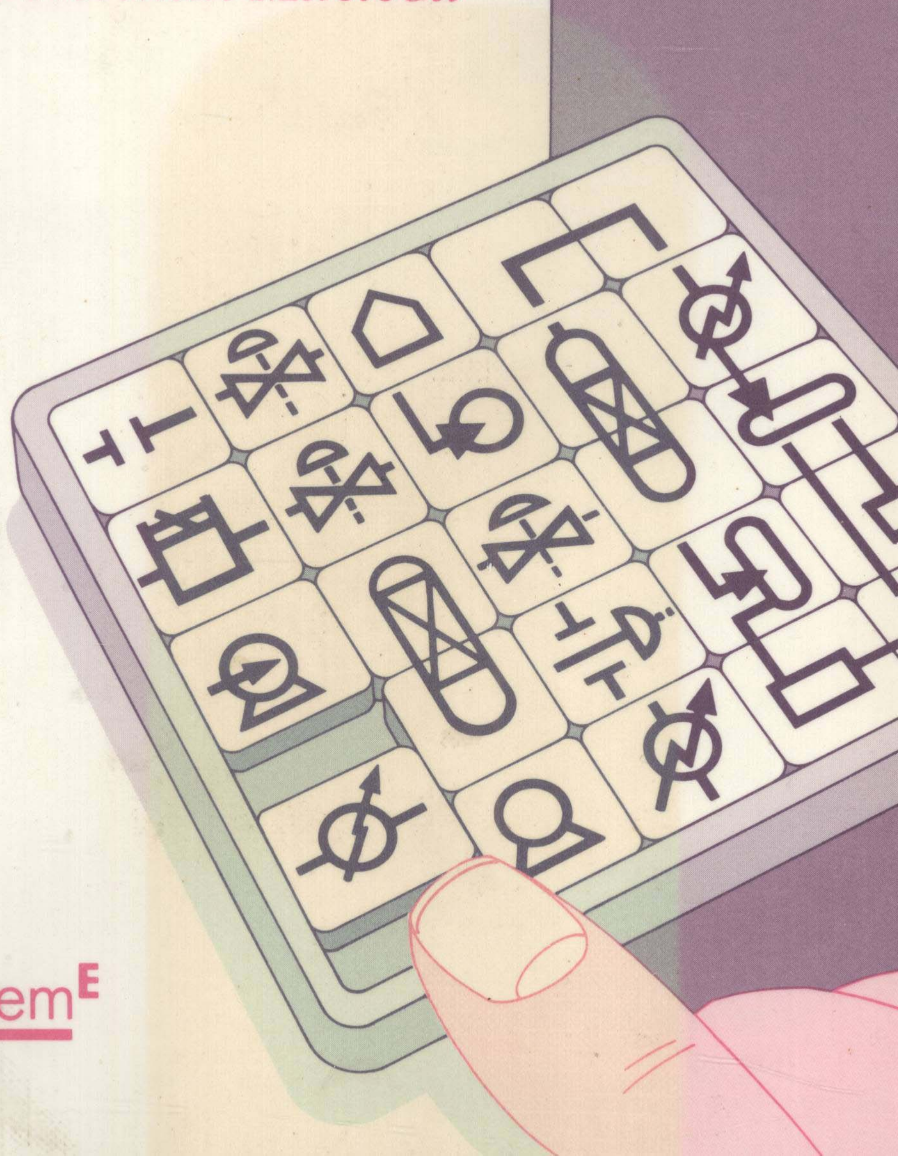
PROCESS DESIGN CASE STUDIES

Ron Scott
with Norman Macleod



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Ron Scott with Norman Macleod and members of staff of the Chemical Engineering Dept, University of Edinburgh

INSTITUTION OF CHEMICAL ENGINEERS

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PREFACE

This book is written for students preparing for the mandatory Institution of Chemical Engineers design project and for others with similar interests. Such students are well versed in chemical engineering theory. They are not always familiar with design procedures and practice, nor with integrating information gained from disparate sources and presenting the results to specialists of other disciplines. For the last ten years, Edinburgh University students have participated in a course of Case Study Design Exercises intended to promote these abilities. These are now presented in this book for wider use.

The author assumes that theoretical principles will be learnt from standard texts; the case studies are chosen primarily to illustrate their application to process design problems. The aim is to show how a process is designed from first principles, rather than by emulating published flowsheets. In this way, creative aspects of design may be stimulated and specific chemical engineering topics given increased relevance. At the least, the case studies may arouse interest in chemical process plants as systems designed in response to the needs of the market place, rather than as collections of disparate operations.

Studies are developed using questions and exercises whenever appropriate so that the text may be used in various ways, eg:

- by chemical engineering undergraduates before and while completing their design project;
- as a self-study course in conjunction with standard texts, students attempting questions and exercises;
- as a basis for a formal taught course along workshop or interactive lines, either in design studies or, in a more general way, to illustrate how engineers apply specific concepts;
- as a refresher for junior industrial staff involved in the development of innovative processes;
- as background reading for research and plant operating staff seeking to promote their skills and effectiveness in collaborating with process technologists and designers;

Finally, it must be pointed out that questions in these second and third categories are usually about design choices or system arrangements. Unlike the factual or scientific questions in the first category, they may not have unique 'right' answers; on occasion, the reader may well be able to devise equally valid, or indeed 'better', answers than those suggested (though the writer does not expect this to happen very often!). It is an important characteristic of design questions that generally they do not lead to demonstrably and absolutely 'correct' answers of the kind sought for scientific questions. This and other distinctions between the designer's and scientist's activities will become clearer in what follows.

• for development into a programmed learning text with an interactive VDU responding to students' attempted answers.

USING THIS BOOK

The ultimate function of the process designer is to provide effective answers to sets of interrelated questions about process feasibility. The questions which arise in the detailed working out of any engineering design proposal are of many sorts and orders of difficulty. Some make profound demands on the designer's academic knowledge and understanding, in ways that can be met only by study (or renewed study) of scientific principles at a fundamental level; others require the careful application of pure logic, often aided by kinds of insight and lateral thinking in which designers become practised through experience.

This book is intended to contribute to the education of designers and accordingly contains much condensed experience in the form of solved case studies. The text also poses directly problems of the kind that confront designers in the course of their work, so that the reader may be encouraged to acquire the habit of finding or devising answers independently. The questions inserted as exercises have therefore an important function here; proper attention should be given to them, as well as to the narrative.

The questions in this text are of three kinds. Firstly, there are questions, designated Q., about points of fact, fundamental principle or procedure in, say, thermodynamics, which must be answered before the discussion in which they arise can continue. Such questions are, in effect, answered in the ensuing text in the specific context of the design problem in which they appear, but the reader should first pause to consider the general answer, if necessary consulting the appropriate specialist text-book to find it.

Secondly, paragraphs in these case histories sometimes end with a question mark, where some design choice or difficulty has to be resolved. Again, in the interests of narrative continuity an answer is generally supplied in the next paragraph; nevertheless, any such question is intended not to be rhetorical, but to be reflected on and answered by the reader, who should pause at the question mark to consider it — meanwhile, perhaps, covering what follows with a sheet of paper.

Thirdly, questions in the form of supplementary exercises are placed at the end of each chapter. These are intended to enlarge the reader's understanding of the foregoing material, in the way usual with text books. Outline answers are given in Appendix II.

NOTES

(1) The Library and Information Service of the Institution of Chemical Engineers in Rugby, UK, offers a worldwide service for the supply of the references listed in this book.

(2) Solutions to exercises appear in Appendix II, pages 106–118.

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1. WHAT IS PROCESS DESIGN?

A definition of design — the creative application of fundamental principles to the fulfillment of a market need. Economic constraints on design. The need for an iterative strategy to find design(s) that best accommodate these. Setting up a database for design work. Safety considerations and the designer.

The aim of process design is to specify the most economical and effective practical procedures and plant required to produce a new product, to manufacture an existing product by new means, or, more generally, to bring about some designated material transformation on a commercial scale, so as to satisfy a market need. Design information, the body of fact with which the designer has to work, originates from research, from existing operations, or from commercial sources. This information is used in trial calculations on alternative process schemes in a search for an optimal process with minimum resource costs.

Process design is normally followed by project appraisal at management level. The first function of a designer is usually to establish to the satisfaction of the management of his company that there is an economic case for proceeding with some particular process scheme.

DESIGN OBJECTIVES AND MARKET NEEDS

What do we mean by 'design' or the act of 'designing' in the present context? We shall use the definition, 'design is the creative application of engineering theory and experience to achieve a practical objective that satisfies a market need'.

The practical objective may be a process or plant to produce a marketable product; less obviously, it may be the product itself. Examples of 'designed' products in the process industries include plastics, laminates, alloy steels and novel food products.

A product or process which does not satisfy (or generate) a market need will not normally be proceeded with, or will be short-lived.

What markets? Markets take a variety of forms. Chemical products are often intermediates between natural resources and products for use by the ultimate consumer: their markets are often within the chemical industries themselves.

In general, the closer the market is to the final consumer, the more complex the product and its quality criteria, and the higher the added value and potential reward. Thus novel products with attractive end-use properties may command a very high price: hence the current industrial interest in 'speciality' or 'performance' chemicals.

Making existing products by new processes may also open up new markets by virtue of reductions in price or improvements in quality. As an example, terephthalic acid, the intermediate for polyester manufacture, was originally produced by the oxidation of *p*-xylene by nitric acid. This process is now obsolete. A purer, and ultimately cheaper, product is now produced, for example, by oxidation of xylene by air in an acetic acid solvent with a cobalt bromide catalyst. The market for 'Terylene' expanded spectacularly when such new and cheaper processes for terephthalic acid appeared.

A new process may also serve an established market for an existing product by allowing this to be obtained from commercially attractive raw materials. In New Zealand, for instance, gasoline is being made from methanol derived from natural gas, using a novel process based on a zeolite catalyst.

A further kind of market demand is for process and plant improvements, to increase the capacity of existing installations or to improve their economics. Environmental pressures also create new demands for processes; for example to remove sulphur dioxide from power station stack gases.

These differing objectives all require successful designs for their achievement. The first aim of good design, in this context, is to satisfy market needs at least overall cost. Cost in this sense measures the total demand on available resources.

THE DESIGN PROCESS — PROBLEM SOLVING WITH CONSTRAINTS

'Available resources' include capital for plant construction, feedstocks, energy supplies, water-, sewerage-, transport-, etc services to the plant site, labour for operation and maintenance, social and environmental amenities (eg absence of hazard and pollution). If a process is to be successful it must not make unacceptable demands on such resources.

Though some of these are difficult to evaluate in monetary terms, the worth that society attaches to any resource is ultimately expressed as an equivalent cost of consumption, or resource cost. For common commodities and raw materials, this will simply be the local market value (allowing for the commercial effects of any proposed new demand); for loss of amenity and increase of hazard the equivalent costs in developed societies are constantly being raised by the pressure of public opinion and are often prohibitively high in particular areas of Western Europe and the U.S.A.

Thus, different resources have widely differing costs, which themselves vary with location and time. The process designer must take account of this in devising means of satisfying the requirement for a marketable product while minimising the total resource cost.

THE WIDER FUNCTIONS OF THE DESIGNER

It is the designer's task to solve the technical problems of, say, the synthesis of a desired product, within the (socio-)economic constraints of optimal use of resources. This, fundamentally, is what distinguishes the process designer from the pure chemist or physicist. As scientists, these latter are concerned solely with the scientific principles underlying the intended process. The designer must have wider horizons.

In the first place, he must appreciate the proposed process as a whole; not merely the chemistry or physics of the stages in which the desired product is to be formed, but also the totality of all the many steps by which the crude starting materials delivered to the plant may be transformed into packaged, or otherwise transportable, product of marketable specification.

Every one of these steps has a resource cost. For several of these possible process steps, or sequences of steps, alternatives may be devised which are functionally equivalent. Usually such alternative sequences or process routes will have different resource cost implications. The designer has then to assess the costs associated with all such alternative routes; only then will he be able to choose that of lowest resource cost, thus identifying an optimal process route or design.

DESIGN AS AN ITERATIVE PROCESS

It is generally impossible to estimate accurately in advance the resource implications even of quite minor process changes. Often, several alternative process routes, or part-routes, have to be explored and costed in detail before it becomes clear which is the most economic. Moreover, at any stage of the design process such calculations may reveal that there are unacceptably high costs associated with an entire subset of process alternatives, traceable to some earlier 'wrong turning' in the chosen process route. The systematic exploration of alternative designs has then to be restarted at an earlier point and must follow a different course.

It is thus characteristic of process design work that, after the formation of the initial scheme, it proceeds with the tentative exploration of the detailed implications of alternative technically feasible process routes. This procedure is essentially iterative; often, a path first chosen is found to lead to an unsatisfactory or questionable result, so a return has to be made to an earlier point from which another route can be explored. Many examples illustrating this iterative character of design procedures are to be found in this book; and it is worth pointing out that iteration is a feature of virtually all kinds of engineering systems design. Such design is characteristically goal-oriented (as distinct from the most orthodox kind of machine-component design, which is directed by codes of practice); the earlier choices of the design scheme are justified solely in terms of their consequences for the overall or end result. Only after these consequences have been compared with those generated by other available choices can a given design scheme be judged optimal or not.

SOURCES OF DESIGN INFORMATION

After defining market and product, the designer must begin his iterative task with an initial attempt ('first shot') at selecting the best means of meeting these objectives. This will include the processing system which converts reactants to products, the plant in which these operations are to be performed and the plan for implementing the design. Where can the designer find information enabling him to do this?

Information supporting process design may originate from many sources, including existing operations, innovative research and commercial sources. Let us examine some of these.

RESEARCH

The successful application of innovative research presents the designer with his most severe, yet most rewarding challenge. Real progress in the chemical and process industries originates in the laboratory, yet there is understandably less confidence in designs based on results from bench scale equipment than in those deriving from full scale application. How can the chemical engineer respond to this challenge?

The effective planning of research aimed at gathering design data for a new process demands an understanding of economic, as well as technical, aspects of the process. If the economic factors affecting the optimal choice of process conditions are not appreciated, laboratory data may be obtained for circumstances unrelated to those of a viable process. The chemical engineer is uniquely well placed to guide researchers away from such pitfalls. The chemical engineer should accordingly be involved in any research relevant to a new process as soon as its commercial exploitation can be foreseen. His main tasks at the research stage include devising practical and economical means of performing the operations proposed on the commercial scale, and ensuring that reliable data for scaling up and plant design are obtained for the practical circumstances that he has envisaged.

EXISTING OPERATIONS

Designs based on existing operations are likely to engender the greatest confidence. In order to develop such designs the engineer must, on the one hand, have a sound fundamental understanding of existing processes and, on the other hand, of the limits imposed by physical and chemical properties of the materials used or produced. A systematic comparison will then reveal where existing operations may be improved.

LICENCE OR PURCHASE

Present-day costs of research and process development are so high as to encourage the licensing or purchase of design information from external sources. No manufacturer designs his own nitric acid or ammonia plants today, save the very few who already have substantial experience in the field. Such plants are almost invariably purchased from an experienced contractor. In such circumstances what contribution can the purchaser's designer make?

His task is then largely to ensure that his company's standards are met, that the contractor's claims for the process are sound, and that the raw material, product and site requirements are appreciated. He may also have to make a technical and economic evaluation of competitive bids.

Buying external information about a new process while that is still at the stage of process development is a less reliable expedient, placing great demands on the chemical engineering advice available to the purchaser. To compensate for this, the financial terms should be more favourable so that the potential rewards may be greater. The buyer's chemical engineer may start by reviewing the patent literature and evaluating non-confidential assessment data provided by the vendor. If the process appears attractive, negotiation may proceed to the stage where some insight into process principles and procedure are granted under a confidentiality agreement, although this may limit the buyer's commercial or technical freedom.

STORING DESIGN INFORMATION — THE DATA BOOK

Since process design proceeds iteratively, the same basic design information will be used many times in trial calculations for different, alternative, schemes. Moreover, these trial calculations may be the work of many hands; design is usually a co-operative enterprise with contributions from different individuals. Basic data used in design must therefore be consistent throughout if trial calculations on alternatives are to yield comparable results. How can this be assured?

The basic design information is recorded together with its origin in a data book. This book is then to be the sole source of data used in all design calculations. Physical property data collected from existing operations should include details of the purity of materials involved, since the properties of commercially available intermediates and products frequently differ from those recorded in the literature for pure materials. Whenever possible, industrial designs should use properties actually measured, rather than values from the literature.

Compiling a data book is not a 'once off' exercise. It starts even before any process calculations are made, with specifications of relevant materials. It continues to grow throughout the life of the project. Some data likely to be required are indicated in Figure 1.1.

SAFETY AND HAZARDS

Safety is a resource in a special category. The cost of compromising it is nowadays prohibitive almost everywhere, and this valuation is endorsed in virtually all countries by heavy statutory penalties for unsafe practices. The safety of a processing plant is thus of paramount importance. A company's investment must be protected against legal claims for breaches of safe practice, but the social obligations of an organisation which owns and operates processing

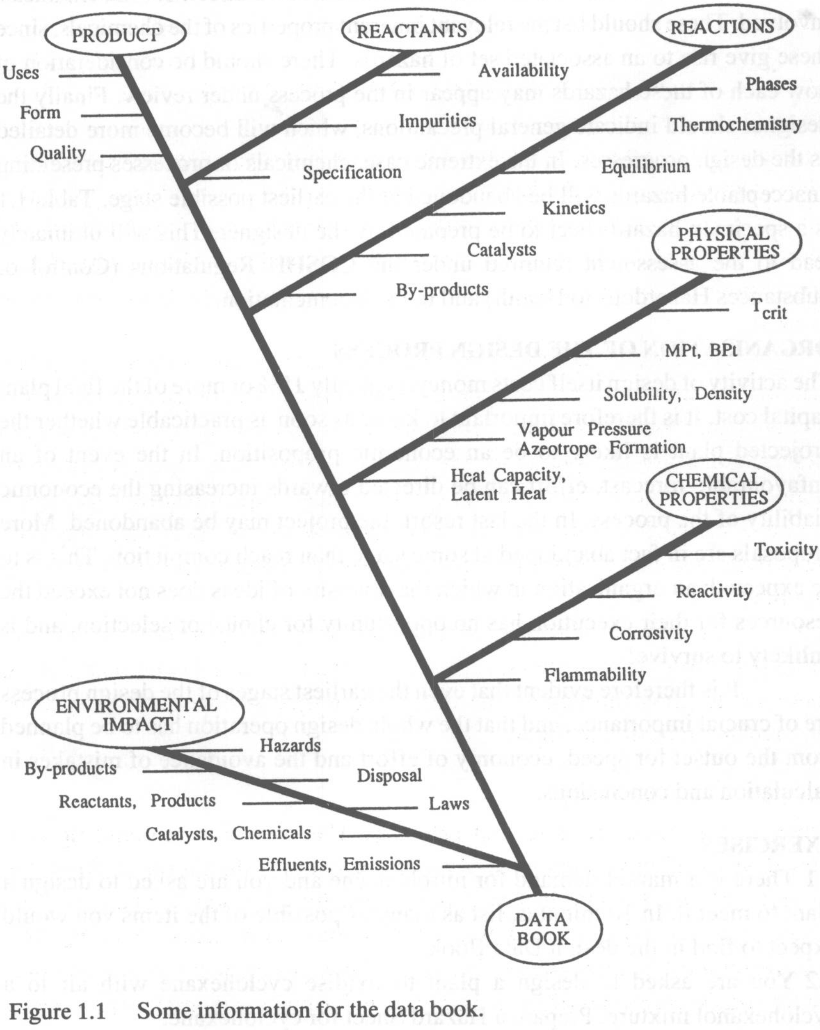

Figure 1.1 Some information for the data book.

plant go beyond the responsibilities specified by the law. Workers in the plant should not be exposed to a level of risk that could lead to accidents, ill health, etc. Of as much importance is the environment, where the product is. Users of the product are to be considered, and the local community and the environment must not suffer unacceptably. Safety aspects should therefore be considered at the earliest stage of design. How can this be done?

Data book information should include Hazard Sheets for the chemicals involved. These should list the relevant inherent properties of the chemicals, since these give rise to an associated set of hazards. There should be consideration of how each of these hazards may appear in the process under review. Finally the designer should indicate general precautions, which will become more detailed as the design progresses. In the extreme case, chemicals or processes presenting unacceptable hazards will be abandoned at the earliest possible stage. Table 1.1 is a specimen hazard sheet to be prepared by the designer. This will ultimately lead to the assessment required under the COSHH Regulations (Control of Substances Hazardous to Health) and to its documentation.

ORGANISATION OF THE DESIGN PROCESS

The activity of design itself costs money, typically 15% or more of the final plant capital cost. It is therefore important to know as soon as practicable whether the projected plant is likely to be an economic proposition. In the event of an unfavourable forecast, effort can be directed towards increasing the economic viability of the process. In the last resort, the project may be abandoned. More proposals are in fact abandoned at some stage than reach completion. This is to be expected: an organisation in which the diversity of ideas does not exceed the resources for their execution has no opportunity for choice or selection, and is unlikely to survive!

It is therefore evident that even the earliest stages of the design process are of crucial importance; and that the whole design operation has to be planned from the outset for speed, economy of effort and the avoidance of mistakes in calculation and conclusions.

EXERCISES

1.1 There is a market demand for nitrobenzene and you are asked to design a plant to meet it. In 10 minutes, list as many as possible of the items you would expect to find in the design Data Book.

1.2 You are asked to design a plant to oxidise cyclohexane with air to a cyclohexanol mixture. Prepare a Hazard Sheet for cyclohexane.

TABLE 1.1
Specimen hazard sheet: sulphuric acid

Formula:	H_2SO_4
Synonyms:	Oil of vitriol; oleum (when it contains dissolved SO_3); ROV; BOV.
Appearance:	Colourless to dark brown, viscous liquid.
Freezing point:	10.5°C. Note that observed freezing points depend on the purity and, especially, the amount of dissolved water.
Boiling point:	350°C (with decomposition).
Chemical properties:	Sulphuric acid is a strong acid, that is, it is completely dissociated in dilute solution in water. (Strength and concentration are often used synonymously, but have quite distinct technical meanings.)
Reaction with water:	Sulphuric acid is miscible with water in all proportions with considerable heat evolution; because of this, dilution of the acid by addition of water is potentially explosively violent. Dilute solutions should be prepared by cautious addition of the acid to water.
Reaction with metals:	The acid dissolves metals evolving hydrogen or sulphur dioxide. Cast iron resists strengths above about 75% w/w whilst lead is not attacked by acid of less than 80% w/w.
Considerations for plant design when sulphuric acid is used:	
Hazards arise from:	(a) Unplanned or uncontrolled mixing of acid and water (especially adding water to acid) resulting in heat generation and violent ejection from open vessels; and dilution to corrosive strengths, with damage to, or failure of, equipment; (b) Reaction with organic materials producing heat and perhaps asphyxiating sulphur dioxide; (c) Splashes and spillages causing skin irritation and chemical burns of varying severity; (d) Acid leakage onto structures, floors and drains may corrode metals and form sulphates with ceramics, leading to 'floor heave' and structural failure.

(continued overleaf)