. | Filling rate | 30 cans per minute |
| 4. | Rejects | 2% maximum |
| 5. | Samples | 1 per 1000 cans |
| 6. | Overspray after filling head removed | 1 off can valve capacity |
| 7. | Function testing | 3 valve actuations |
| 8. | Maximum air concentration in suspension in the can | 1% w/w |
| 9. | Maximum water content in the suspension in the can | 1% w/w |
| 10. | Operating shift pattern | 3 shifts per day<br>Start Monday 6 p.m.<br>Finish Friday 10 p.m. |
| 11. | Formulation maximum hold time | 40 h |
| 12. | Air extraction rate each can filling booth | 1000 $Nm^3/h$ |
| 13. | Air extraction rate each function tester | 1000 $Nm^3/h$ |

### *Deliverables*

- Full mass balance and energy balance;
- Preparation of detailed PFD covering the whole process (see Fig. A5.8 for a starting point);
- Detailed P&ID to industry standards covering equipment in group in No. 3 above;
- Equipment sizing for all components;
- GA.

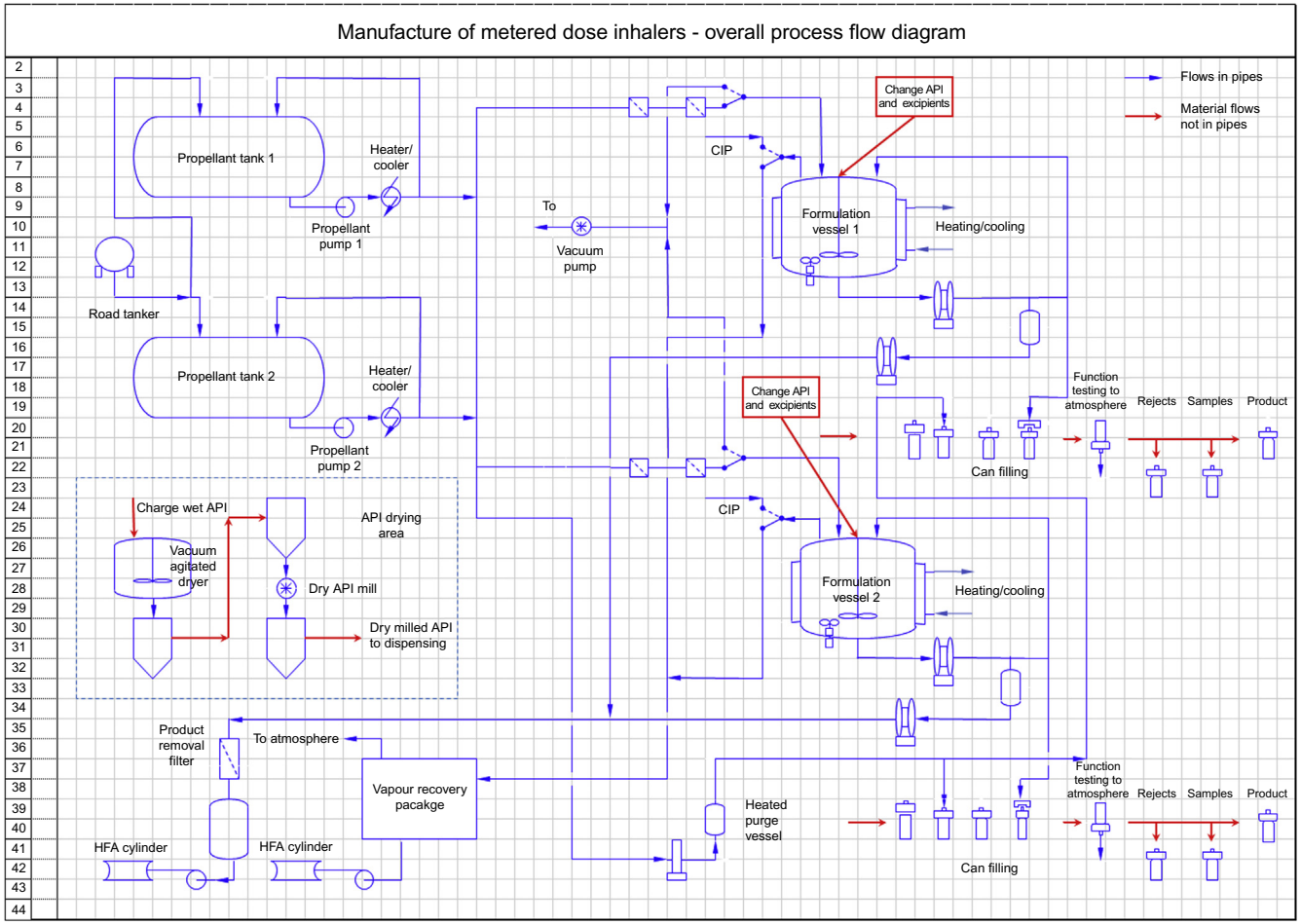



**Figure A5.8** Manufacture of metered dose inhalers: overall process flow diagram. *Courtesy: Keith Plumb.*

### *Equipment sizing should include*

- Operational size, for example, L, L/min, kW, etc.;
- Design capacity as above but with design margin added;
- Approximate physical dimensions;
- Materials of construction;
- Design pressure;
- Motor power;
- NPSH for pumps, etc.

Complete industry standard data sheet for the formulation vessel, homogenizer, and agitator.

Blank data sheet to be provided.

### *Learning outcomes*

D1: Define a problem and identify constraints.

D2: Design solutions according to customer and user needs.

S1: Knowledge and understanding of commercial and economic context of chemical/environmental engineering processes.

P1: Understanding of and ability to use relevant materials, equipment, tools, processes, or products.

P5: Ability to use appropriate codes of practice and industry standards.

P8: Ability to work with technical uncertainty.

### *Assessment criteria*

- Apply British Standards;
- Size unit operations via rules of thumb;
- Undertake mass and energy balance and hydraulic calculations;
- Produce appropriate plant layout drawing (plan and elevation);
- Produce P&ID.

### *Grading criteria*

| **ALL Assessment Criteria passed to a satisfactory level** | **3RD** |
|---|---|
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of some analysis. Integrate into system design and produce drawings to BS that clearly show design intent. | 2:2 |
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of detailed analysis. Integrate into system design and produce a drawing to BS that clearly shows design intent. Cost, safety, and robustness are considered. | 2:1 |
| Produce Excel spreadsheet which sizes unit operations and pipework with evidence of critical analysis. Integrate into system design and produce detailed drawings to BS that clearly show design intent. Cost, safety, and robustness are analyzed. | 1ST |

## Further Reading


Biggs, J. B. (2003). *Teaching for quality learning at university* (2nd ed.). Buckingham: Open University Press/ Society for Research into Higher Education.

Brennan, J. (2010). Scepticism about philosophy. *Ratio*, *23*(1), 1–16.

Cross, N. (1982). Designerly ways of knowing. *Design Studies*, *3*(4), 221–227.

Cross, N. (2006). *Designerly ways of knowing*. New York, NY: Springer US.

Gordon, N. A. (2010). Group working and peer assessment—Using WebPA to encourage student engagement and participation. *Innovation in Teaching and Learning in Information and Computer Sciences*, *9*(1), 20–31.

Hattie, J. (2009). *Visible learning; A synthesis of over 800 meta-analyses relating to achievement*. London: Routledge.

Loddington, K., Pond, K., Wilkinson, N., & Willmot, P. (2009). A case study of the development of WebPA: An online peer-moderated marking tool. *British Journal of Educational Technology*, *40*(2), 329–341.

Mann, K., Gordon, J., & MacLeod, A. (2007). Reflection and reflective practice in health professions education: A systematic review. *Advances in Health Sciences Education*, *14*(4), 595–621.

Marzano, R. J. (1998). *A theory-based meta-analysis of research on instruction*. Aurora, CO: Mid-continent Research for Education and Learning.

Moran, S. (2013). Experience: The father of wisdom. The Chemical Engineer, October 2013.

Moran, S. (2014). When models fail. The Chemical Engineer, June 2014.

Moran, S. (2015b). Could do better. Unpublished.

Moran, S. (2016a). Chemical plant design and construction. In B. Elvers (Ed.), *Ullmann's encyclopedia of industrial chemistry*. Weinheim: Wiley-VCH.

Moran, S. (2017d). Understanding the basics of industrial effluent treatment. *Chemical Engineering Progress*, *113*(3), 39–43.

Moran, S., & Gräfen, H. (2016). Construction materials in the chemical industry. In B. Elvers (Ed.), *Ullmann's encyclopedia of industrial chemistry*. Weinheim: Wiley-VCH.

Moran, S., & Henkel, K.-D. (2016). Reactor types and their industrial applications. In B. Elvers (Ed.), *Ullmann's encyclopedia of industrial chemistry*. Weinheim: Wiley-VCH.

Moran, S., & Zlokarnik, M. (2017). Scale-up in chemical engineering. In B. Elvers (Ed.), *Ullmann's encyclopedia of industrial chemistry*. Weinheim: Wiley-VCH.

Moran, S., Dhafr, N., & Ahmad, M. (2017). Chemical plants: Performance measurement of processes. In B. Elvers (Ed.), *Ullmann's encyclopedia of industrial chemistry*. Weinheim: Wiley-VCH.

Moran, S., Middleton, J. C., & Carpenter, K. J. (2017). Loop reactors. In B. Elvers (Ed.), *Ullmann's encyclopedia of industrial chemistry*. Weinheim: Wiley-VCH.

Nicol, D., & Macfarlane-Dick, D. J. (2006). Formative assessment and self-regulated learning: A model and seven principles of good feedback practice. *Studies in Higher Education*, *31*(2), 199–218.

Orsmond, P. (2004). *Self- and peer-assessment: Guidance on practice in the biosciences*. Teaching bioscience: Enhancing learning series. Leeds: Higher Education Academy Centre for Bioscience.

Strivens, J. (2007). What theory should we use—If any? Interpreting "scholarship" on programs for new university teachers. *PRIME*, *2*(2), 81.

The Worldwide CDIO Initiative. (2018). Online. Available from <http://www.cdio.org/> Accessed 18.11.18.

United Kingdom, Ministry of Justice. (2017). Practice direction 35—Experts and assessors. Available from <https://www.justice.gov.uk/courts/procedure-rules/civil/rules/part35/pd_part35> Accessed 23.04.18.

# Appendix 6: Consolidated design codes and standards

## Introduction

This appendix includes a small number of obsolete and withdrawn standards which are still commonly quoted in a process plant design context. These are shown crossed through, marked with their current status and, where applicable, the current equivalent standard which has superseded them is provided. Whilst the status of the codes and standards listed below was accurate at the time of writing, many are updated on a regular cycle whilst others are withdrawn or replaced. Readers are therefore advised to check with the issuing organization that the codes and standards listed here are still the most current.

## International codes and standards

### International Standards Organization (ISO)

| | | |
|---|---|---|
| ISO 1819 | Continuous mechanical handling equipment—Safety code—General rules | 1977 |
| ISO 2954 | Mechanical vibration of rotating and reciprocating machinery. Requirements for instruments for measuring vibration severity | 2012 |
| ISO 3977-3 | Gas turbines—Procurement: Design requirements | 2004 |
| ISO 3103 | Tea—Preparation of liquor for use in sensory tests | 1980 |
| ISO 5048 | Continuous mechanical handling equipment—Belt conveyors with carrying idlers—Calculation of operating power and tensile forces | 1989 |
| ISO 5657 | Reaction to fire tests. Ignitability of building products using a radiant heat source | 1997 |
| ISO 5660-1 | Reaction to fire tests. Heat release, smoke production and mass loss rate. Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement) | 2015 |
| ISO 6944 | Fire containment. Elements of building construction. ventilation | 1985 |
| ISO 6944-1 Ed 1 | ducts | 2008 |
| ISO 7119 | Continuous mechanical handling equipment for loose bulk materials—Screw conveyors—Design rules for drive power | 1981 |
| ISO 9000 | Quality management systems: Fundamentals and vocabulary | 2015 |
| ISO 9001 | Quality management systems: Requirements | 2015 |
| ISO 10437 | Petroleum, petrochemical and natural gas industries—Steam turbines—Special-purpose applications | 2003 |
| ISO 10816-1 | Mechanical vibration. Evaluation of machine vibration by measurements on non-rotating parts. General guidelines | 1995 |
| ISO 13705 | Petroleum, petrochemical and natural gas industries—Fired heaters for general refinery service | 2012 |
| ISO 13709 | Centrifugal pumps for petroleum, petrochemical and natural gas industries | 2009 |

| | | |
|---|---|---|
| ISO 14040 | Life cycle assessment: principles and framework | 2006 |
| ISO 14122 | Permanent Machinery—Permanent means of access to machinery | |
| ISO 14122-1 | Part 1: Choice of fixed means of access between two levels | 2001 |
| ISO 14122-2 | Part 2: Working platforms and walkways | 2001 |
| ISO 14122-3 | Part 3: Stairs, stepladders and guard-rails | 2001 |
| ISO 14122-4 | Part 4: Fixed ladders | 2004 |
| ISO 14661 | Thermal turbines for industrial applications (steam turbines, gas expansion turbines)—General requirements | 2000 |

## International Code Council (ICC)

| | |
|---|---|
| 2015 | International Fuel Gas Code |

## European law and standards

### European legislation

| | | |
|---|---|---|
| 92/57/EEC | Temporary or mobile construction sites | 1992 |
| 94/9/EC | Equipment and protective systems intended for use in potentially explosive atmospheres ("ATEX" Directive) | 1994 |
| 97/23/EC | Pressure equipment directive | 1997 |
| 99/92/EC | Minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres | 1999 |
| 2012/18/EU | Control of major-accident hazards involving dangerous substances ("Seveso III" Directive) | 2012 |
| 2014/34/EU | Equipment and protective systems intended for use in potentially explosive atmospheres (recast) ("ATEX" Directive) | 2014 |

## Euronorm (EN) standards

| | | |
|---|---|---|
| EN 618 | Continuous handling equipment and systems. Safety and EMC | 2002 |
| +A1 | requirements for equipment for mechanical handling of bulk materials except fixed belt conveyors | 2010 |
| EN 620 | Continuous handling equipment and systems. Safety and EMC | 2002 |
| +A1 | requirements for fixed belt conveyors for bulk materials | 2010 |
| EN 858-1 | Separator systems for light liquids (e.g. oil and petrol). Principles of product design, performance and testing, marking and quality control | 2002 |

| | | |
|---|---|---|
| EN 858-2 | Separator systems for light liquids (e.g. oil and petrol). Selection of nominal size, installation, operation and maintenance | 2003 |
| EN 1012-1 | Compressors and vacuum pumps. Safety requirements. Air compressors | 2010 |
| EN 1092-1 | Flanges and their joints. Circular flanges for pipes, valves, fittings and accessories, PN designated. Steel flanges | 2007 |
| EN 1092-1 + A1 | | 2013 |
| EN 1127-1 | Explosive atmospheres. Explosion prevention and protection. Basic concepts and methodology | 2011 |
| EN 1539 | Dryers and ovens in which flammable substances are released. Safety requirements | 2015 |
| EN 1759-1 | Flanges and their joints. Circular flanges for pipes, valves, fittings and accessories, class-designated. Steel flanges, NPS 1/2 to 24 | 2004 |
| EN ISO 9001 | Quality management systems. Requirements | 2015 |
| EN ISO 10628-1 | Diagrams for the chemical and petrochemical industry. | |
| EN ISO 10628-2 | —Part 1: Specifications of diagrams | 2014 |
| | —Part 2: Graphical symbols | 2012 |
| EN 12285-1 | Workshop fabricated steel tanks. Horizontal cylindrical single skin and double skin tanks for the underground storage of flammable and non-flammable water polluting liquids | 2003 |
| EN 12285-2 | Workshop fabricated steel tanks. Horizontal cylindrical single skin and double skin tanks for the aboveground storage of flammable and non-flammable water polluting liquids | 2005 |
| EN 12547 | Centrifuges. Common safety requirements | 2014 |
| EN 13121-3 | GRP tanks and vessels for use above ground. Design and workmanship | 2008 |
| + A1 | | 2010 |
| EN 13445 | Unfired Pressure Vessels (series) | 2014- |
| EN 13480-3 | Metal Industrial Piping. Design and calculation | 2012 |
| EN 13480 series | Metal industrial piping | 2012- |
| EN ISO 13857 | Safety of machinery. Safety distances to prevent hazard zones being reached by upper and lower limbs | 2008 |
| EN 13923 | Filament-wound FRP pressure vessels. Materials, design, manufacturing and testing | 2005 |
| EN 14015 | Specification for the design and manufacture of site built, vertical, cylindrical, flat-bottomed, above ground, welded, steel tanks for the storage of liquids at ambient temperature and above | 2004 |
| EN 14129 | LPG equipment and accessories. Pressure relief valves for LPG pressure vessels | 2014 |
| EN 14491 | Dust explosion venting protective systems (Incorporates VDI 3673) | 2012 |
| EN 14620 series | Design and manufacture of site built, vertical, cylindrical, flat-bottomed steel tanks for the storage of refrigerated, liquefied gases with operating temperatures between 0°C and −165°C | 2006 |
| EN 60079 series | Hazardous area classification | Various |
| EN 60079-14 | Explosive atmospheres. Electrical installations design, selection and erection | 2014 |

## Other European codes, standards and guidance

| | | |
|---|---|---|
| GEST 79/82 | Euro-Chlor, *Materials of construction for use in contact with chlorine*, Version 11 | 2013 |

## British codes and standards

### Statutory regulations

| | | |
|---|---|---|
| 1997 | No. 1713 | The Confined Spaces Regulations |
| 1998 | No. 2306 | The Provision and Use of Work Equipment Regulations |
| 1998 | No. 2307 | The Lifting Operations and Lifting Equipment Regulations (LOLER) |
| 1999 | No. 2001 | The Pressure Equipment Regulations |
| 2000 | No. 128 | The Pressure Systems Safety Regulations |
| 2002 | No. 2677 | The Control of Substances Hazardous to Health (COSHH) Regulations |
| 2002 | No. 2776 | The Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) |
| 2015 | No. 51 | The Construction (Design and Management) Regulations |
| 2015 | No. 483 | The Control of Major Accident Hazards (COMAH) Regulations |

### Health and Safety Executive (HSE)

| | | |
|---|---|---|
| CRR285/2000 | Thermal radiation criteria for vulnerable populations | 2000 |
| CS 2 | The storage of highly flammable liquids | 1977 |
| ~~CS 5~~ | ~~Storage and use of LPG at fixed installations~~ *(N.B.: now obsolete but still commonly cited)* | ~~nd~~ |
| CS 15 | The cleaning and gas freeing of tanks containing flammable residues | 1997 |
| CS 21 | Storage and handling of organic peroxides | 1991 Amends. 1998 |
| EH 40 | Workplace exposure limits | 2005 |
| EH 70 | The control of fire-water run-off from CIMAH sites to prevent environmental damage | 1995 |
| FIS 25 | Safeguarding flat belt conveyors in the food and drink industries | nd |
| GS 28/2 | Safe erection of structures, Part 2: Site management and procedures | 1998 |

| | | |
|---|---|---|
| ~~HSG 15~~ | ~~Storage of liquefied petroleum gas at factories~~ *(N.B.: now obsolete but still commonly cited)* | ~~nd~~ |
| HSG 28 | Safety advice for bulk chlorine installations | 1999 |
| HSG 30 | Storage of anhydrous ammonia under pressure in the UK: spherical and cylindrical vessels | 1986 |
| HSG 34 | Storage of LPG at fixed installations | 1987 |
| HSG 51 (3rd Ed) | The storage of flammable liquids in containers | 2015 |
| HSG 64 | Assessment of fire hazards from solid materials and the precautions required for their safe storage and use | 1991 |
| HSG 71 | Chemical warehousing: the storage of packaged dangerous substances | 2009 |
| HSG 136 | A guide to workplace transport safety | 2014 |
| HSG 139 | The safe use of compressed gases in welding, flame cutting and allied processes | 1997 |
| HSG 140 (2nd Ed) | Safe use and handling of flammable liquids | 2015 |
| HSG 176 (2nd Ed) | The storage of flammable liquids in tanks | 2015 |
| OC 278/34 (rev) | The filling and storage of aerosols with flammable propellants | 1993 |
| OC 449/7 | Prevention or creation of liquid slugs in flarelines | 1993 |
| PM 3 | Safety at autoclaves | 1998 |
| R2P2 | Reducing risks, Protecting people | 2001 |
| HSE COMAH Technical Measures: Design Codes—Pipework (online) [accessed November 18, 2018] available at http://www.hse.gov.uk/comah/sragtech/techmeaspipework.htm | | 2010 |
| HSE COMAH Technical Measures: Plant Layout (online) [accessed November 18, 2018] available at http://www.hse.gov.uk/comah/sragtech/techmeasplantlay.htm | | 2015 |
| HSE COMAH Technical Measures: Design Codes—Plant (online) [accessed November 18, 2018] available at http://www.hse.gov.uk/comah/sragtech/techmeasplant.htm | | 2015 |
| HSE COMAH Technical Measures: Reliability of utilities (online) [accessed November 18, 2018] available at http://www.hse.gov.uk/comah/sragtech/techmeasutilitie.htm | | 2015 |
| HSE COMAH Technical Measures: Lifting procedures (online) [accessed November 18, 2018] available at http://www.hse.gov.uk/comah/sragtech/techmeaslifting.htm | | 2015 |
| HSE COMAH Technical Aspects: Heat Exchangers (online) [accessed November 18, 2018] available at http://www.hse.gov.uk/comah/sragtech/systems8.htm | | 2015 |
| HSE COMAH Technical Aspects: Hazardous Area Classification and Control of Ignition Sources (online) [accessed November 18, 2018] available at http://www.hse.gov.uk/comah/sragtech/techmeasareaclas.htm | | 2015 |

## British Standards Institution (see also H2.0 European Standards for EN standards)

| | | |
|---|---|---|
| BS 470 | Inspection, access and entry openings for pressure vessels | 1984 |
| BS 799-5 | Oil burning equipment, specification for carbon steel oil storage tanks | 2010 |
| BS 1113 | Specification for design and manufacture of water-tube steam generating plant (including superheaters, reheaters and steel tube economizers) | 1999 |
| BS 1192<br>+A1 | Collaborative production of architectural, engineering and construction information. Code of practice | 2007<br>2015 |
| BS1553-1 | Specification for graphical symbols for general engineering. Piping systems and plant | 1977 |
| BS 1560 3.2 | Circular flanges for pipes, valves and fittings | 1989 |
| BS 1646-3 | Symbolic representation for process measurement control functions and instrumentation. Specification for detailed symbols for instrument interconnection diagrams | 1984 |
| ~~BS 2594~~ | ~~Specification for carbon steel welded horizontal cylindrical storage tanks~~<br>*N.B. Superseded by BS EN 12285-2:2005 and BS EN 12285-1:2003* | ~~1975~~ |
| ~~BS 2654~~ | ~~Specification for manufacture of vertical steel welded non-refrigerated storage tanks with butt-welded shells for the petroleum industry~~<br>*N.B. Superseded by BS EN 14015:2004* | 1989 |
| BS 2971 | Specification for Class II welding of carbon steel pipework for carrying fluids | 1991 |
| BS 3293 | Specification for carbon steel pipe flanges (over 24 in. nominal size) for the petroleum industry | 1960 |
| BS 3416 | Bitumen base coatings for cold applications, suitable for use in contact with potable water | 1991 |
| BS 4082-1<br>BS 4082-2 | Specification for external dimensions for vertical in-line centrifugal pumps 'I' Type and 'U' Type | 1969 |
| BS 4250 | Specification for commercial butane and commercial propane | 2014 |
| BS 4409-1 | Screw conveyors. Specification for fixed trough type | 1991 |
| BS 4409-2 | Screw conveyors. Specification for portable and mobile type (augers) | 1991 |
| ~~BS 4504~~ | ~~Circular flanges for pipes, valves and fittings~~<br>*Superseded by BS EN 1092-1 2007 + A1 2013; BS 1092-2 1997 and BS 1092-3 2003* | ~~1969~~ |
| BS 4531 | Specification for portable and mobile troughed belt conveyors | 1986 |
| ~~BS 4741~~ | ~~Specification for vertical cylindrical welded steel storage tanks for low temperature service: single-wall tanks for temperatures down to −50°C~~<br>*Superseded by BS EN 14620 series:2006* | ~~1971~~ |
| BS 4994 | Specification for design and construction of vessels and tanks in reinforced plastics<br>*Current but superseded by BS EN 13923:2005, BS EN 13121-3:2008 + A1:2010* | 1987 |

| | | |
|---|---|---|
| BS 5070-1<br>BS 5070-2<br>BS 5070-3 | Engineering diagram drawing practice. Recommendations for general principles | 1988 |
| BS 5257 | Specification for horizontal end suction centrifugal pumps (16 bar) | 1975 |
| BS 5306 | Code of practice for fire extinguishing installations and equipment on premises | 2006- |
| ~~BS 5387~~ | ~~Specification for vertical cylindrical welded steel storage tanks for low temperature service: double-wall tanks for temperatures down to −196°C~~<br>*Superseded by BS EN 14620 series:2006 (see BS 4741 above)* | ~~1976~~ |
| BS 5395-1 | Stairs. Code of practice for the design of stairs with straight flights and winders | 2010 |
| BS 5410-1 | Codes of practice for oil firing | 2014 |
| BS 5410-2 | | 2013 |
| BS 5410-3 | | 1976 |
| BS 5493 | Code of practice for protective coating of iron and steel structures against corrosion<br>*Current but partially replaced by BS EN ISO 12944 series 1998 and BS EN ISO 14713 series 2009* | 1977 |
| BS 5667-1 | Specification for continuous mechanical handling equipment—safety requirements. General (ISO 1819: 1977) | 1979 |
| BS 5908-1 | Fire and explosion precautions at premises handling flammable gases, liquids and dusts. Code of practice for precautions against fire and explosion in chemical plants, chemical storage and similar premises | 2012 |
| BS 5908-2 | Guide to applicable standards and regulations | 2012 |
| BS 5958 | Code of practice for the control of undesirable static electricity<br>*Current but partially superseded by PD CLC/TR 60079-32-1:2015* | 1991 |
| BS 6008 | Method for preparation of a liquor of tea for use in sensory tests | 1980 |
| BS 6464 | Specifications for reinforced plastic pipe, fittings and joints for process plant | 1984 |
| BS 6739 | Code of practice for instrumentation in process control systems: installation design and practice | 2009 |
| BS 6990 | Code of practice for welding on steel pipes containing process fluids or their residuals. | 1989 |
| ~~BS 7777~~ | ~~Flat-bottomed, vertical, cylindrical storage tanks for low temperature service~~<br>*Superseded by BS EN 14620 series:2006* | ~~1993~~ |
| PD 5500 | Specification for unfired, fusion welded pressure vessels | 2015 |
| BS 8888 | Technical product documentation and specification | 2017 |
| BS ISO TR 9705-2:2001 | Reaction to fire tests. Full scale room tests for surface products. Technical background and guidance | 2001 |

## Institution of Chemical Engineers guidance

| | |
|---|---|
| Sustainability Metrics | nd |
| Abbott, J. A. (Ed.) *Prevention of fires and explosions in dryers: A user guide* (2nd ed.) | 1990 |
| Lindley, J. *User guide for the safe operation of centrifuges* | 1987 |

## Chemical Industries Association (CIA) guidance

| | | |
|---|---|---|
| Process plant hazard and control building design: An approach to categorization<br>*Cited but no longer available* | | 1990 |
| *RC21/10* | Guidance for the location and design of occupied buildings on chemical manufacturing sites (3rd ed.) | 2010 |

## UK LPG Association Codes of Practice

| | | |
|---|---|---|
| LPGA COP 01/1 | Code of Practice 1: Part 1—Bulk LPG Storage at Fixed Installations: Design, Installation and Operation of Vessels Located Above Ground | January 2009, amended 2012, 2013 |
| LPGA COP 01/2 | Code of Practice 1: Part 2—Bulk LPG Storage at Fixed Installations for Domestic Purposes | May 2012 |
| LPGA COP 01/3 | Code of Practice 1: Part 3—Bulk LPG Storage at Fixed Installations: Examination and Inspection | May 2012 |
| LPGA COP 01/4 | Code of Practice 1: Part 4—Bulk LPG Storage at Fixed Installations: Buried/Mounded LPG Storage Vessels | February 2008, amended March 2013 |
| ~~LPGA COP 15~~ | ~~Valves and fittings for LPG service, Part 1 Safety valves~~<br>*Superseded by BS EN 14129: 2014 LPG Equipment and accessories. Pressure relief valves for LPG pressure vessels* | ~~2000~~ |
| LPGA COP 17 | Purging LPG vessels and systems | August 2001 |
| LPGA COP 22 | Design, installation and testing of LPG Piping systems | August 2011, amended February 2012 |

## Institution of gas engineers and managers

| | | |
|---|---|---|
| ~~IGEM SR/7~~ | ~~Bulk storage and handling of highly flammable liquids used within the gas industry~~<br>*N.B. Withdrawn* | ~~1989~~ |
| IGEM SR/14 Ed 2 | Fixed volume storage for lighter than air gases | 2010 |

| | | |
|---|---|---|
| IGEM/SR/25 Ed 2 | Hazardous area classification of natural gas installations | 2010<br>Amends. 2013 |
| IGEM/UP/2 Ed 3 | Installation pipework on industrial and commercial premises | 2014 |
| IGEM/UP/16 | Design for natural gas installations on industrial and commercial premises with respect to hazardous area classification and preparation of risk assessments | 2011<br>Amends. 2013 |

## Institute of Petroleum

| | |
|---|---|
| Model Code of Safe Practice in the Petroleum Industry Part 3, Refining Safety Code ISBN 0471261963 | 1981 |
| Model Code of Safe Practice Part 9: Liquefied Petroleum Gas Volume 1: Large Bulk Pressure Storage and Refrigerated LPG ISBN 0471916129 | 1997 |
| Calculations in Support of IP 15: The Area Classification Code for Petroleum Installations ISBN 0852933398 | 2001 |

## Other British codes and standards

| | |
|---|---|
| AEC (UK) BIM Technology Protocol Version 2.1.1 | June 2015 |
| EEMUA (2015) 147 Recommendations for the design and construction of refrigerated liquefied gas storage tanks, 2nd ed. | 2015 |
| Energy Institute Model Code of Safe Practice Part 9, Large bulk pressure storage and refrigerated LPG, ISBN: 9780471916123 | February 1987 |
| Loss Prevention Council REC RC 8 Recommendations for the storage, use and handling of common industrial gases in cylinders (excluding LPG) | 1992 |
| Loss Prevention Council REC RC 20A-C Recommendations for the storage and use of flammable liquids | 1997 |
| Water Industry Mechanical and Electrical Specifications (WIMES) 7.01: Decanter Centrifuges for Sewage and Water Sludge Thickening and De-Watering, 3rd ed. | 2008 |

## U.S. codes and standards

### American Petroleum Institute (API) standards

| | | |
|---|---|---|
| API Publ 303 | Generation and management of wastes and secondary materials | 1992 |
| API Publ 345 | Management of residual materials: petroleum refining performance | 1998 |
| ~~API Publ 421~~ | ~~Design and Operation of Oil-Water Separators~~<br>*N.B. Withdrawn, but still in common use* | 1990 |

| | | |
|---|---|---|
| API RP 505 | Recommended practice for classification of locations for electrical installations at petroleum facilities Classified as Class I, Division I and Division 2, Third Edition | 2012 |
| API RP 520 | Sizing, selection, and installation of pressure-relieving Devices,<br>Part I—Sizing and selection, ninth edition<br>Part II, Installation, Sixth Edition | 2014<br>2015 |
| API RP 556 | Instrumentation, control, and protective systems for gas fired heaters, second edition | 2011 |
| API RP 752 | Management of hazards associated with location of process plant permanent buildings, third edition | 2009 |
| API RP 2001 | Fire protection in refineries, ninth edition | 2012 |
| API Specification 12 K | Indirect heater design information, eighth edition | 2008 |
| API Std 521 | Pressure-relieving and depressuring systems, sixth edition | 2014 |
| API Std 530 | Calculation of heater-tube thickness in petroleum refineries, seventh edition | 2015 |
| API Std 560 | Fired heaters for general refinery service, fifth edition<br>*(N.B. Identical to ISO 13705: 2012)* | 2016 |
| API Std 610<br>ISO 13709 | Centrifugal pumps for petroleum, petrochemical and natural gas industries, eleventh edition | 2011<br>2009 |
| API Std 611 | General-Purpose steam turbines for petroleum, chemical, and gas industry services, fifth edition | 2008 |
| API Std 612 | Petroleum, petrochemical and natural gas Industries—Steam Turbines—Special-purpose applications, seventh edition | 2014 |
| API Std 613 | Special purpose gear units for petroleum, chemical and gas industry services, fifth edition | 2003 |
| API Std 614 | Lubrication, shaft-sealing and oil-control systems and auxiliaries, fifth edition | 2008 |
| API Std 616 | Gas turbines for the petroleum, chemical, and gas industry services, fifth edition | 2011 |
| API Std 617 | Axial and centrifugal compressors and expander-compressors, eighth edition | 2014 |
| API Std 618 | Reciprocating compressors for petroleum, chemical, and gas industry services, fifth edition | 2007<br>Amended 2009, 2010 |
| API Std 619 | Rotary-Type positive-displacement compressors for petroleum, petrochemical, and natural gas industries, fifth edition | 2010 |
| API Std 620 | Design and construction of large, welded, low-pressure storage tanks, twelfth edition | 2013 |
| API Std 650 | Welded tanks for oil storage, twelfth edition | 2013, amended 2014 |

| | | |
|---|---|---|
| API Std 660 | Shell-and-tube heat exchangers, ninth edition | 2015 |
| API Std 670 | Machinery protection systems, fifth edition | 2014 |
| API Std 674 | Positive displacement pumps—reciprocating | 2010<br>Amended 2014, 2015 |
| API Std 675 | Positive displacement pumps—controlled volume for petroleum, chemical, and gas industry services, 3rd edition | 2012<br>Amended 2014 |
| API Std 676 | Positive displacement pumps—rotary, third edition | 2009 |
| API Std 677 | General-purpose gear units for petroleum, chemical and gas industry services, third edition | 2006 |
| API Std 682 | Pumps-Shaft sealing systems for centrifugal and rotary pumps, fourth edition | 2014 |
| API Std 685 | Sealless centrifugal pumps for petroleum, petrochemical, and gas industry process service, second edition | 2011 |
| API Std 2000 | Venting atmospheric and Low-pressure storage tanks, seventh edition | 2014 |
| API Std 2510 | Design and construction of liquefied petroleum gas installations (LPG) | 2001 |

## American National Standards Institute (ANSI) standards

| | | |
|---|---|---|
| ANSI/API 682 | Pumps—Shaft sealing systems for centrifugal and rotary pumps | 2014 |
| ANSI/ISA 5.1 | Instrumentation symbols and identification | 2009 |
| ANSI/CEMA Std B105.1 | welded steel conveyor pulleys | 2009 |
| ANSI/CEMA Std No. 300 | Conveyor equipment manufacturers' association, screw conveyor dimensional standards | 2009 |
| ANSI/CEMA Std No. 350 | Conveyor equipment manufacturers' association, screw conveyors for bulk materials | 2009 |
| ANSI/CEMA Std No. 402 | Belt conveyors | 2003 |
| ANSI/CEMA Std No. 403 | Belt driven live roller conveyors | 2003 |
| ANSI/CEMA Std No. 404 | Chain driven live roller conveyors | 2003 |
| ANSI/CEMA Std No. 405 | Slat conveyors | 2003 |
| ANSI/CEMA Std No. 406 | Lineshaft driven live roller conveyors | 2003 |

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|---|---|---|
| ANSI/CEMA Std No. 407 | Motor driven live roller (MDR) conveyors | 2015 |
| ANSI/CEMA Std No. 601 | Overhead trolley chain conveyors | 1995 |

## American Society of Mechanical Engineers (ASME) standards

| | | |
|---|---|---|
| ASME BPVC | Boiler and pressure vessel code<br>Section I: Rules for construction of power boilers<br>Section III: Nuclear piping<br>Section VII: Recommended guidelines for the care of power boilers<br>Section VIII: Rules for construction | 2015 |
| ASME B16.1 | Gray iron pipe flanges and flanged fittings: classes 25, 125, and 250 | 2015 |
| ASME B16.5 | Pipe flanges and flanged fittings | 2013 |
| ASME B16.9 | Factory made wrought buttwelding fittings | 2012 |
| ASME B31.1 | Power piping | 2014 |
| ASME B31.3 | Process piping | 2014 |
| ASME B31.4 | Pipeline transportation systems for liquids and slurries | 2016 |
| ASME B31.5 | Refrigeration piping and heat transfer components | 2013 |
| ASME B31.8 | Gas transmission and distribution piping systems | 2014 |
| ASME B31.9 | Building services piping | 2014 |
| ASME B31.12 | Hydrogen piping and pipelines | 2014 |
| ASME B73.1 | Specification for horizontal end suction centrifugal pumps for chemical process | 2012 |
| ASME B73.2 | Specifications for vertical in-line centrifugal pumps for chemical process | 2003 |
| ASME PTB-7 | Criteria for shell-and-tube heat exchangers according to part UHX of ASME Section VIII-Division 1 | 2014 |
| ASME Y14.100 | Engineering drawing practices | 2013 |

## AIChE Center for Chemical Process Safety (CCPS) guidance

| | |
|---|---|
| Guidelines for chemical transportation safety, security, and risk management, 2nd Edition | August 2008 |
| Guidelines for evaluating process plant buildings for external explosions, fires, and toxic releases, 2nd Edition | April 2012 |
| Guidelines for chemical process quantitative risk assessment, 2nd Edition | 1999 |
| Guidelines for hazard evaluation procedures, 3rd Edition | April 2008 |
| Inherently safer chemical processes: a life cycle approach, 2nd Edition | December 2008 |

| | |
|---|---|
| Layer of protection analysis: simplified process risk assessment | October 2001 |
| Guidelines for analyzing and managing the security vulnerabilities of fixed chemical sites | June 2003 |
| Guidelines for fire protection in chemical, petrochemical, and hydrocarbon processing facilities | August 2003 |
| Guidelines for consequence analysis of chemical releases | March 1995 |
| Guidelines for vapor cloud explosion, pressure vessel burst, BLEVE and flash fire hazards, 2nd Edition | July 2010 |
| Understanding explosions | July 2003 |
| Guidelines for facility siting and layout | September 2004 |

## American National Fire Protection Association (NFPA) standards

| | | |
|---|---|---|
| NFPA 15 | Standard for water spray fixed systems for fire protection | 2012 |
| NFPA 20 | Standard for the installation of stationary pumps for fire protection | 2016 |
| NFPA 22 | Standard for water tanks for private fire protection | 2013 |
| NFPA 24 | Standard for the installation of private fire service mains and their appurtenances | 2016 |
| NFPA 30 | Flammable and combustible liquids code | 2015 |
| NFPA 58 | Liquefied petroleum gas code | 2014 |
| NFPA 11 | Standard for low-, medium-, and High-Expansion foam | 2016 |
| NFPA 59 A | Standard for the production, storage and handling of liquefied natural gas (LNG) | 2016 |
| NFPA 70 (NEC) | National electrical code | 2014 |
| NFPA 86 | Standard for ovens and furnaces | 2015 |
| NFPA 654 | Standard for the prevention of fire and dust explosions from the manufacturing, processing and handling of combustible particulate solids | 2013 |
| NFPA 1142 | Standard on water supplies for suburban and rural fire fighting | 2012 |

## US Department of Labor, Occupational Safety and Health Administration

| | | |
|---|---|---|
| OSHA Std. 1910.24 | Fixed industrial stairs | 1974, amended |
| OSHA Std. 1910.27 | Fixed ladders | 1974, amended |
| OSHA Std. 1910.110 | Storage and handling of liquefied petroleum gases | 1974, amended |
| OSHA Std. 1926.752 | Steel Erection: site layout, site-specific erection plan and construction sequence | 2002, amended |

## Miscellaneous US sodes and standards

| | | |
|---|---|---|
| AIHA ERPG | American institute for industrial hygiene emergency response planning guidelines | 2015 |
| ASTM E681-09 | American society for testing and materials, standard test method for concentration limits of flammability of chemicals (Vapors and Gases) | 2015 |
| CAGI 3075 | Compressed Air and Gas Institute (CAGI) B19.1 safety standard for compressor systems | 2011 |
| MSS SP-97 | Manufacturers' Standardization Society: integrally reinforced forged branch outlet Fittings—Socket welding, threaded, and buttwelding ends | 2012 |
| ESL-TR-87-57 | US Air Force: Protective construction design manual | 1989 |
| TM5-1300 | US Army: Structures to resist the effects of accidental explosions | 1990 |
| NBIMS-US | US National institute of building sciences, Version 3 | April 2015 |
| International Conference of Building Officials (ICBO), Uniform Building Code | | 1997 |
| American Institute of Chemical Engineers (n.d.) AIChE sustainability index [online] [accessed November 18, 2018] available at http://www.aiche.org/ifs/resources/sustainability-index | | n.d. |
| Tubular Exchanger Manufacturers Association, Inc. *TEMA Standards*, 9th Edition, TEMA, New York | | 1997 |

## Other national codes and standards

| Country | Guidance | Date |
|---|---|---|
| China | Code of China GB 150.1-2011 pressure Vessels-Part 1: General Requirements | 2011 |
| China | Code of China Standard JB 4732-1995 (2005) steel pressure Vessels—Design by analysis | 2005 |
| Germany | AD 2000 Merkblatt: codes of practice on pressure vessels | various |
| Iran | Iranian ministry of petroleum, IPS-E-PR-190: engineering standards for layout and spacing | 1996 |
| Russia | GOST R 53630-2006: Steel welded vessels and apparatus. general specifications | 2007-2008 |
| Russia | GOST R 52857.1-2007: Vessels and apparatus. Norms and methods of strength calculation | 2007-2008 |

## Books and Scholarly Research

Azhar, S. et al. (2012). *Modular v. Stick-Built* Construction: Identification of Critical Decision-Making Factors. In: 48th ASC annual international conference proceedings [online]. Available from: <http://ascpro.ascweb.org/chair/paper/CPRT202002012.pdf> Accessed 18.11.18.

Baker, W. E., et al. (1983). *Explosions hazards and evaluation*. Amsterdam: Elsevier.

Barton, J. (2002). *Dust explosion prevention and protection—A practical guide*. Houston,Texas: Gulf Professional Publishing (Elsevier).
Bausbacher, E., & Hunt, R. (1993). *Process plant layout and piping design*. Englewood Cliffs, NJ: Prentice-Hall.
Bowers, P., Beale, R., & Smith, P. (2010). *Plant layout and construction design*. Houston, TX: Gulf Publishing Company.
Couper, J. R., et al. (2012). *Chemical process equipment: Selection and design*. Oxford: Elsevier/Butterworth-Heinemann.
Cox, B. G., & Saville, G. (1975). *The high pressure safety code*. London: High Pressure Technology Association.
Drury, J., Falconer, P., & Heery, G. (2003). *Buildings for industrial storage and distribution*. London: Routledge.
Goose, M. H. (2000). *Location and design of occupied buildings at chemical plants—Assessment step By step*. Symposium Series No. 147, Rugby: IChemE.
Green, D. W., & Perry, R. H. (2007). *Perry's chemical engineers' handbook* (8th ed). New York: McGraw-Hill.
Haynes, W. M. (Ed.), (2015). CRC handbook of chemistry and physics *(a.k.a. the 'Rubber Book')* (96th ed.). Boca Raton, FL: CRC Press.
Hurley, M. (Ed.), (2015). *SFPE handbook of fire protection engineering* (5th ed). New York: Springer.
Kepner, C. H., & Tregoe, B. B. (1965). *The rational manager*. New York: McGraw-Hill.
Kern, R. (1978). Instrument arrangements for ease of maintenance and convenient operation. *Chemical Engineering*, *85*, 127.
Kern, R. (1977a). Arrangements of process and storage vessels. *Chemical Engineering*, *84*, 93.
Kern, R. (1977b). How to find the optimum layout for heat exchangers. *Chemical Engineering*, *84*, 169.
Kern, R. (1977c). How to get the best process plant layouts for pumps and compressors. *Chemical Engineering*, *84*, 131.
Kern, R. (1977d). How to manage plant design to obtain minimum cost. *Chemical Engineering*, *84*, 130.
Kern, R. (1977e). Layout arrangements for distillation columns. *Chemical Engineering*, *84*, 153.
Kern, R. (1978a). Arranging the housed chemical process plant. *Chemical Engineering*, *85*, 123.
Kern, R. (1978b). Controlling the cost factors in plant design. *Chemical Engineering*, *85*, 141.
Kern, R. (1978c). How to arrange the plot plan for process plants. *Chemical Engineering*, *85*, 191.
Kern, R. (1978d). Space requirements and layout for process furnaces. *Chemical Engineering*, *85*, 117.
Kirk-Othmer (Ed.), (2007). *Kirk-Othmer encyclopedia of chemical technology*. Hoboken, NJ: Wiley-Blackwell.
Kletz, T. (1991). *Plant design for safety—A user-friendly approach*. London: Taylor & Francis.
Kletz, T. (1999). *Hazop and Hazan—Identifying and assessing process industry hazards* (4th ed). London: Taylor & Francis.
Kletz, T. (2001). *Learning from accidents* (3rd ed). Oxford: Butterworth-Heinemann.
LePree, J. (2016). Is modular right for your project? *Chemical Engineering*, *123*, 1.
Mannan, S. (Ed.), (2012). *Lees' loss prevention in the process endustries* (4th ed). Oxford: Elsevier/Butterworth-Heinemann.
Mannan, S. (2013). *Lees' process safety essentials*. Oxford: Elsevier/Butterworth-Heinemann.
Mills, D. (2015). *Pneumatic conveying design guide*. Oxford: Elsevier/Butterworth-Heinemann.
Moore, C. V. (1967). The design of barricades for hazardous pressure systems. *Nuclear Engineering and Design*, *5*, 81.
Moran, S. (2017). *Process plant layout* (2nd ed). Oxford: Butterworth-Heinemann.
Moran, S. (2018). *An applied guide to water and effluent treatment plant design*. Oxford: Elsevier.
Muir, D. M. (1992). *)* Dust and fume control: A user guide. Rugby: IChemE.
M. W. Kellogg Company. (2009). *Design of piping systems*. Eastford, CT: Martino Fine Books.
Peng, L.-C., & Peng, T.-L. (2009). *Pipe stress engineering*. New York: ASME Press.
Rase, H. F. (1963). *)* Piping design for process plants. Hoboken, NJ: Wiley.
Trinks, W., et al. (2004). *Industrial furnaces*. Hoboken, NJ: Wiley.
USA, Centers for DiseaseControl. (2009). *Biosafety in microbiological and biomedical laboratories* (5th ed.) Washington, DC: US Department of Health and Human Services.

# Glossary

There are a number of words and phrases which are not in common use and, more problematically, there are a number which are in common use, but mean different things to different people. In this glossary, I define the sense in which I am using them in this book. This is intended to be the most commonly held meaning.

**$\Delta P/dP$** differential pressure
**$\Delta T/dT$** differential temperature
**AACE** American Association of Cost Engineering
**ANSI** American National Standards Institute
**ASTM** American Society for Testing and Materials
**API** American Petroleum Institute
**Basic engineering design data (BEDD)** information compiled to allow conceptual design in petrochemical sector
**Best practice** exceptional practice, cf. good practice
**Block flow diagram (BFD)** an academic's approximation of a PFD
**BS** British Standard
**CAD** computer-aided design/drawing
**Capex** capital expenditure
**CFD** computational fluid dynamics—using computers to model fluid dynamics
**Conceptual design** the initial stage of design; content varies between sectors
**Consultancy** a company which offers advice, and rarely progresses design beyond conceptual stage
**Contracting company** a company which contracts to build plants, and usually does its own detailed design
**Control and instrumentation engineer** a hybrid chemical/software engineer or sometimes instrument technician found mainly in petrochemical industry operating companies
**CoV** coefficient of variance
**CPI**
**1.** chemical process industries
**2.** Chemical Price Index
**DCS** distributed control system
**DEFRA** (UK) Department for Environment, Food & Rural Affairs
**Deliverables** things delivered under a contract; in a plant design context, mainly drawings
**Design basis** information compiled to allow design at any stage, in general terms. See BEDD for a sector-specific exception
**Design philosophy** accounts of decisions on how a number of common design problems and issues will be handled during a design; best generated early in the design process
**Designer** someone who designs a plant and, in the context of this book, is willing to be legally responsible for it
**Dimensioned drawing** drawing marked with dimensions of real-world counterparts of items illustrated. Not guaranteed to be a scale drawing
**DIN** Deutsches Institut für Normung
**Draffie** draftsman/woman

**Due diligence** generating sufficient certainty in your opinions, considering the potential downside if you are wrong

***dxf*** drawing exchange format, a file format developed by Autodesk (authors of AutoCAD) which allows usually less than perfect file sharing with other CAD programs

**EA** UK Environment Agency

**EPC** engineering, procurement, and construction company, aka "contracting company"

**Engineering** the profession of imagining and bringing into being a completely new artifact which safely, cost-effectively, and robustly achieves a specified aim

**Engineering science** the application of scientific principles to the study of engineering artifacts

**ESD** emergency shutdown—usually precedes "valve"

**FEANI** Fédération Internationale d'Associations Nationales d'Ingénieurs

**FEED** Front-End Engineering Design—an initial design exercise

**FPSO** a floating production storage and offloading vessel—a process plant on a boat

**Functional design specification (FDS)** a description for the software engineer in carefully chosen words of what a plant designer wants the software to do

**General arrangement (GA) drawing** a scale drawing which shows the layout in space of a plant; aka a "plot plan" among other things

**Good practice** the consensus heuristics of practitioners, cf. best practice

**Hazard assessment** Mecklenburgh's "What-If" hazard evaluation/identification technique: layout review

**HAZID** Hazard Identification Study

**HAZOP** Hazard and Operability Study

**HiPPO** highest paid person opinion, cf. the truth

**HMI** human–machine interface

**HSE**

**1.** Health, Safety, and Environment

**2.** (UK) Health and Safety Executive

**IET** The (UK) Institution of Engineering and Technology—successor to the IEE—Institution of Electrical Engineers (amongst others)

**IChemE** The (UK) Institution of Chemical Engineers

**IPPC** Integrated Pollution Prevention and Control

**ISO** International Standards Organization

**Iso** an isometric piping drawing

**Layout review** Mecklenburgh's "what-if" hazard evaluation/identification technique

**MCC** motor control center

**Mogden formula** a formula used in the United Kingdom to calculate trade effluent charges

**MOC**

**1.** management of change—QA to do with making sure changes to plant and design are controlled

**2.** materials of construction

**MPI** main plant items

**MS** microsoft

**Natural science** the activity of trying to understand natural phenomena, cf. engineering science

**NB** nominal bore—the approximate internal bore of a pipe

**NPS** nominal pipe size

**NPSH** net positive suction head

**OD** outside diameter—the diameter of the outside of a pipe, cf. NB

**Olfactorithmetic** the ability to detect an implausible numerical answer by "smell"

**Operating company** a company whose main activity is managing and operating process plants

**Opex** operating expenditure

**Optimization** improving a process by balancing a number of variables against cost, safety, and robustness

**Partial design** an academic approximation of parts of the design process which falls far short of total design (qv)

**PERT** program/project evaluation and review technique. A program evaluation tool, allied with critical path analysis

**PV** photovoltaics—solar cells, as we used to call them

**PID** proportional, integral, derivative—usually precedes "controller," cf. P&ID

**Pinch analysis** a largely academic exercise to minimize resource usage

**Piping and instrumentation diagram (P&ID)** the process engineer's signature drawing, showing physical and logical interrelationships between process plant components, cf. PID

**Piping engineer** specialist in piping and sometimes plant layout used in some industries and countries to produce plant layouts

**PLC** programmable logic controller—industrial computer

**Plot plan** See GA

**Precision** To do with whether the instrument will give me the same reading against the same true value the next time I test it (though I do use it in other senses in the book)

**Problem** a design problem will require the use of engineering judgment and imagination to solve, as data and/or design methodologies are lacking

**Process design** an abstract conceptual "design" of a chemical process with no real consideration of cost, safety, or robustness

**Process flow diagram (PFD)** a drawing which represents the mass balance, resembling in many ways a simplified P&ID

**Process intensification**

1. a largely academic conception of combining unit operations
2. Trevor Kletz's term for what is now usually called minimization in inherent safety techniques

**PRV** pressure-relief valve, cf. PSV

**PSV** pressure safety valve—differs from a PRV in that it has a lever allowing it to be opened manually

**QA** quality assurance

**QRA** Quantitative Risk Assessments

**R + D** research and development, cf. Engineering

**Repeatability** precision under tightly controlled conditions over a short time period

**Reproducibility** variability over time

**RP** recommended practices—especially those of the API

**RTFM** (in polite terms) kindly read the manual

**SCADA** supervisory control and data acquisition

**Sharknado** a tornado, but with added sharks. In common with zombie apocalypse and alien invasion, an eventuality beyond the scope of a process plant designer's necessary disaster preparedness.

**Scale drawing** drawing whose dimensions are consistently some ratio of the size of their corresponding real-world counterparts

**State of the art** the set of heuristics of a designer or designers

**Task** a design task involves using a well-established methodology and robust data to grind out an obvious answer

**Tiffie** instrument technician

**TLA** three-letter acronym—engineering joke

**Total design** "Total Design is the systematic activity necessary, from the identification of the market/user need, to the selling of the successful product to satisfy that need—an activity that encompasses product, process, people and organization."—Stuart Pugh

**UPS** uninterruptible power supply

**Validation** ensuring software matches reality
**Verification** ensuring software is free of coding errors
**WOD** write-only documentation—engineering joke

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Second Edition

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## About the author


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ISBN 978-0-12-814860-0

9 780128 148600

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