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Systematic Generation of Engineering Line Diagrams

by

Suella Long


A Doctoral Thesis

**Submitted in partial fulfilment of the requirements
for the award of**

Doctor of Philosophy of the Loughborough University

January 1999

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SYNOPSIS

This thesis describes research into a methodology for the systematic development of engineering line diagrams (ELDs) from process flowsheets with a particular emphasis on safety, health and environmental (SHE) and operability issues.

The current approach to the consideration of safety in design is largely reactive, relying on design reviews such as the HAZOP. If design safety is to be improved, then a comprehensive system, incorporating both proactive and reactive methods, must be adopted. The facility to develop proactive safety systems relies upon the presence of a systematic design procedure. Since design at this stage seems generally to be rather haphazard, there is a need to introduce structure to the design task before any progress can be made in the improvement of safety.

Introducing structure to the design task not only provides a framework for the incorporation of SHE and operability issues, but should also improve the effectiveness of the overall design and the efficiency with which it is completed. More specifically, fewer good design opportunities should be lost due to poor information handling and the amount of rework arising from misunderstandings between different disciplines should be minimised. In addition, learning how to perform the design task should become easier for new recruits.

Relevant work in the fields of process design, process safety, engineering drawings and ELD development is discussed. An analysis of perceptions of the design task within industry is presented. The generation of a systematic method by iterative case study work with designers is described. The structural features of this method are explained. Some examples of the application of the method are given and the results of a trial within industry are discussed.

This research has shown that there is no existing work which captures the logic for the order in which decisions for developing a first ELD are made. Neither is there a complete analysis of the activities and issues contributing to ELD development. A novel method for the systematic generation of ELDs has been produced and used as a framework for the incorporation of SHE and operability issues into design. Trials of the method within industry have shown it to be successful.

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CHAPTER I - INTRODUCTION

This thesis describes research into engineering line diagram (ELD) development from process flowsheets. In particular, it is concerned with the proactive incorporation of inherent safety, health and environmental (SHE) issues into this stage of process plant design. The research was undertaken for the PREMIUM project: a collaborative project between ICI Engineering and Loughborough University.

In this first chapter, a brief introduction to the general topics of process plant design and SHE in design is given, before focusing on the specific topic of how to improve consideration of SHE issues in the generation of ELDs.

Process plant design is a term used to describe the creative application of engineering theory and experience to achieve a practical objective which satisfies a market need (Scott & Macleod, 1992). It is a complex task made up of many different design activities to which a number of different engineering disciplines contribute and throughout which several different types of information must be managed.

Process plant design is an expensive activity, contributing approximately 12% to the overall cost of a project (Lockie, 1996). Fig. 1.1 below demonstrates how the opportunity to make economically viable changes to the design decreases with the project time elapsed.

Whether a project is concerned with creating a new process plant or with carrying out modifications to existing plant, the objective should be to create a design which is safe and operable whilst keeping down costs. In order to achieve this objective, it is necessary to identify any safety, health or environmental hazards early in the project timescale. In this way, changes can be made to improve the inherent SHE features of the design at minimal cost. If the identification of such hazards is left until a late stage in the project, then any changes made are likely to be both costly and inferior.

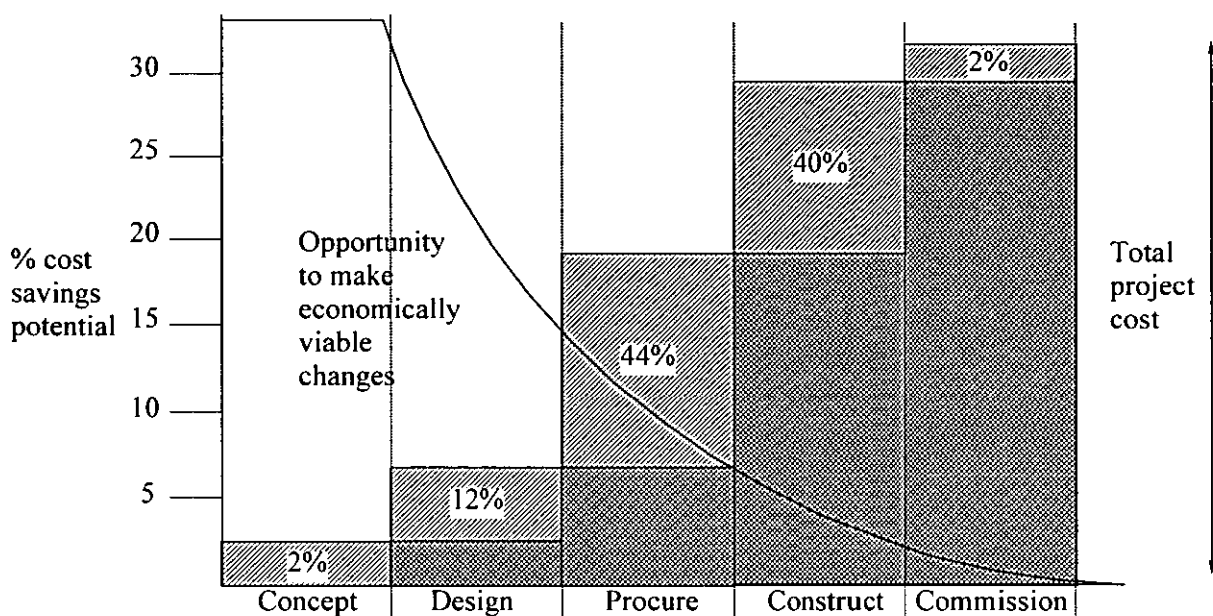


Fig. 1.1 - Project costs (adapted from Lockie, 1996) showing the declining opportunity to make savings and the relative contribution of each stage to total costs

Until quite recently (~1990), the only method for identifying hazards used consistently in process design was the Hazard and Operability Study (HAZOP). This study is generally carried out at the end of the detailed process design stage (i.e. the 'late stage' in table 1.1), on the firm ELD. Although this technique is effective in the identification of hazards, a number of problems can arise through the timing of the application of the technique (Turney, 1990). Table 1.1 illustrates these problems.

Table 1.1 - Timing of hazard and operability studies (after Turney, 1990)

<i>At a late stage</i>	<i>At an early stage</i>
Benefits	Benefits
<ul style="list-style-type: none"> - Design well developed. - Hazard study an effective check. 	<ul style="list-style-type: none"> - Flexibility to consider inherently safe design
Disadvantages	Disadvantages
<ul style="list-style-type: none"> - Design frozen, main plant items often on order. - Little opportunity for 'inherently' safe design. - Safety achieved by 'bolt-on' systems. 	<ul style="list-style-type: none"> - Design details not thought through. - Hazard and operability studies become design meetings. - Too many changes. May be necessary to restudy final design.

One of the measures which has been taken to overcome these problems of timing is the development by ICI of a 6-stage hazard study process to be applied as shown in fig 1.2 (Turney, 1990). This 6-stage system provides a continuous reiterative study of the potential SHE hazards of the design. Hazard study 3 is equivalent to the conventional HAZOP.

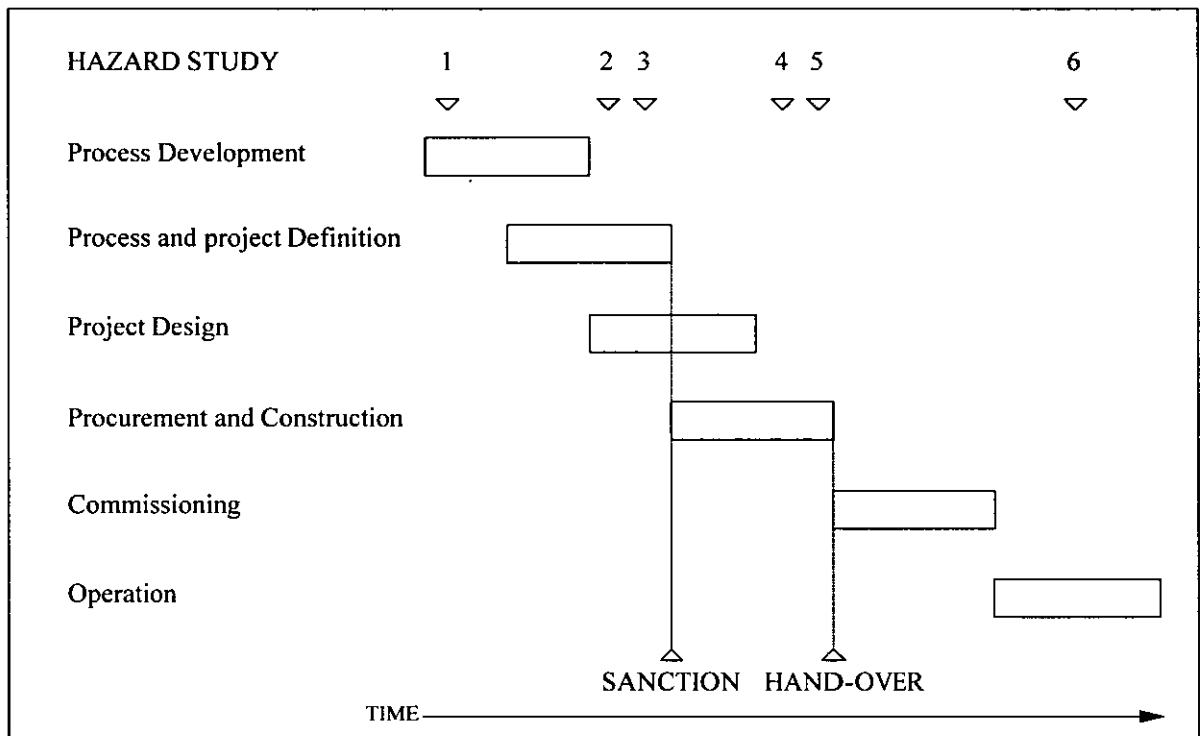
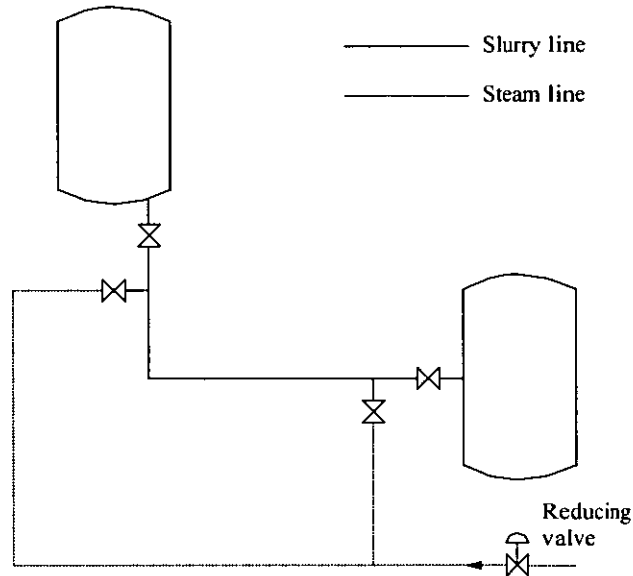


Fig. 1.2 - Typical project programme showing ICI hazard study procedures (after Turney, 1990)

Though this procedure should lead to improvements in design, it does not represent a complete approach to the consideration of SHE issues. The reason for this is that hazard studies are reactive systems - they are carried out after particular design steps have taken place. If such systems are not complemented by proactive methods, which aim to influence the design before and during each design step, then much of their value as a cross check on the design work is lost. In addition, allowing poor design to persist under the assumption that it will be corrected at a later point in the project wastes both time and money, not least because late changes often lead to modification chains such as that illustrated in fig 1.3. Modification chains are defined by Kletz as modifications which produce a chain of subsequent changes and a degree of unwanted complication that was never foreseen (Kletz, 1986).

One of the strengths of the HAZOP is that it examines the system as a whole and as a team effort whereas individual designers tend only to check their own areas of interest. The incorporation of SHE aspects into the design should therefore be improved if a team-based forward looking approach to the development of the design is taken.

(a) - Original design



(b) Step 1. Second line with steam connections added

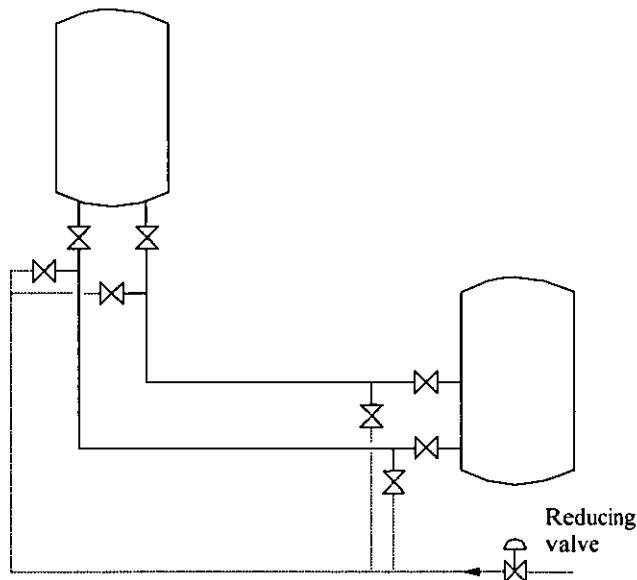
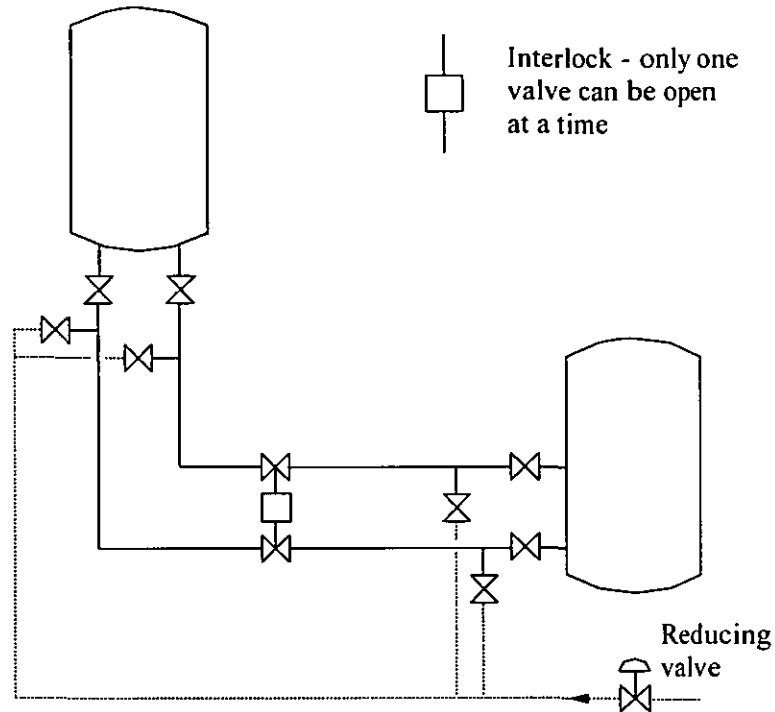


Fig. 1.3 - A modification chain (after Kletz, 1986). The steps in the chain arise from the following arguments:

A slurry is to be transferred under pressure from one vessel to another. To clear chokes in the transfer line and to clear the line at shutdowns connections are provided so that the line can be steamed from either end. Nevertheless it is feared that chokes might interrupt production.

Step 1 - Install a second transfer line for use during the initial period of operation with the intention that it be removed when sufficient operating experience has been gained. This also requires steam connections so that it can be flushed from either end.

(c) Step 2. Interlocked isolation valves added



(d) Step 3. Steam connections added to centres of transfer lines so that they can be flushed outwards from dead-ends

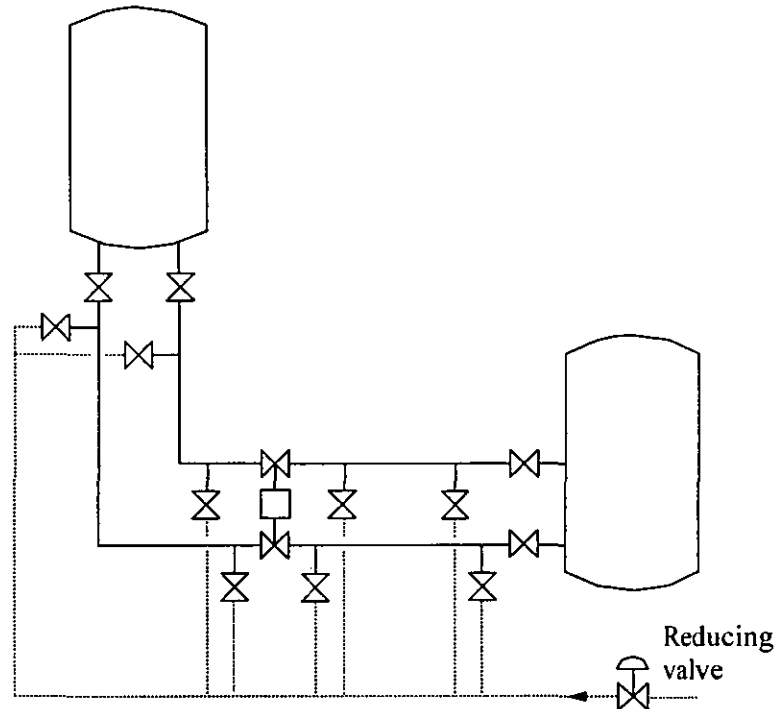


Fig. 1.3 (cont'd) - A modification chain (after Kletz, 1986)

Step 2 - Relief and blowdown study indicates that the two lines could be operated simultaneously, even though this was not intended. The downstream vessel should therefore have twice the relief capacity. To avoid this, additional interlocked isolation valves are fitted.

Step 3 - This causes two more dead-ends in each line. It must be possible to flush with steam from these dead-ends to each vessel, so four more steam connections are added.

(e) Step 4. Relief valve added to steam supply line

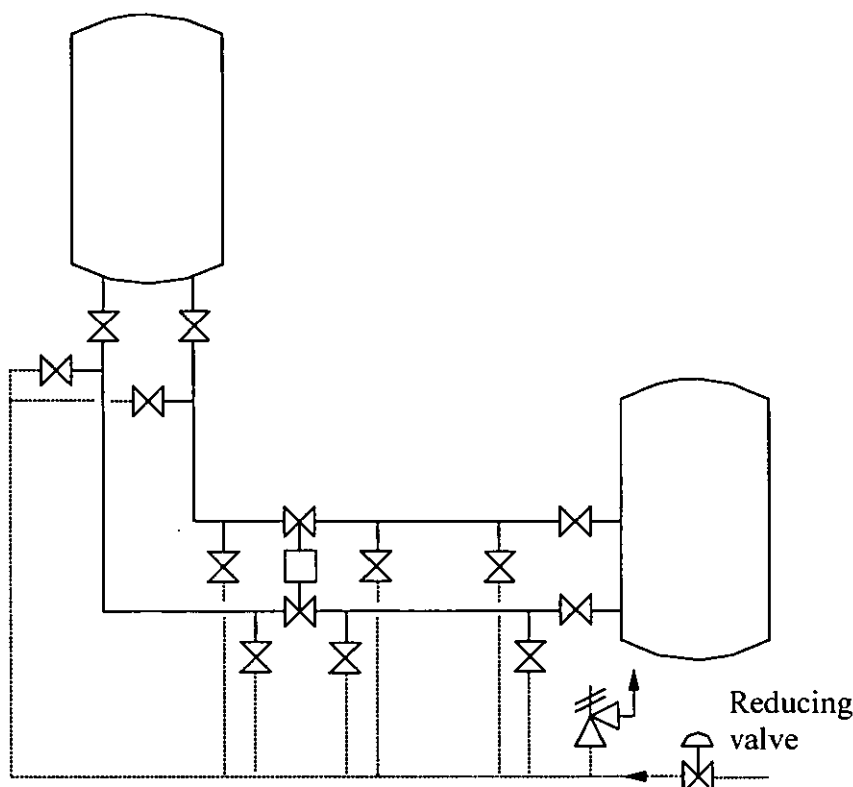


Fig. 1.3 (cont'd) - A modification chain (after Kletz, 1986)

Step 4 - To be certain the spare line is always ready for use, the steam must be kept flowing continuously. The transfer line is designed to withstand the process pressure, not the steam pressure. This is acceptable for an occasional flush but not if the steam is flowing continuously. A relief valve must therefore be fitted to the common steam line, downstream of the pressure-reducing valve, to ensure that the design pressure of the process equipment is not exceeded.

Referring back to fig. 1.1, the 'design' stage represents a turning point in the project in terms of cost versus versatility. Detailed process design, that is the development of ELDs from process flowsheets, constitutes a significant part of this stage and provides substantial opportunity to implement cost effective changes for improvement of inherent SHE performance. Focusing on this specific stage of design, there is a need to understand how the design is carried out before any proactive approach to the incorporation of SHE issues into design can be developed. Once the design task is fully understood, it can be structured so as to support the management of all the different people and information involved with a view to optimising consideration of SHE issues.

This thesis describes research leading to the generation of a methodology which provides a logical, systematic approach to the development of ELDs from process flowsheets

incorporating comprehensive handling of SHE and operability issues. Following the introduction, chapter 2 reviews the literature pertinent to the topics of notional engineering line diagram development and safety. Chapter 3 describes a survey of current practice and some task analysis work carried out in support of the literature review. Chapters 4, 5 and 6 present the conception, development, structure and application of a new methodology articulating the order in which decisions for developing a first ELD should be made and detailing the relevant activities and issues which should be addressed. Chapter 7 discusses the outcome of this research, with chapters 8 and 9 covering the conclusions and further work respectively. References are provided in chapter 10.

CHAPTER II: LITERATURE REVIEW

2.0 Introduction

The literature reviewed falls under four main subject headings:

- process design
- process safety
- process engineering drawings
- line diagram development

The first section of the literature survey, on the general topic of process design, covers: design environment, definitions, design methodologies, nature of the design task and basic design principles. This section is intended to 'set the scene' for the thesis in terms of design.

The next section of the survey is concerned with process safety in design. This section looks at: the general safety climate; safety culture; safety systems; the differences between the concepts of inherent safety and safety; integrated safety, health and environment (SHE) management; and engineered safety. Again, this section is intended to give a brief overview of all the concepts relevant to the thesis in terms of safety in design.

The third section, which is concerned with engineering drawings, starts to focus a little more on some of the detail relevant to the thesis. This section gives a brief description of the types of drawing used in design before going on to talk specifically about process flowsheets and engineering line diagrams, giving a summary of their history, definitions and novel work to date.

The final section of the survey is concerned with the specific subject of the thesis: the development of engineering line diagrams from process flowsheets. Existing work in the field of line diagram development is discussed and the two key concepts of decision support and information handling in design development are introduced.

A discussion of the conclusions drawn from the literature reviewed is given in section 2.5.

2.1 Process Design

Process design is often referred to as both an art and a science. It is an art because it is a creative activity which involves the generation of ideas to achieve a desired purpose. It is a science because it is dependent upon the application of fundamental concepts such as heat and mass transfer, physical chemistry and thermodynamics.

Many different disciplines contribute to the design process. A core project team will typically consist of process / project engineers, control engineers, mechanical engineers and operations representatives. However, depending upon the nature of the project, additional team members ranging from chemists at the conceptual design stage to equipment specialists at the detailed engineering design stage may be needed.

There is a variety of interpretations of the term 'process design'. These have been devised by different authors to highlight key features in the context of different priorities in design. A straightforward definition is given by Landau & Cohan (1966): "Process design is the application of chemical engineering principles to the design of a chemical, petroleum refining or other process plant". Pohjola, Alha & Ainassaari (1994), who are interested in performance drivers in process design, define process(ing) as "control of phenomena for a purpose". Meanwhile Nishida, Stephanopoulos & Westerberg (1981) who are concerned with the potential for application of computer tools in design define process synthesis as "the act of determining the optimal interconnection (structure) of processing units as well as the optimal type and design of the units within a process". These latter definitions are more abstract as they relate to specific aspects of design.

The design process is, according to Lees (1996), perceived to consist of the following three stages:

1. Research and development
2. Process design - including development of the flowsheet and detailed process design

3. Engineering design and equipment selection.

The above description represents the typical approach for design of continuous plant. Batch process design differs from continuous in that:

- chemistry, rather than equipment, is used much more as a driver for avoiding engineering difficulties
- the use of standard equipment is more common
- there tends to be a much greater degree of manual intervention in the operation of batch processes.

Consequently, the emphasis at the different stages of design changes for batch plants - much more time needs to be spent on procedural issues including sequencing and scheduling, while the process design required in terms of equipment configuration and associated drawings may be quite limited. However the same basic principles apply and the same stages in the design process can be identified.

This thesis is focused around stages 2 and 3 of the design process as described above. More specifically, it is concerned with the development of engineering line diagrams from process flowsheets. The position of this process design activity in relation to the many other design activities which occur within the design phase of a project is shown in Fig. 2.1.

As highlighted in chapter 1, there is a need to understand how this part of process plant design is carried out before any proactive approach to the incorporation of SHE issues can be developed. This understanding can be gained by collecting together all the activities and issues contributing to ELD development in some form of methodology, as Scott & Macleod imply:

“Professional designers may use a modular approach to ELD construction. They know from experience what lines and arrangements are required for standard equipment items (e.g. a distillation column and ancillaries); and by adding to each major equipment item on the flowsheet such associated groups of ancillaries they are able to build up the whole diagram.

The principles of line diagram construction are, however, better illustrated by a painstaking systematic approach through the following steps..."

(Scott & Macleod, 1992)

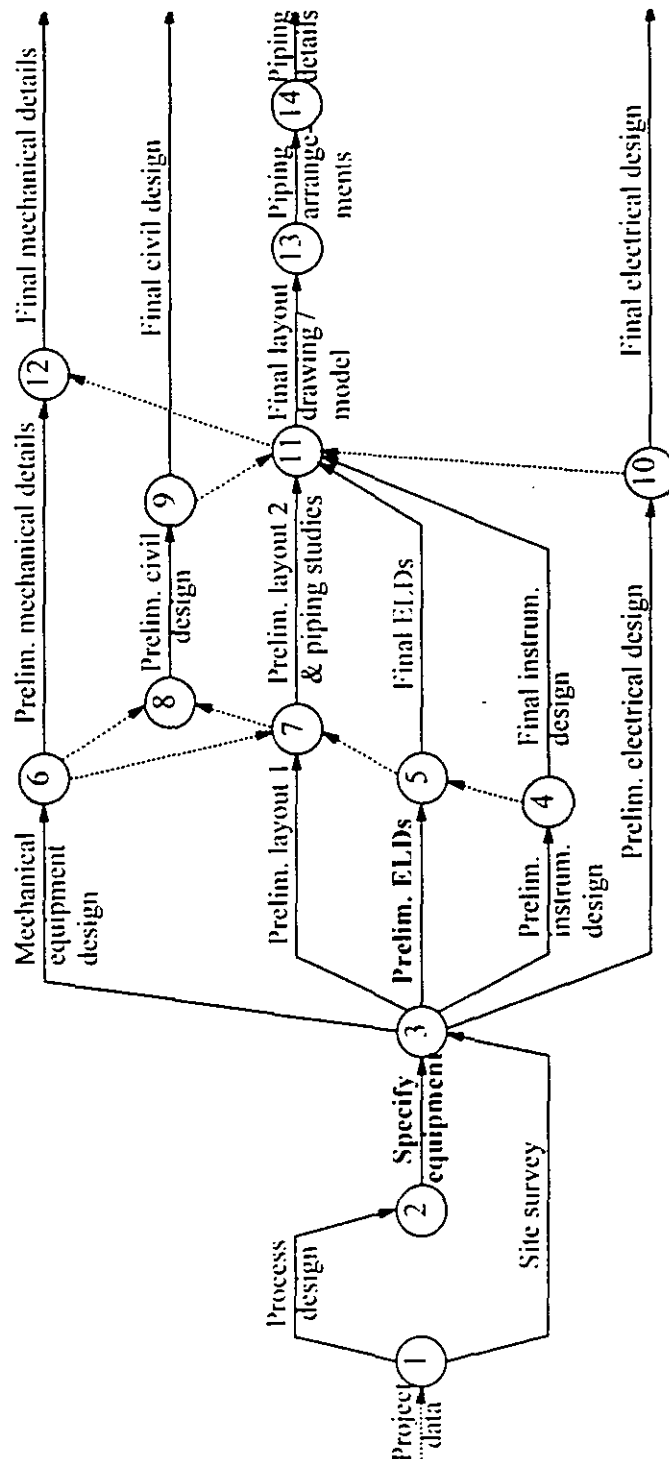


Fig. 2.1 Typical plant layout and design network (from Lees, 1996) showing in bold relief the design stages studied in this thesis

2.1.1 Design Methodologies

A methodology, according to Tanskanen, Pohjola & Lien (1995), is an attempt to effectively systematize an activity. A variety of process design methodologies exist within the literature. Most of these are concerned with conceptual design, that is the development of the process flowsheet. While the emphasis of this thesis is on the development of engineering line diagrams rather than process flowsheets, these conceptual design methodologies can be used to identify similarities in the nature of the design process. In addition, they can be used to gather information on the features which make a good methodology.

Douglas (1985) presents a procedure for synthesizing process flowsheets which is based upon a hierarchy of decision levels supported at appropriate points by heuristics. The purpose in developing this procedure was to fill the gap in the literature associated with “the logic and / or the order in which decisions for developing a first flowsheet are made”. A parallel gap exists in the literature on developing engineering line diagrams from process flowsheets.

Douglas identified that the major errors in existing designs were caused by fixing the flowsheet too early in the development of a process. This situation arises because the process design problem is always underdefined so that various assumptions must be made in order to progress with the design. These assumptions fall into three categories:

- those which fix part of the process flowsheet and, when changed, generate process alternatives
- those which fix some of the design variables and, when changed, affect optimisation
- those which fix connections to the environment and, when changed, affect operability and control.

Douglas found that, typically, the effects of changing the majority of these assumptions are not considered until a base-case design - based on profitability - has been developed. This limits the opportunity for identifying better process alternatives. By introducing a more systematic method for handling the assumptions and screening the process alternatives, Douglas argues that “reasonable” process designs will consistently be developed.

A conceptual design methodology has also been developed by Pohjola, Alha & Ainassaari (1994). These authors believe that “the chemical engineering approach to systematising process design should start from understanding the process and especially the phenomena to be controlled”. This belief stems from the observation that process behaviour is not completely fixed by structure but is also dependent on various other phenomena and the way in which these are controlled. The methodology presented is again hierarchical in nature. It is based upon the Douglas principle of systematising ‘procedural’ knowledge but also introduces the concept of ‘declarative’ knowledge describing the design target.

Continuing the work of Pohjola et al, Tanskanen et al (1995), highlight the following weaknesses in the Douglas methodology:

- the methodology, which can be considered to be controlled by performance driven strategy, does not include process controllability and safety issues as part of its performance measure
- the methodology is unit operations driven, which means that the process is broken down structurally in a predefined way (which is arbitrary). This limits creative design to new combinations of old operations.

The aim of the methodology worked on by Tanskanen et al is to “guarantee a reasonable consumption of resources by suggesting that design decisions be made in the relevance order, with the relevance referring to the relevance with respect to process performance (sic)”. In other words, performance in terms of control, profit and safety is used as the driver for the decomposition of the design problem. The key questions asked are:

1. Can we control the phenomenon (to make it have the rate and the extent we desire)?
2. Can we control it profitably and safely?

The philosophy of the methodology is described below and an example is used to illustrate what is meant by the terminology.

First of all, a single boundary process topology is assumed. If the control of phenomena cannot be guaranteed within this single boundary process topology, then the interior (i.e. the process) is “disaggregated” into sub-interiors (sub-processes). This facilitates the introduction of discontinuities in the material state distributions and allows phenomena in each sub-

interior to be controlled separately. The boundaries of the sub-interiors should preferably be permeable (e.g. vapour / liquid boundaries) rather than impermeable (e.g. vessel walls) in order to increase the degrees of freedom in interaction. Impermeable boundaries are used where necessary for rigidity reasons. Each sub-interior itself may then be disaggregated, and so on, until a solution has been reached.

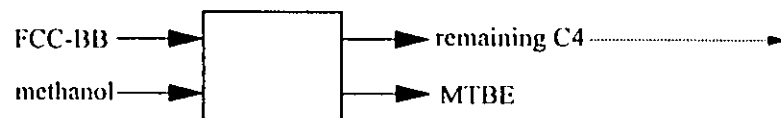
As an example, Tanskanen et al describe the conceptual design of an MTBE (methyl tertiary-butyl ether) production unit. The first step is to assume a single-boundary process topology, the purpose of which is to restrict material. From the functional specification of the unit, the input and output flows through this boundary are known. This is illustrated in fig. 2.2 (a). Given this topology, the question of how the MTBE and remaining carbon can be removed separately from the same interior with a single liquid phase arises. This functional specification is hard to fulfil and so the “primitive flowsheet” is believed not to have sufficient inherent controllability. Therefore, it is necessary to “disaggregate” the interior to form a two-boundary interior, shown in fig. 2.2 (b).

The two-boundary interior creates two different output material flows, in this case vapour and liquid. If the correct type of equipment is chosen within this two-boundary limit - in this case a reactive distillation column - then it is possible to achieve the required controllability. However, in order to increase the controllability of undesirable phenomena such as heat generation and catalyst deactivation, it may be necessary to disaggregate the process further, this time using a rigid boundary, to give a three-boundary interior. This is interpreted physically by the introduction of a second column upstream of the reactive distillation column.

Tanskanen et al (1995) argue that the structural disaggregation of the process using both permeable and impermeable boundaries lifts the limits on creative design identified in the Douglas methodology. Controllability, rather than profitability, is used as the key performance driver with safety and profitability being evaluated once the technical feasibility has been confirmed.

DISAGGREGATION

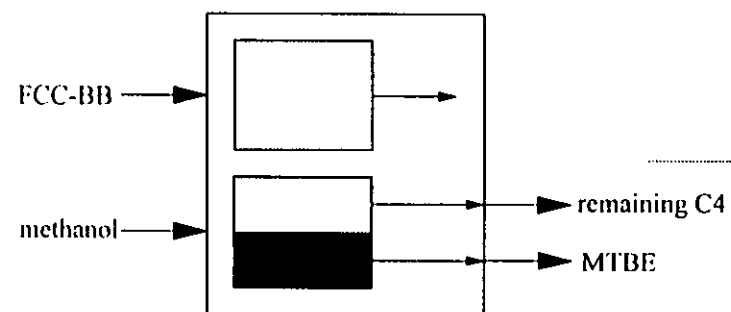
a) Primitive flowsheet



b) Two boundary process



c) Three boundary process



FEASIBLE STATE DISTRIBUTIONS (fulfilling the process purpose)

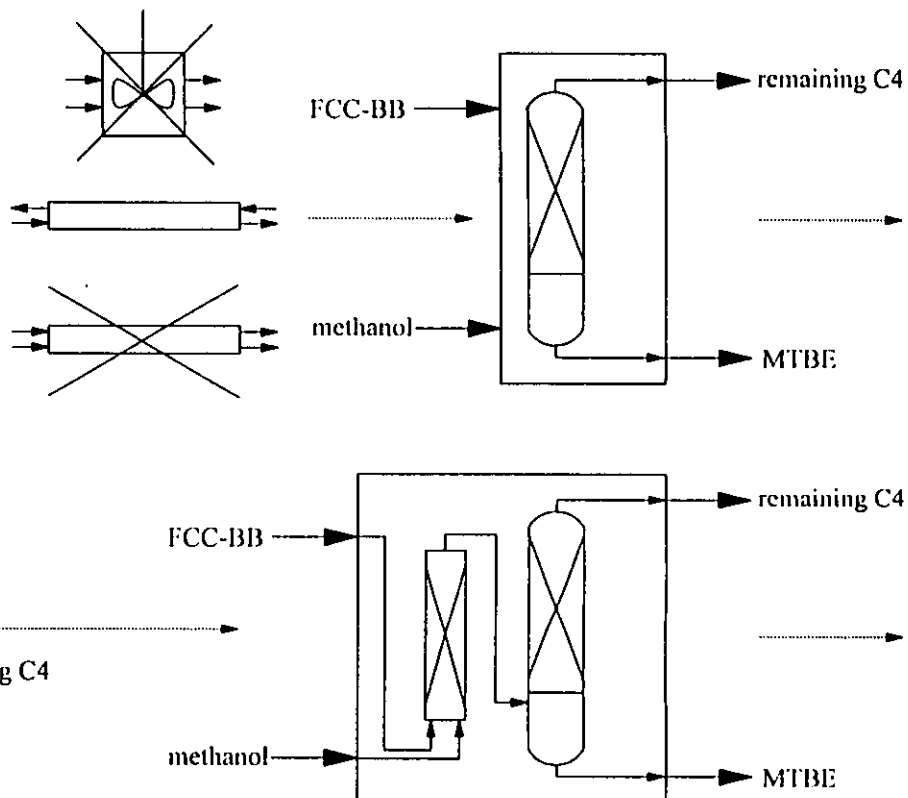


Fig. 2.2 - "Boundary disaggregation and feasible distributions" (from Tanskanen et al, 1995)

2.1.2 The Design Task

The design of chemical plant is a cyclic activity. Modifications are made as more information becomes available, as constraints or opportunities are recognised and as the situation changes (Lees, 1996). Throughout the development of a design, as these successive refinements are made, it is important to maintain a focus on the overall problem.

There are many different ways in which the design task can be analysed. Chandrasekaran (1990) proposes that design in general should be addressed through a generic vocabulary of tasks and methods that are part of design. He believes that design problems in different domains differ only in the mixture of methods and subtasks which must be combined to meet the task objectives. In computational terms, the key to understanding design is to understand the structure of the task, and how the tasks, methods, subtasks and domain knowledge are related.

Meanwhile, Takeda, Veerkamp, Tomiyama & Yoshikawa (1990) describe a design process as a mapping from the function space to the attribute space whereby the designer starts with the functional specification of a design object and continues the design process until a design solution is obtained. An illustration of this is given in Fig. 2.3.

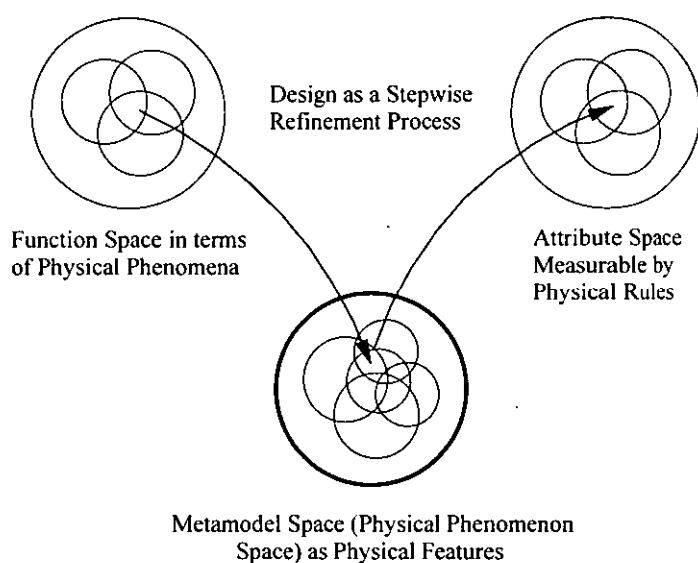


Fig. 2.3 "Design process in the Real Knowledge" (from Takeda et al, 1990)

Silverman & Mezher (1992) describe the design task as a generate-test-refine-remember process. A design is generated, tested under various conditions, refined until a “stopping rule” is reached, then stored to help to start a new process for the next design task. A number of life cycle repetitions of the generate-test-refine-remember steps are required to produce a robust design. These authors write:

“an engineer who creates a design needs to determine whether the design is free of errors that can lead to high manufacturing costs, tragic accidents because of design defects, low use because of poor product quality , and a host of other downstream concerns. The domain of engineering design is much harder than other domains, and errors are more likely to arise and remain undetected until it is too late to do something about them...”.

There are a number of factors which may contribute to this vulnerability to error in engineering design. One of the most fundamental problems in engineering design is that famously expressed by Kletz (1991): people don’t always know what they don’t know. He gives as an example of this the events leading up to the explosion at Flixborough:

“The explosion at Flixborough in 1974, which killed 28 people, was due to the failure of a large (0.7m) diameter temporary pipe which was designed and installed very quickly by men who had great practical experience and drive but did not know how to design large pipes operating at high temperature and pressure. This is understandable; the design of large, highly-stressed pipes is a specialised branch of mechanical engineering. But they did not know this and did not realise that they should have called in an expert in piping design. Instead they went ahead on their own. Their only drawing was a full-sized sketch in chalk on the workshop floor.”

The problem of not knowing what you don’t know is obviously particularly acute in newly qualified engineers who have little if any experience.

Silverman & Mezher (1992) attribute such errors in engineering design to the “misuse of various types of knowledge”. They define four categories of knowledge which may be used to complete a task:

- A - Irrelevant knowledge
- B - Correct knowledge
- C - Overlooked knowledge
- D - Missing knowledge

Typically, the designer will be focusing on the 'irrelevant' and 'correct' knowledge and will ignore the 'overlooked' knowledge. The designer is obviously unaware that there is missing knowledge as illustrated in the example from Kletz above. These categories of knowledge can be grouped into two types of error: misconceptions and missing concepts. The error classes, along with a sample of illustrative lower-level processes that contribute to them are given in table 2.1. In order to improve the outcome of a task, some means must be found to help the designer to eliminate the 'irrelevant' knowledge, to use the 'overlooked' knowledge and to identify and use the 'missing' knowledge.

Table 2.1 Categories of Possible Designer Errors and Sample of Illustrative Causes (Silverman & Mezher, 1992)

MISCONCEPTIONS - Commissions (Category A) and Omissions (Category C)	
ACCIDENTS/SLIPS/LAPSES	
	Memory Lapses
	Skill Slips
COGNITIVE BIASES	
	Availability Bias in Information Aquisition
	Representativeness Bias in Information Processing
	Confirmation Bias in Feedback Processing
MOTIVATIONAL BIASES	
	Corporate and Societal Culture
	Need to belong
	Reward systems
MISSING CONCEPTS - Category D Errors	
	Insufficient training
	Knowledge Decay/Half Life
	Rotation to New Position/Promotion
	Interdisciplinary Breadth of Engineering Domain

On the subject of eliminating the use of 'irrelevant' knowledge, one of the mindsets which must be overcome is neatly summarised by Wells (1981): "...when studying design there is a tendency to 'look at a solution without seeing the problem". Use of methodologies such as those described in section 2.1.1 should help designers to move away from this mindset and to develop designs which are fit for purpose both in terms of technology and cost *and* in terms of safety, operability and location.

One method of encouraging the use of 'overlooked' and 'missing' knowledge in design is to use expert systems. Silverman & Mezher (1992) describe how expert critics may be used to encourage better use of knowledge. They write: "...critics can help the expert before he / she psychologically commits to an erroneous solution. For example, one can include before-task influencers and situated tutors in a decision network that also contains batch, after-task critics. This approach is particularly important in engineering design applications where many of the errors result from missing knowledge...". This emphasises the fact that the ability to influence knowledge use both proactively and reactively is a key contributor to good design.

Another approach which should help to avoid the misuse of knowledge in design is to record fully the design history. Chung & Goodwin (1994) describe a "design information system that captures three different aspects of design history: exploration of design alternatives, reasons for design decisions and design constraints". This system was developed to address the issue of continuity in design. The authors write:

"In the process industry, the design of a chemical plant is a difficult and time-consuming task that requires the co-operation of skilled personnel from many different disciplines. Team members propose solutions and possible designs and argue for or against the alternatives....these teams make decisions concerning many different aspects of the plant....it is very important that relevant information is captured during the design stage so that engineers who come to work on the design later may be able to get answers to questions like 'Why certain decisions were made?', 'What alternatives have been explored?', and 'Will this change violate any design constraints?'."

Similar work has also been carried out by Banares-Alcantara in conjunction with various other authors (King & Banares-Alcantara, 1996). His work is based upon 'KDBS' - a support system for the conceptual design of chemical processes. This uses four networks to represent the design process as it evolves through time:

- one for the design objectives
- one for the design alternatives
- one for models of these alternatives
- one for design rationale describing the decisions made during the evolution of the alternatives.

The systems described above address the issues of 'missing' and 'overlooked' knowledge described by Silverman & Mezher (1992). When Chung & Goodwin's system was applied the engineer found that it gave "a better understanding of what areas of the design had been explored and what the advantages and disadvantages of the possible solutions were". Other benefits listed include:

- saving time in future designs
- helping to avoid past mistakes
- helping to prevent disasters caused by modifications to existing plants.

(Goodwin & Chung, 1994)

2.1.3 Design Principles

Up until the 1980's, the emphasis in plant design tended to be on developing plant which met the product requirements at reasonable cost. Issues such as safety and operability were often not considered until very late in the design. Consequently, the facilities required to meet safety and operability expectations were very much 'add-ons' to the process. In the case of operability, modifications during commissioning were quite commonly required to compensate for poor original design.

These days, design engineers are much more aware of the importance of good safety and operability of a process. These features are now considered in parallel with technical

feasibility and cost. However, there is still the tendency in many cases to use cost as the primary driver in design. Safety and operability features are then viewed in terms of their extra (short term) cost rather than in terms of their potential (long term) cost benefits.

Some of the principles that are now considered to be key to good design are:

- safety and loss prevention
- waste minimisation and pollution prevention
- operability.

Safety and loss prevention

All engineers have a duty to use their best endeavours to ensure that the plant which they design is as safe as is reasonably practicable. In order to carry out this duty, they must provide appropriate measures to restrict the potential for loss associated with:

- death or injury to workers
- death or injury to the general public
- damage to plant
- damage to third party property
- damage to the environment
- loss of earnings from lost production and lost sales opportunity.

(Skelton, 1997)

The issues of safety and loss prevention must constantly be addressed throughout the lifetime of any plant. Methods of incorporating safety and loss prevention features during the design phase of a project are discussed at length in section 2.2.

Process Operability

Process operability should be a fundamental objective of good design. Yet it was not until quite recently that designers began to talk to commissioning engineers and operators and involve them in the design process. In 1982, Roodman (1982) wrote “The major emphasis during plant design is on steady-state operation - the process and equipment are primarily

designed for steady-state conditions". This problem is still evident today: it is not until the engineering line diagram or process and instrumentation diagram is developed that any serious consideration is given to non-steady state or non-routine operations. In addition, operating procedures still do not tend to be written until after the plant has been built.

Roodman goes on to suggest the following measures to improve the consideration of operability in process design: "After a process is chosen, at least an outline of a preliminary operating guide should be prepared for each plant area, to enable a complete process flow diagram to be drawn - including equipment for process start-up and shutdown. Also, an overall plan should be made up for total plant start-up and shutdown sequencing, to allow optimum use of start-up equipment for multiple areas, and to provide utility requirements and sources for both start-up and shutdown".

As well as addressing the issues of operating procedures and facilities, operability can also be an inherent feature of a process. Lees (1996) gives a description of the features which make a plant inherently less operable: "a process which has no 'fallback' positions and which in the extreme case presents the operator with a stark choice of continuing to run at a given set of conditions or of shutting down completely". This idea is picked up again under 'user-friendly' plants in section 2.2.3 on inherent safety.

Pollution prevention and waste minimisation

Pollution prevention and waste minimisation are both concerned with reducing the effects that the plant has on the environment. Both local and global effects must be considered. Local concerns might include the risk of pollution of nearby rivers or watercourses or the effects of fugitive emissions on employees. Global concerns are commonly reported upon - air pollution leading to acid rain; the greenhouse effect; photochemical smog; problems of disposal and landfill are just some examples.

Environmental problems, like operability and safety issues, used to be approached in an 'add-on' manner, typically using end-of-pipe treatment. Moores (1995) writes: "historically environmental regulations addressed end-of-the-pipe parameters; thus industry followed and

focused its compliance efforts there...". Despite widespread acknowledgement that it is more cost effective to minimise production of wastes and emissions than to control them at the end of the pipe, the chemical process industries have only recently turned to pollution prevention or waste minimisation as an alternative. Moores lists the following reasons for this change in approach:

- previous regulated limits could usually be met through relatively low-cost end-of-pipe technologies
- ever tightening end-of-pipe regulations have disproportionately increased treatment costs
- in some cases, compliance can no longer be achieved by conventional end-of-pipe technologies
- the regulation of air, water and solid wastes in concert means that water pollution problems can no longer be 'solved' by converting them to air pollution problems, air pollution problems by changing them to solid waste management and disposal problems and so on.

In summary, an integrated approach to the solution of air, water and solid waste problems through source reduction and pollution prevention is required. This approach must not only integrate the solution of the different types of environmental problems but also integrate the solution of environmental problems with those of health and safety. The concept of inherent safety, health and environment (SHE), which provides such an integrated approach, is discussed in section 2.2.4.

Following this trend of 'integration', the preferred approach to the pollution and waste minimisation problem, from the theoretical point of view, is a life cycle approach (with respect to the processed materials). Rather than treating the plant as a separate entity, the whole supply and distribution chain should be considered part of the pollution prevention and waste minimisation problem. In practice, this type of analysis can be very involved and will necessarily raise awkward issues of ownership, distribution of responsibility and so on. However, in the current climate of ever tightening environmental regulations it may not be long before a life cycle approach becomes compulsory.

Crittenden & Kolaczowski (1995) provide a comprehensive account of the waste minimisation philosophy, methods of approach and solution options. The basic concept is to design the plant in such a way that it inherently produces less waste - whether through better conversion, better separation, better heat integration or any of a number of other methods available.

2.2 Safety in Design

'Safe' is defined in The Pocket Oxford Dictionary of Current English (Allen, 1984) as "free of danger or injury, affording security or not involving risks, reliable, certain, prevented from escaping or doing harm". In process design, safety is usually measured in terms of risk. This, in turn, is defined as "the likelihood of a specified undesired event occurring within a specified period or in specified circumstances" (Jones, 1992). Since risk depends on the probability of an event occurring and on the consequences of that event, the presence of a hazard does not automatically imply the presence of high risk.

Values for fatal accident rates and the probability of accidents show that the chemical industry is one of the safest industries (Wells, in Liu, McGee & Epperly, 1987). Yet plant safety remains one of the chemical industry's major concerns. From society's point of view, chemical processing is a high risk activity. The consequences of an accident can be huge. Accidents can result in the release of toxic materials or large amounts of energy with disastrous consequences for workers and third parties. Releases from chemical plant can go well beyond the site boundary and can cause both long term and short term effects. Though the frequency of such incidents is low, the combination of involuntary exposure, lack of personal control over the outcome and lack of understanding of the materials and processes involved, together with the potential for widespread consequences, leads to a disproportionate amount of fear in the community.

As a result of this fear in the community and of the increased hazard potential which has accompanied the persistent move towards larger scales of production to reduce unit costs, the

chemical industries are continually looking towards better means of ensuring safety in plant design and operation.

2.2.1 Approach to Safety

The following are some key requirements for the proper consideration of safety in a chemical plant at the design stage:

- a good knowledge of the process activities and the chemical materials handled
- a systematic approach to the evaluation of the process

(Wells, 1980)

- early implementation of loss prevention considerations so that there is reasonable confidence that major expenditure to avoid hazards will not arise at a later stage of the project
- an ongoing awareness of the consequences of the decisions made.

Skelton (1997) writes that safety in design must be both proactive and reactive. Steps must be taken to ensure that the design is safe from the outset. At the highest level, this philosophy must be represented by a safety culture within the company. According to Skelton “a company will only have a good safety record if it has the right attitude to safety and it must start at the top”. Otherwise, referring back to Silverman & Mezher’s (1992) categories of error, there will be a misconception in design in the form of a motivational bias.

Koivisto (1996) highlights the following weaknesses in the traditional approach to safety in design:

“Current design practice often results in a situation where several alternative solutions are being weighed according to economic and functional criteria. More intangible criteria such as safety are typically taken into account at specific decision points rather than continuously.... The problem is that current design methodology (cf. Douglas, 1988) and current design practice imply that safety be considered systematically only at design points

where the process structure and state are fixed and not as a steering factor in process synthesis and analysis”.

This failure to use safety as a steering factor is attributed to “the lack of awareness of suitable methods and tools and even the lack of such methods and tools themselves”. Part of the problem, Koivisto believes, is the way in which safety has traditionally been defined. “First of all”, she writes, “the definitions do not use the properties or characteristics of the process or its environment systematically as the basis of the definition”. This is why safety is often regarded as an ‘add-on’ feature of the process, rather than an integral part of design. The second deficiency noted is “the restricted content of the concepts which are used to define safety”. Currently, the definition of safety tends to include only features which are known from past experiences. Using such a definition precludes “the possibility that safety could be influenced by something totally new...” as it has in recent years by the concept of environmental safety. Here we see a parallel with the observations made by Tanskanen et al (1995) on the Douglas methodology. The important point made by both sets of authors is the need to avoid systems which are overrestrictive and which inhibit the generation of totally new ideas or concepts.

Koivisto (1996) presents a “safety conscious design methodology”, based on the performance driven strategy of Pohjola et al (1994), in which safety is assessed in terms of “the probability that control of phenomena is lost” and “consequences”. The methodology provides a “prescriptive-synthetical” approach to safety in design, the characteristic of which is an “awareness of what the process safety should be after some design decision”. This is in contrast to the current “descriptive-analytic” approach where safety is seen as the result of the design decisions and needs to be analysed for acceptability.

Company culture and the safety conscious design methodology described above are examples of proactive safety influences - they can be used as drivers in design. Other examples of proactive safety influences are codes and standards, legislation and good practice. A code of practice is defined by Wells (1980) as “a system or collection of regulations, often involving safety matters. It usually takes the form of a systematic collection of laws and rules which may be given statutory force by some legislative body”. Meanwhile a standard is “an

agreement or authority to follow a certain rule or model, generally when dealing with recurring items". Companies may use public standards such as BS, ANSI, DIN or their own in-house standards.

Legislation and regulations bring all companies in a country to a minimum accepted level of safety. Beyond that, it is up to the company itself to maintain a philosophy of good practice. Wells (in Liu et al, 1986) believes that "good practice is the main suppressor of hazards" and that good practice is represented by a combination of:

- good specification of design criteria
- adherence to codes, standards and regulations
- good control and maintenance
- reliable plant.

Examples of reactive safety systems include safety reviews and hazard studies. A typical procedure involves carrying out safety reviews at the following six stages:

- conceptual design
- completion of flowsheet development
- basic process design freeze (HAZOP)
- completion of detailed design
- pre-commissioning
- completion of first year in operation

(Skelton, 1997)

Wells (1981) provides a comprehensive account of safety reviews in design. His paper includes a number of additional reviews such as relief and blowdown, electrical distribution, paving and drainage, which should be carried out alongside the basic hazard studies described above.

2.2.2 Design Safety Principles

The UK Management of the Health & Safety at work etc. Act Regulations 1992 quoted in Skelton's (1997) book give a good summary of the concept of safe design:

- if possible, avoid the risk altogether - for example by not using a particular substance or process
- combat risks at source rather than by palliative measures
- adapt work to individuals - for example apply good ergonomics
- take advantage of technological progress
- include risk prevention as part of a coherent policy
- give priority to measures which protect the whole workplace
- ensure everyone understands what they need to do
- ensure the existence of an active health and safety culture throughout the organisation.

The first point on this list illustrates the importance of the concept of safety as an inherent feature of the process. As Lees (1996) writes: "The safety of the plant is determined primarily by the quality of the basic design rather than by the addition of special safety features. It is difficult to overemphasise this point." The trouble is that most chemical manufacturing processes are, to a greater or lesser extent, inherently unsafe. This means that once the options for making the plant inherently safer have been exhausted, there will still be a need to introduce some (engineered) safety devices. In addition, a plant will require good operating practices to help ensure that dangerous situations are prevented from happening and that the consequences of any incident arising from the failure of these safeguards are minimised.

2.2.3 Inherent Safety

The concept of inherent safety is based upon the premise that the best way of dealing with a hazard is to remove it completely. An inherently safer process is described by Coulson, Richardson & Sinnott (1991) as "one in which safe operation is inherent in the nature of the process; a process which causes no danger, or negligible danger, under all foreseeable circumstances (all possible deviations from the design operating conditions)". Inherent safety

is, in principle, the best way of ensuring safety because it does not rely on the correct functioning of safety devices.

The concept of inherent safety was first introduced by Kletz (1978) in the 1970's in a paper entitled "What you don't have can't leak". This phrase is now well-known in the domain of inherent safety and represents its fundamental goal: the removal or reduction of hazardous inventories.

Inherently safer design can be achieved by any one or a combination of the following methods:

- intensification, using so little hazardous material that it will not matter if it all leaks out
- substitution, using a safer material instead
- attenuation, using a hazardous material in the least hazardous form
- limitation of effects of failures, not by adding on protective equipment but by equipment design or by changing the conditions of use

(Kletz, 1996)

The idea can be extended to produce 'user-friendly' plants (in which human error or equipment failure do not have serious effects on safety) by utilising the additional concepts of:

- simplification
- avoiding knock-on or domino effects
- making incorrect assembly difficult or impossible
- making status clear
- designing equipment that is able to withstand incorrect installation or operation
- making equipment easy to control
- software / procedures

(Kletz, 1996)

Many papers have now been written on inherent safety. Some, such as that by Scheffler (1996) describe the application of inherent safety principles in specific types of process plant (in this case latex plants). Others, including papers by Snyder (1996), Englund (1991, 1995) and Hendershot (1988) provide examples of inherently safer design in unit operations,

services and equipment. Lutz (1995) gives a comprehensive checklist of inherently safer options from chemistry through design philosophy to emergency planning.

Hendershot (Jan. & Oct. 1995) also addresses the issues of conflicts in inherent safety and the differences between inherent safety and safety. On the subject of conflicts, Hendershot (Jan. 1995) writes :

“Perhaps in an ideal world it would be possible to simultaneously minimise the risk associated with all of the process hazards. However, in the real world, the various hazards are not independent of each other, but are inextricably linked together. A process modification which reduces one hazard will always have some impact, positive or negative, on the risk resulting from another hazard.”

Hendershot (Jan. 1995) gives as an example of safety conflicts the choice between alternative process solvents, one of which is toxic and non-volatile, the other non-toxic and volatile. The comparison is shown in table 2.2.

Table 2.2 Some inherent safety advantages and disadvantages of alternative process solvents (from Hendershot, Jan. 1995)

Solvent	Inherent Safety Advantages	Inherent Safety Disadvantages
Non-toxic, volatile	Solvent is non-toxic, reducing hazards in normal handling, and in the event of a discharge due to a runaway reaction; the volatile solvent limits temperature rise in case of a runaway due to the ‘tempering’ effect when the solvent boils.	High vapour pressure of solvent results in potential for high pressure in the reactor in case of a runaway exothermic reaction.
Toxic, non-volatile	Runaway reaction exotherm may not be sufficient to raise the reaction mixture temperature to its boiling point, so there is no hazard of overpressurizing the reactor.	Potential exposure of personnel to toxic solvent, environmental damage in case of a spill.

Such conflicts do not only arise within the isolated domain of inherent safety. More commonly, the conflicts are due to the opposing requirements of safety and environment. The

trade-off which is made when people replace chlorofluorocarbons (CFCs) with other materials is a prime example. The alternative materials are inherently safer with respect to long term environmental damage. However they are often more hazardous with respect to flammability and acute toxicity.

These examples emphasise the importance of systematic evaluation of process safety and hazard issues. We must take care not to oversimplify the problem by optimising the solution in terms of one hazard and overlooking others. This theme of an integrated approach to hazard evaluation is picked up again in section 2.2.4 on inherent SHE.

In discussing the differences between safety and inherent safety, Hendershot (Oct. 1995) expresses the opinion that inherently safer processes are not the only means of attaining desired levels of process safety. Instead, they are a means of making it easier to achieve process safety objectives. He argues that sometimes, the benefits of the inherently unsafe route can warrant the expenditure of technical and financial resources which would be required to operate the technology safely. Hendershot (Oct.1995) illustrates this point by comparing road and air travel. In many respects, travel by road is the inherently safer option. Yet it is a well-known fact that travel on a commercial airliner is safer than travel by car. The reason attributed to this is the “large number of engineering, procedural and training features of the commercial airline transport system which allow it to overcome its inherent safety disadvantages...”.

A process engineering example of the problem of finding the right balance between safety and inherent safety is noted by Mansfield et al (1995) who made the following discovery in their discussions on inherent safety with industry:

“One company noted that increasing pressures to produce ‘friendly’ products meant that some of the manufacturing processes were becoming more hazardous due to the need to use more active reagents. In many ways this may be ‘inherently safer’ overall since it ensures the more serious hazards are on the plant where they can be dealt with effectively, and not at large in society.”

The point which Hendershot (1997) is driving at is that inherent safety is not a 'black and white' issue and is not the be all and end all of safe design. Though inherently safer plants offer greater safety potential they may not necessarily be safer. The overall safety of a process depends on good implementation of technology and good management.

Kletz (1996) writes about how the chemical process industries have been slow to adopt the inherent safety approach in comparison to other new safety methods such as quantitative risk assessment. He gives as a primary reason for this the fact that a fundamental change in the design process is required to accommodate the systematic study of alternatives during the early stages of design. Other reasons cited by Mansfield et al (1995) include:

- general lack of awareness
- lack of tools and methods
- need for some hard proof of the benefits.

According to Lutz (1996), the tide may now be turning as the desire for lower lifetime costs per unit of production is driving a "culture shift" towards inherently safer design. This is by no means a reason to become complacent, however, as the observations of Moores (1995) discussed in section 2.1.3 show that a similar promise of cost benefits from waste minimisation was not sufficient incentive to drive people across the 'culture barrier'.

2.2.4 Inherent Safety, Health and Environment (SHE)

Whilst there have been many papers written on the subject of inherent safety, very little is to be found in the literature on inherent environmental protection and health. Hendershot (Jan.1995) touches on the problem in his analysis of the conflicting interests of inherent safety but apart from that there is little else of any consequence. Turney (1990) writes:

"Up to the present, Safety, Health and Environmental aspects of a project have been considered in different ways..... Safety has progressed from the use of codes of practice to include the use of hazard studies and quantified assessment.... Environmental studies have generally concentrated on steady state emissions with, until recently, relatively little

attention being devoted to incidents.... Health issues have been considered largely by qualitative or semi-qualitative methods...”

In his paper, Turney (1990) presents the six stage ICI hazard study procedure as a method of combining Safety, Health and Environmental Studies. However, he emphasises that: “It is wrong for hazard studies to be the only way in which safety, health and environmental aspects are incorporated into the project. If this is so, much of the value of the hazard study, as a cross check on other work, is lost.” This comes back to the issue of proactive and reactive safety systems. The hazard study is reactive - it does not support creation of better designs but is used to validate the designs which have previously been generated. The question is, in what other ways can SHE aspects be incorporated into the project?

Mansfield et al (1995) have been looking at this issue of ways of incorporating SHE aspects into a project. The objective of their work, known as the INSIDE Project, is to “promote the use of inherent safety, health and environmental (SHE) protection across Europe and to develop tools to enable chemists and engineers to optimise processes and designs using the ‘inherent’ principles”. One of the key observations made during their review of the current status of inherent SHE was the need for “an integrated approach to safety, health and environmental issues... to handle the conflicts and mutual benefits that can arise”. This reflects the concerns expressed by Hendershot regarding oversimplification of the design problem. A common example is the conflict between safety and environmental requirements in relief venting. Fitting vent capture systems may improve the quality of emissions to the environment but introduces a safety problem by increasing the risk of overpressurisation.

One of the suggestions made by companies interviewed for the INSIDE project was that “in practice some form of systematic method would be needed to integrate inherent SHE in to the development and design activities...”. Mansfield et al (1995) have used this and other information collected from literature and industry to develop a tool to “promote identification and adoption of inherently SHE [sic] options”. The framework for this tool is shown in fig. 2.4.

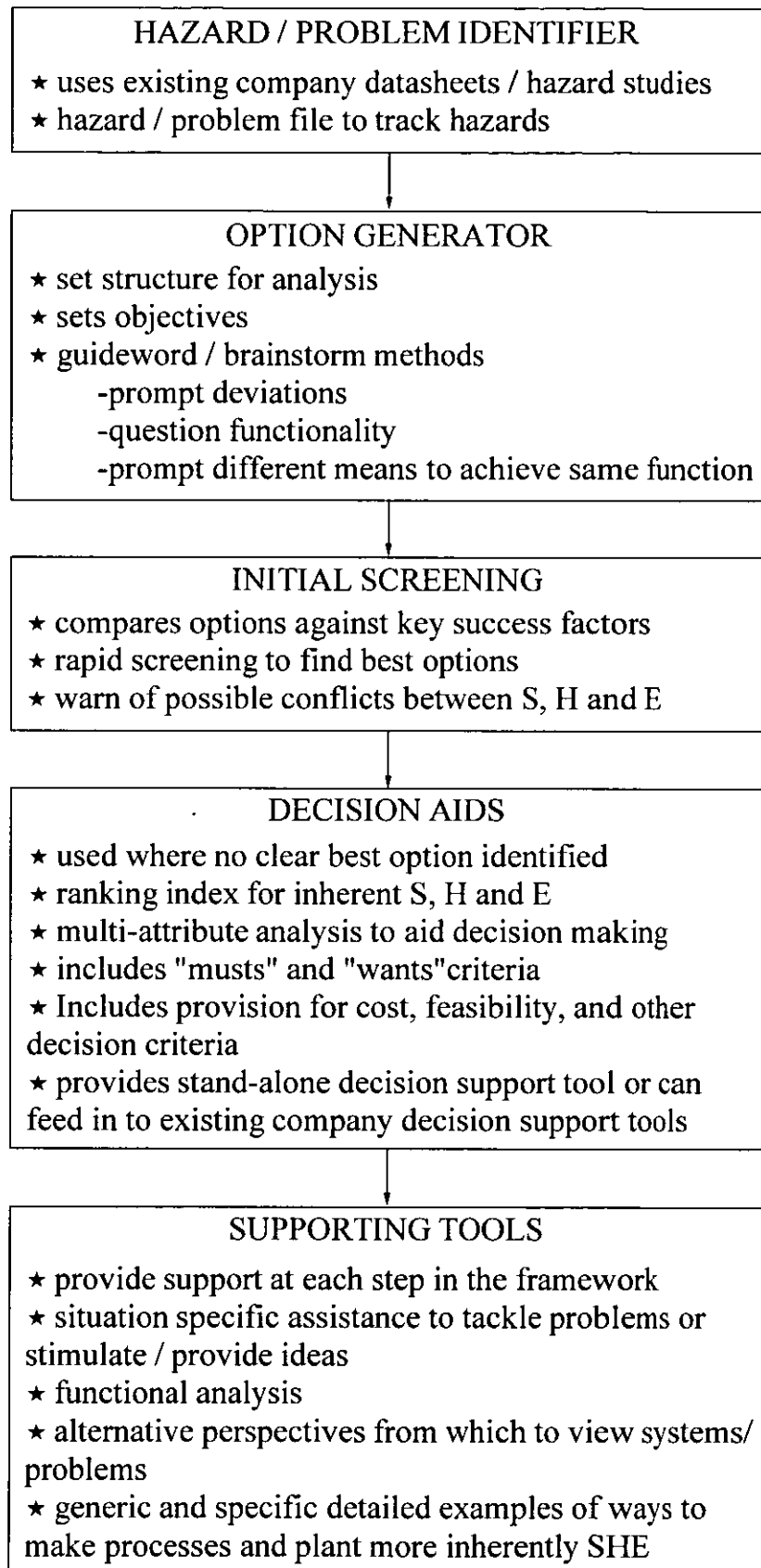


Fig. 2.4 Inherent SHE Tool Framework (from Mansfield et al, 1995)

2.2.5 Engineered Safety

Though inherent safety should be a primary objective in reducing the risk associated with any process plant, it can rarely provide the complete solution to process safety. This point is illustrated by Hendershot (1997) when he talks about safety potential (see section 2.2.3). The inherently safer plant will only be safer if it has the correct technology and management procedures to support it. Consequently, there will always be a place in process plant design for engineered safety.

Engineered safety may take the form of either ‘software’ or ‘hardware’ solutions. ‘Software’ solutions include management procedures, operating procedures and so on. ‘Hardware’ solutions are engineering solutions such as trips, alarms and other protective devices. During the design stages of a project, the focus is generally on the provision of hardware solutions, as the ultimate objective of design is to reach the stage where the plant is ready to be built. Since software solutions cannot be implemented until the plant is ready to operate, there is a tendency not to think too much about these during the design phase.

The first priority of engineered safety must be to ensure that the basic design is adequate under normal operating conditions. As Skelton (1997) writes:

“Properly designed, constructed, operated and maintained equipment will not fail catastrophically provided that its mechanical design conditions are not exceeded, the properties of the materials of construction do not deteriorate and the process conditions remain within specification.”

It is therefore important to get the basic design right by taking account of material properties, plant location, ambient conditions and so on. Once this has been achieved, a better perspective can be taken on the protective devices required to prevent the design conditions from being exceeded and in the extreme case to relieve the excessive condition before it can do any harm.

There are numerous ways in which hardware solutions for safety can be engineered into the process plant design. Some of the most fundamental methods are described below.

Fail-safe design

The basic principle of fail-safe design is to ensure that on power or other utility failure the system moves to a safe or stable position. Examples of fail-safe design include:

- ensuring that residual heat can be removed by natural circulation cooling rather than by forced circulation, e.g. by using thermosiphon coolers or natural draft cooling systems
(Skelton, 1997)
- ensuring that control or solenoid valves fail to a safe position (open, closed or 'stay-put') in the event of loss of electricity or instrument air
(Lees, 1996)

Second chance design

This is the term used to describe the provision of a line of defence to guard against a hazard resulting from a deviation from normal operating conditions. Examples of second chance design include:

- use of bunding to contain process spillages
- use of pressure relief systems to prevent over-pressurisation
- provision of arrangements for isolation if there is a loss of containment
- use of alarms to warn of hazardous conditions
- use of trips to take action against hazardous conditions
(Lees, 1996)

Safety margins

Safety margins are normally added in the evaluation of mechanical equipment parameters during the design stage. A typical margin of maximum working value (which may differ widely from normal operating values, e.g. because of abnormal operating conditions, start-up, shutdown, etc.) plus 10% is used. Otherwise, recommended values can be obtained from the appropriate standard or code of practice, or statutory legislation.

The use of safety (and other design) margins is intended to improve process safety (and operability). However, if this use is not carefully monitored, the incumbent overdesign can have the opposite effect. A common example of this is in the design of pumps. Pumps are specified according to their flow versus pressure characteristics. If each person in the design chain introduces a factor of safety for their part of the design, then the pump which is purchased may be capable of a much higher flow or pressure than was intended. If some connected parts of the plant are not designed to withstand this, then overpressure by the pump represents a process hazard. The overdesign reduces rather than increases the plant safety. Oversizing of control valves may have a similar negative effect if the valve is being relied upon to limit flow to a maximum value.

2.3 Engineering Drawings

Sections 2.1 and 2.2 above serve to provide general background information to the research by giving an overview of the topics of process design and safety in design. This next section begins to focus on the specific stage of design addressed by the thesis in considering the principal means of conveying design information - the engineering drawing.

There are three main types of engineering drawing commonly used in process plant design. These are the block diagram, the process flowsheet or process flow diagram and the process and instrumentation diagram or engineering line diagram. The most succinct formal definitions of these drawings are given in DIN 28004 Part 1 (1988). BS 5070 Part 3 (1988) describes the purpose of each diagram. These definitions and descriptions are given below.

Block diagram

Definition: "A block diagram is the representation of a process or a process plant in a simplified form by means of rectangular boxes connected by lines."

Purpose: "to show the essentials of an installation in sufficient block outline to indicate the main design features."

Process Flowsheet

Definition: “A process flowsheet is the representation of a process by means of graphical symbols connected by lines.”

Purpose: “to depict all the essential parts of a process or item of equipment which enables the analysis and calculation of physical characteristics to be undertaken.”

Piping and instrument diagram

Definition: “A piping and instrument diagram (P&I diagram) is the representation of the technical equipment of a given plant by means of graphical symbols connected by lines.”

Purpose: “to show in sufficient detail all pipeline, control and instrument information.”

The British Standards actually define the P&ID with reference to a ‘piping or systems diagram’ - a fourth diagram which is not generally recognised in the literature as one of the key documents in design. This diagram is probably akin to the ‘engineering flow diagram’ described by Sandler & Luckiewicz (1987 - see section 2.3.3) which would normally be used with a separate control and instrumentation diagram.

Block diagrams are used to develop the conceptual design of the process. They depict what is to be done without making any attempt to describe how the various objectives will be achieved. A number of block diagrams showing alternative process routes may be generated at the outset of a project. These are then screened to identify one or maybe two designs which are suitable for further development.

Once the process route has been fixed, flowsheets or flow diagrams begin to be developed. These are primarily used to present the heat and mass balances for the process. Because these show more detail, a number of flow diagrams will normally be generated corresponding to one block diagram.

As more information becomes available and more constraints are set, the design progresses in an iterative manner until the amount of detail required makes it sensible to split the flow diagrams into sections. These sections become the basis for the piping or line diagrams.

These are the definitive drawings produced to communicate the process design - they should eventually show all the detail necessary to support construction and operation of the plant.

This thesis focuses on the detailed stage of process design and specifically the development of engineering line diagrams from process flowsheets. Before elaborating on the definitions and functions of these diagrams, it is worth explaining a little about their origins.

2.3.1 History of Engineering Drawings

The information which follows on the history of engineering diagrams has been included as it is useful in helping to develop a fuller understanding of the motives behind the drawings and the priorities which have emerged with time. Old concepts which might have been forgotten or become obscure are revisited.

It is only really quite recently that the set of drawings described above has become the standard means for presenting process design development. Though British Standards on the use of graphical symbols in engineering drawings appeared as early as 1949, it was not until 1974 that the first standard on drawing types and style was produced. This section describes how designs were presented prior to the introduction of any standards.

A comprehensive account of the types of drawing used in plant design up until about 1960 is given in the different editions of Vilbrandt's book "Chemical Engineering Plant Design" (1st edn, 1934, 2nd edn, 1942, 3rd edn, 1949, 4th edn, 1959). Vilbrandt (1942) writes on the development of flow diagrams:

“For the preliminary stage there are three of these showing: 1) the flow of materials and chemicals through the process; 2) the sequence of chemical engineering unit operations involved; and 3) equipment to be used in the process.... These three diagrams are called qualitative flow diagrams and after careful development of each, the three are correlated into one....”

An example of such a 'qualitative flowsheet' is given in fig. 2.5. Note the 'still-life' form of representation and the extensive use of notes on the drawing. Such elaboration is no longer common practice as can be seen by comparing this diagram with the modern representation of a PFD given in section 2.3.2.

Once the separate qualitative flowsheets had been drawn up and combined into one 'equipment flowsheet' as described above, 'quantitative flowsheets' were developed. These were diagrams showing details of equipment size, quantities of materials, heat transfer needs and other service requirements (see fig. 2.6). From these it was easy to check what parts of the process information were still lacking. Finally, with a complete quantitative flow diagram in hand, equipment could be selected based on standard items available at the time.

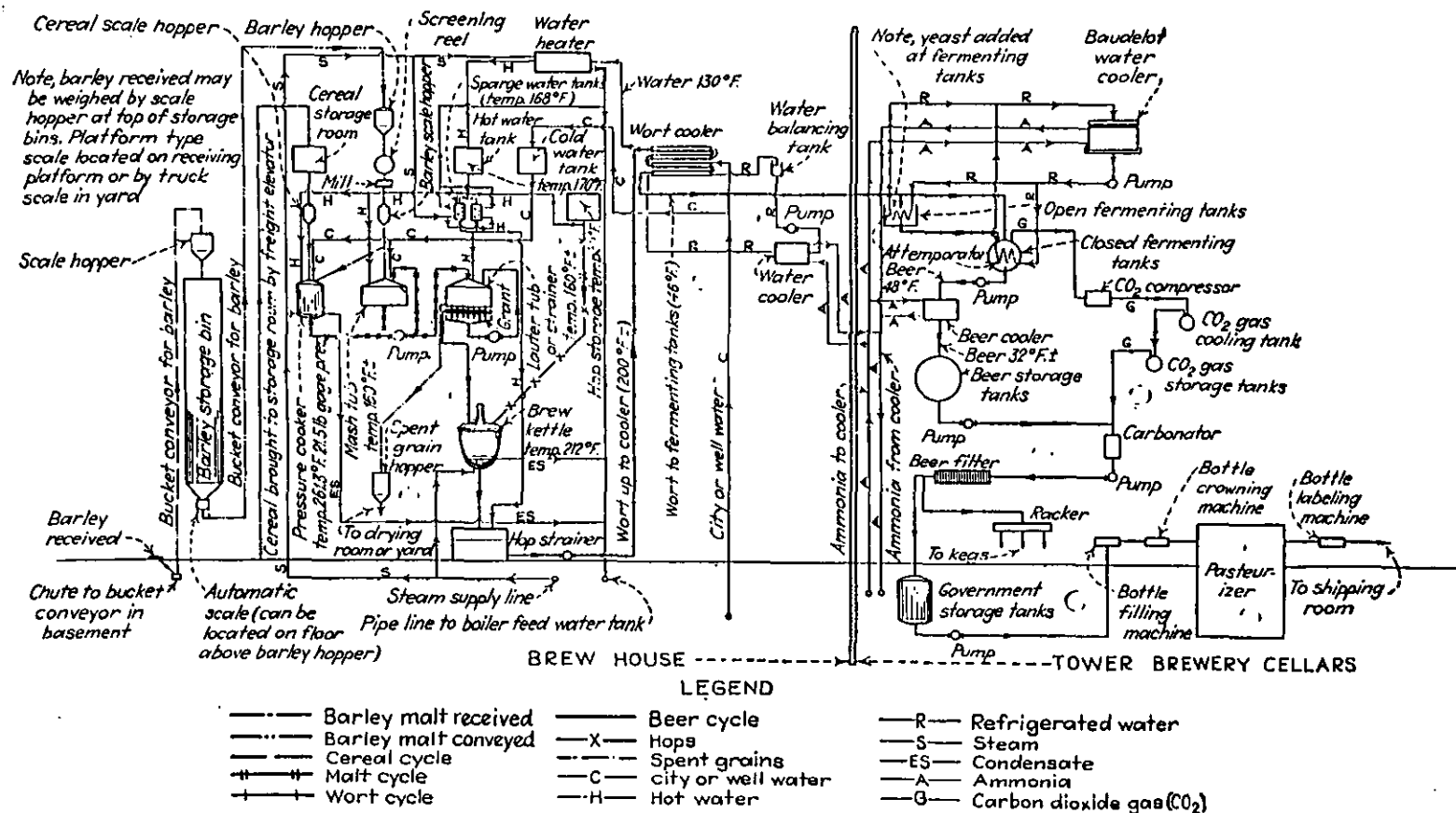
There is no mention in Vilbrandt's book of control and instrumentation requirements for the plant although these are represented in an equipment flowsheet used in one of the worked examples.

By 1959, the approach to design drawings has undergone a quite dramatic change. The 4th edition of Vilbrandt's book (1959) talks of material and energy balance flowsheets. These may be shown separately or together and in block form or including equipment and instrumentation. The use of tabulation of information is introduced, though the practice of writing all the numbers next to the equipment on the drawing has still not disappeared, particularly for simpler flowsheets.

In addition to the material and energy balance flowsheets, the following types of diagram are described:

- the 'detailed equipment flowsheet', which should include process piping, valving, drains, bypasses, vents etc. as well as the process equipment requirements. "Such flowsheets", Vilbrandt says, "are useful for plant construction work".

Fig. 2.5 Example of a 'Qualitative Flow Diagram' representing a brewery cycle (from Vilbrandt, 2nd edn, 1942)



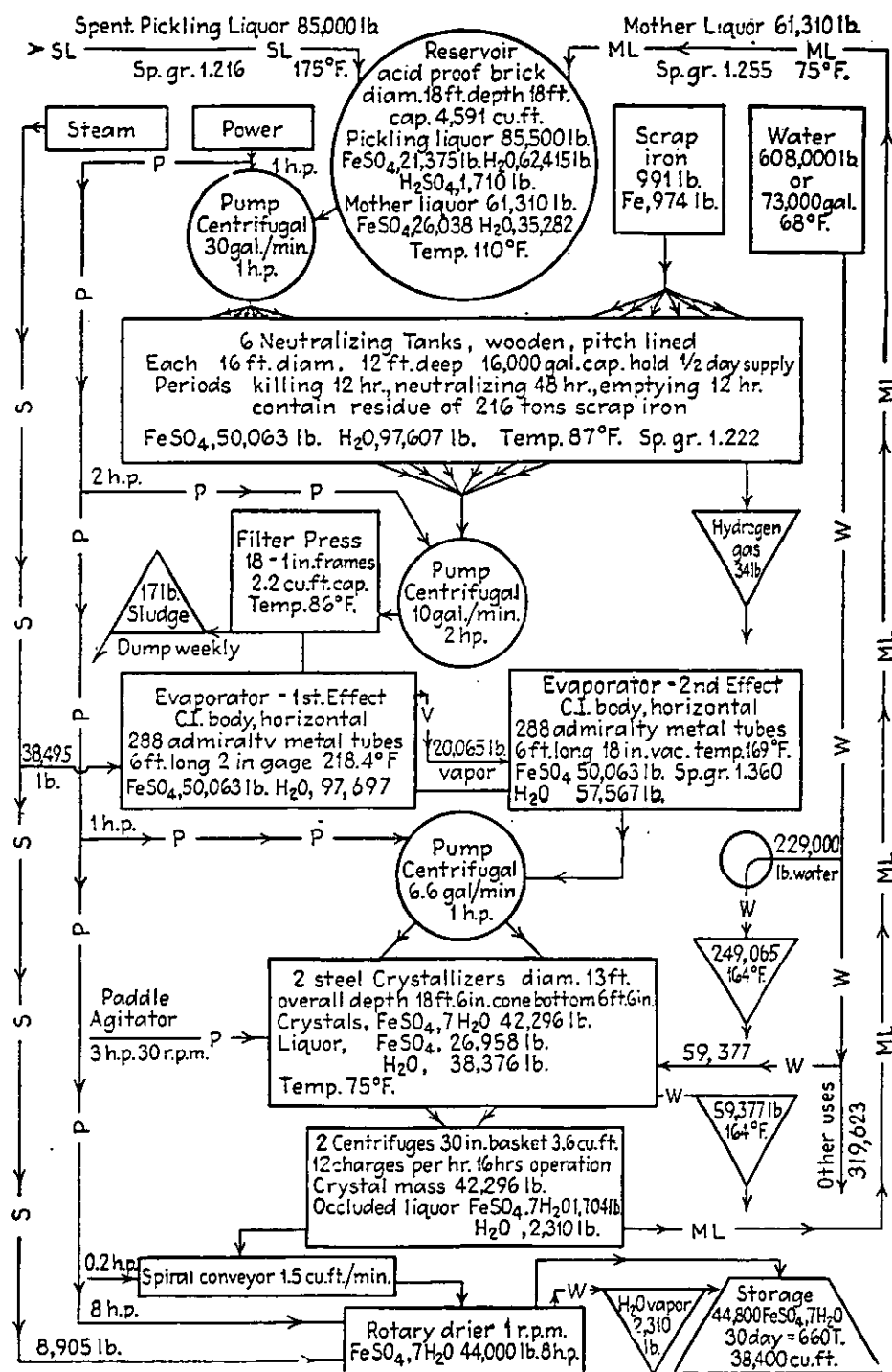


Fig. 2.6 Example of a 'Quantitative Flow Sheet' for a ferrous sulphate recovery plant (from Vilbrandt, 2nd edn, 1942)

- the 'instrumentation flowsheet' which is "useful for determining the requirements for process control and instrumentation." These could be incorporated into simplified flowsheets, or, if instrumentation was complex, a separate flow diagram could be used "bringing into bold relief all instruments and controls".
- the 'auxiliary flowsheet' covering requirements such as steam, water, fuel, air and other utilities.

In these descriptions we can see the parallels to modern day variations on the conventional flowsheet and line diagram.

One important concept highlighted by Vilbrandt (4th edn, 1959), which was new at the time, is that of using the diagrams to show layers of information which when combined form the complete design . He describes the concept as follows:

"A simplified equipment flowsheet is made up in black and white. Mounted on top of these are transparencies which contain one on each sheet, the detailed piping, the instrumentation, and the auxiliaries. Each transparent sheet is lined with different colour ink. In this manner any or all of the flowsheets required for a complete engineering flow diagram can be shown separately or together."

Though schematic drawings have been found in papers dating as far back as 1926 (Simon & Hinchley, 1926), the move from the more typical 'still-life' style drawings shown above to the widespread use of schematics and symbols did not take place until some 30 years later. The change in approach is illustrated quite clearly in the successive editions of Vilbrandt's book and, as would be expected, coincides to a large extent with the introduction of the first public standards relating to chemical engineering design. In Britain, these standards were:

BS 974 : 1953 Symbols for use on flow diagrams of chemical and petroleum plant

BS 1553 : Part 1 : 1949 Graphical symbols for piping systems and plant

BS 1646 : Part 1 : 1950 Symbolic representation for process measurement control functions and instrumentation.

Eventually, in 1974, the first standard giving definitions of block, flow and line diagrams (BS5070) was introduced.

2.3.2 Process Flowsheets and Process Flow Diagrams

Formal definitions of the term 'process flowsheet' and of the purpose of the process flowsheet were given in section 2.3. In this section, the defining characteristics and attributes of the process flowsheet and process flow diagram (PFD) are discussed.

Various analogies have been used to help describe flowsheets or flow diagrams in the numerous texts detailing the overall design process. These include reference to the drawing as "a diagrammatic model of the process" (Coulson et al, 1991) or "the road map of a process" (Ludwig, 1984).

An old but useful summary of the characteristics of an engineering flowsheet is given by Rase & Barrow (1967):

"It [the flowsheet] must be drawn so that the process flow and operations are immediately apparent. This is accomplished by omitting all but the essential detail using frequent arrows to indicate direction of flow, employing heavy lines for major flow lines, and indicating temperatures, pressures and flow quantities at various significant points in the diagram. Pertinent process design data are shown, such as heat exchanger duty, vessel design information, and special requirements such as required elevations of certain equipment. Convenient symbols for standard items, such as pumps and exchangers, are often used... Valves, utility lines and spare items of equipment are omitted except where needed to clarify the process. Only instruments essential to the control of the process are shown".

The attributes which make a PFD are elaborated upon below.

Defining attributes

DIN 28004 Part 1 (1988) defines the information which should be shown on the process flowsheet. This information is categorised into 'basic' and 'supplementary' as follows:

Basic information:

- type of equipment and machinery (except drives) required for the process
- designation of equipment and machinery (except drives)
- route and direction of flow of feedstocks or products, as well as of the process fluids and energy or energy carriers within a given process
- designation and throughputs or flowrates of feedstocks and products
- designation of energy or energy carriers
- characteristic operating conditions

Supplementary information:

- designation and throughputs or flowrates of process fluids
- throughputs or amounts of energy or energy carriers
- arrangement of main valves / fittings
- basic functions of instrumentation at critical points
- supplementary operating conditions
- characteristic dimensions of equipment and machinery (except drives), set out in separate lists, if necessary
- relative height of main items of equipment and machinery.

Fig. 2.7 shows an example of a process flowsheet. A more explicit definition than the one above is given by Sandler & Luckiewicz (1987), who believe that the flowsheet should show:

- important control functions
- all major equipment for unit operations
- lines connecting equipment with flow arrows
- material balance with flowrate in weight and / or on a molar or volumetric basis
- important physical parameters e.g. temperature, pressure, specific gravity, viscosity

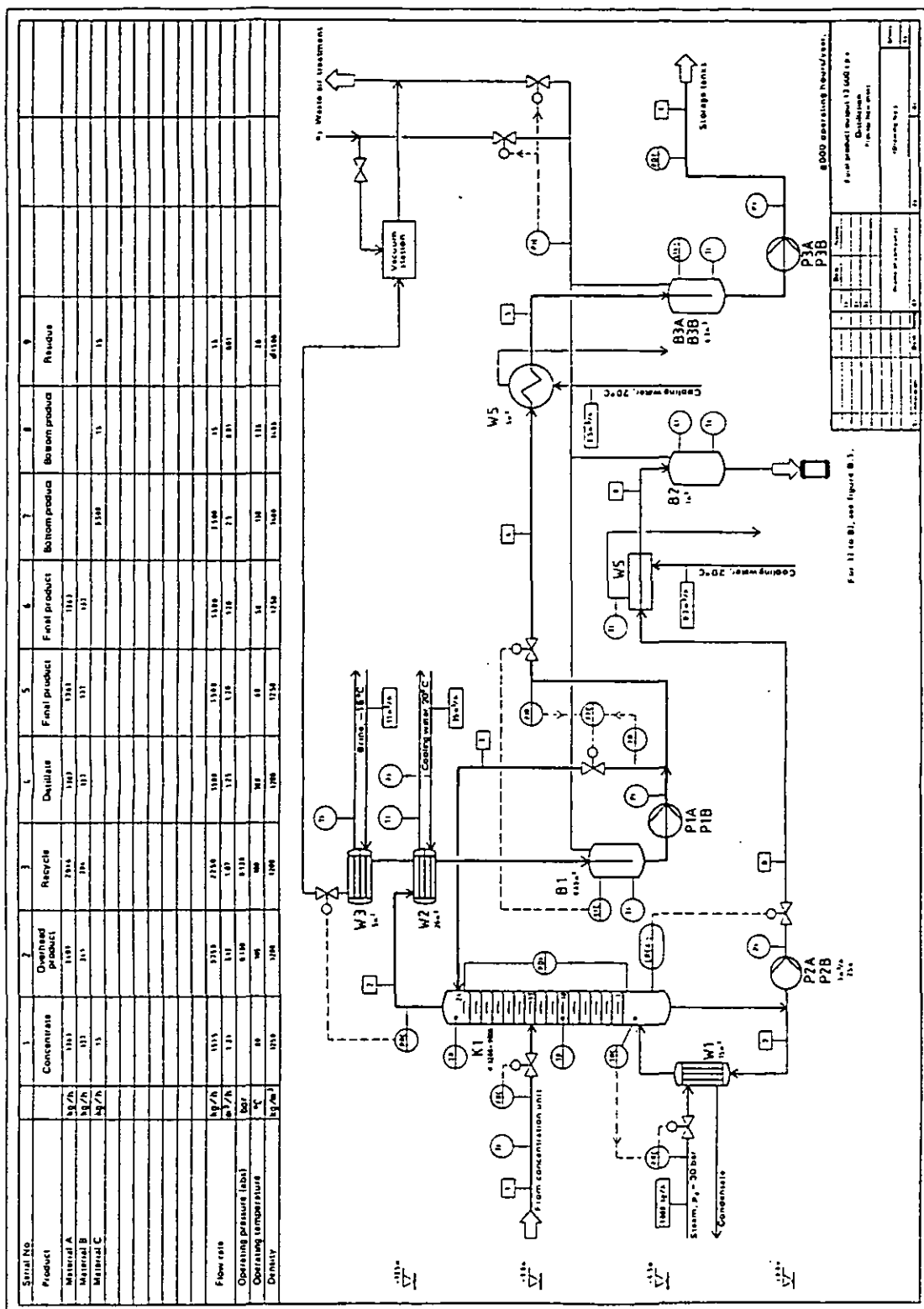


Fig. 2.7 - Example of a Process Flowsheet (from DIN 28004 Part 1, 1988)

- energy balances defined by exchanger duties near units, and by showing heats of vaporisation / fusion if a physical change takes place
- net endothermic / exothermic heats of reaction at any unit where a chemical reaction occurs
- approximate brake horsepowers should be shown for important pumps, compressors and blowers
- major utilities e.g. cooling water
- other equipment e.g. agitators, tanks etc. may be included if crucial to the process itself
- minor streams e.g. pump recycles, side streams omitted

Additional requirements to those given by Sandler & Luckiewicz include:

- major plant items drawn to scale
- plant items positioned in correct elevation relative to each other
- type of equipment clearly indicated
- more important valves
- sizes of more important lines
- item list

(Austin, 1979)

- equipment numbers
- equipment names

(Ulrich, 1984)

- may finally contain trip systems, more detailed instrumentation and valves
- summary of total service requirements is included
- expensive materials of construction noted
- preliminary datasheets for items which represent a large percentage of the plant capital cost (at the initial PFD stage)

(Rose, Wells & Yeats, 1978)

- critical dimensions and performance requirements or capacities for each item
- operating cycles and batch sizes for batch processes

(Landau & Cohan, 1966)

As the wealth of different definitions indicates, there is no real consensus on the features required in order for a drawing to warrant the title 'process flowsheet'. The issue is further complicated by the second term 'process flow diagram'. This is taken by some to be synonymous with 'process flowsheet' while others make a distinction between the two terms, taking 'process flow diagram' to mean a more detailed version of 'process flowsheet'.

Supporting documents

Whilst the emphasis of this research is on the development of engineering drawings, it is important to note that the engineering design 'package' at each stage of the project (i.e. block, flowsheet and line diagram) is not complete without a set of documents providing additional information which cannot be shown on the diagrams. Holmes (1973) writes on this subject:

“Details of equipment, operation, control, materials of construction, heat and mass flows, temperatures, pressures, and flow stream composition must all be provided to enable specialist engineers to design the plant equipment. The piping engineer in particular must have specifications of:

- Schedule of piping connecting equipment items
- Flow rates in piping
- Flow stream compositions in piping
- Physical properties of process materials
- Flow temperatures and pressures
- Instrumentation and control equipment in pipes
- Permissible pressure drop in pipes
- Materials of construction for piping and valves.....”

Rose, Wells & Yeats (1978) give details of the following documents which they believe should form part of the total 'process engineering flowsheet package' and hence be supplied with the PFD: mass balance and heat balance, equipment summary lists and equipment datasheets, and process description.

Novel work

There is plenty of literature detailing the general requirements for process flowsheets and flow diagrams and also how to draw these diagrams correctly (Ulrich, 1984; Mansfield, 1993; Sandler & Luckiewicz, 1987). However, until quite recently there has been very little novel work published in the fields of flowsheet and line diagram development. Hence there are very few papers written on the subjects these encompass. The majority of the new work addresses computer-aided engineering, which is not of primary concern here. Excepting this work, flowsheeting seems to be particularly poorly represented, and the only journal article found on the subject is one on the selection of flowsheet symbols which dates back to 1968 (Hill, 1968).

The article by Hill emphasises the importance of using generic symbols which show *design intent*, i.e. equipment function rather than form, during the earlier stages of design, which ties in with his view of the flowsheet as *a statement of process objectives*. He gives as an example a steam flowmeter (fig. 2.8), for which there are a number of specific symbols and where the selection may depend on the piping configuration which may not be known at the time of the flowsheet preparation. He adds further weight to his argument by advocating the use of simple, standard symbols, writing:

"the enforced use of standards improves communication in two ways: first, the function being performed is emphasised by eliminating the distraction caused by detail; and second, the possibility of error that is likely to occur when a detail is repeated many times is virtually done away with."

The idea of the flowsheet as "a statement of process objectives" with the emphasis on equipment function rather than form ties in with Takeda et al's (1990) view of the design task as a mapping from function to attribute space.

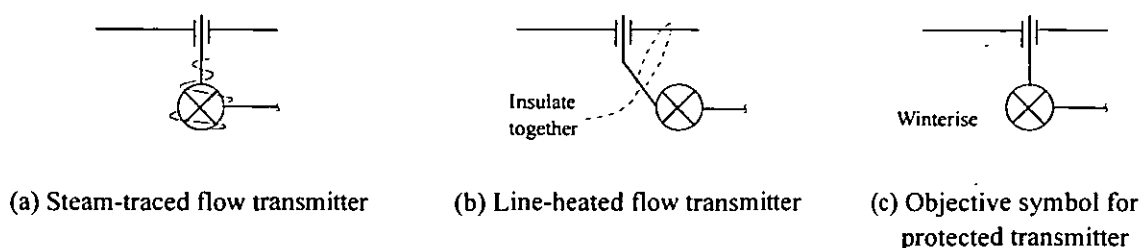


Fig. 2.8 Freeze-protected steam flowmeter can be represented in different ways, according to need.

Two possible mechanical solutions to the problem are shown in (a) and (b). Since the selection may depend on the piping configuration - which may not be known at the time of the flowsheet preparation - a simple symbol that shows intent rather than method, as in (c), solves the problem and improves communication (from Hill, 1968).

2.3.3 Piping & Instrumentation Diagrams (P&IDs), Engineering Line Diagrams (ELDs) and Engineering Flow Diagrams (EFDs)

The piping & instrumentation diagram (P&ID) or engineering line / flow diagram (ELD /EFD) usually evolves from the process flowsheets. It is a comprehensive and definitive document which specifies the precise means by which the process engineer's design objectives will be achieved. It shows the (process) engineering details of the equipment, instruments, piping, valves and fittings and their arrangement (Coulson et al, 1991), including auxiliary and subsidiary equipment and utility and speciality requirements (Sandler & Luckiewicz, 1987).

Like flowsheets, ELDs, EFDs and P&IDs serve two functions: they act as communication tools and as records to assist memory. They are key documents linking the process design to the construction phase of a project, and when complete will be used by piping, instrument, erection and operating staff (Holmes, 1973).

The comparison to road maps is used once again, this time by Sandler & Luckiewicz (1987) who state:

"Engineering flow diagrams are analogous to detailed road maps. They show all the salient features of the 'landscape', which in the case of a chemical plant...consist of all the equipment involved in the process. They indicate the equivalent of the main arteries and secondary connections, i.e., the piping which exists between the salient features and between the various routes. Included on the paths are symbols which indicate regulation of the flow of traffic between the salient features and along the paths".

This analogy is taken one step further by Romeo (1957) whose paper will be discussed later in this section.

Defining attributes

A formal definition of what should be shown on a piping and instrumentation diagram, taken from DIN 28004 Part 1 (1988), is as follows:

Basic information:

- type of equipment and machinery (including drives), piping or conveying routes and valves, together with any installed standby facilities
- designation of equipment and machinery (including drives)
- characteristic dimensions of equipment and machinery (except drives), set out in separate lists, if necessary
- indication of nominal size, pressure rating, material and type of piping, e.g. by pipeline number and piping class
- details of thermal insulation of equipment, machinery, piping, valves and fittings
- basic functions of instrumentation
- characteristic data of drives, set out in separate lists, if necessary

Supplementary information:

- designation of throughputs and amounts of energy or energy carriers
- route and direction of flow of energy or energy carriers
- main types of instrumentation
- main materials of equipment and machinery

- relative height of equipment and machinery
- designation of valves and fittings.

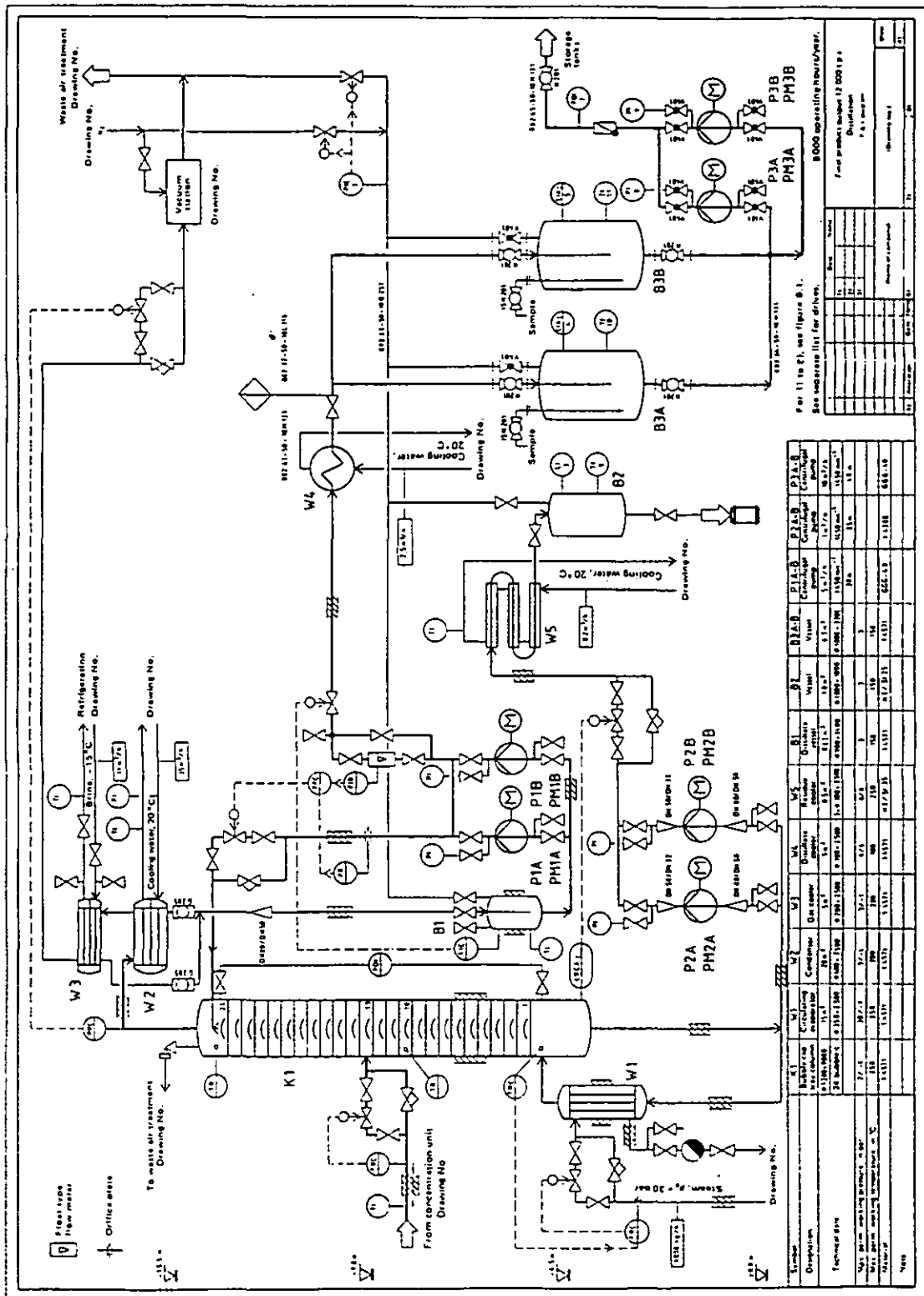


Fig. 2.9 Example of a Process and Instrument Diagram (P&ID) (from DIN 28004 Part 1, 1988)

An example of a piping and instrumentation diagram is shown in fig. 2.9. Again, as for the process flowsheet, the definition given above is best interpreted by comparing it to a more explicit definition, this time taken from Wells, Seagrave & Whiteway (1976). They believe that a line diagram should show the following information:

- all process equipment and piping required for start-up, shutdown, emergency and normal plant operation, including valves, blinds and removable spools
- an I.D. number, an identifier of the material of construction, diameter and insulation requirements for each line
- direction of flow
- identification of main process and start-up lines
- all instrumentation, control and interlock facilities with indication of action on instrument air failure
- key dimensions / duties of all equipment
- operating and design pressures and temperatures for vessels and reactors
- equipment elevations
- set pressures for relief devices
- drainage requirements
- special notes on piping configuration as necessary (e.g. 'no pockets', 'gravity drainage')

Additional requirements detailed in other texts include:

- ancillary piping for process and utility feeds; effluent or residue disposal; vent systems; reprocessing off-specification materials; bypassing equipment items; flow to installed spares
- minor assemblies such as sample points; atmospheric vents; syphon breaks; steaming out or rodding out points; purging connections; test points; dirt traps

(Holmes, 1973)

- spare equipment
- nozzles located in proper relative position
- flanges and fittings not shown except at equipment

(Rase & Barrow, 1967)

- every steam trap and other piping speciality with its I.D. number

- instructions to locate manual valves near the instruments that the operator will need to see when operating the valves (or vice versa)
- instruments located on the central control panel and those shown locally

(Landau & Cohan, 1966)

- equipment to be drawn roughly in proportion
- type and size of valves to be shown

(Coulson & Richardson, 1991)

As with flowsheets and flow diagrams, the significance of the different names (piping and instrumentation diagrams, engineering line / flow diagrams) is unclear (though it may be formalised in particular companies or on particular sites). Coulson & Richardson (1991) claim that P&IDs and ELDs are the same thing, while Sandler & Luckiewicz (1987) say that an EFD, though often synonymous with the P&ID, can also be used to refer to a diagram showing predominantly mechanical information with only the primary instrumentation represented. This diagram would be used in conjunction with an instrumentation diagram to replace the P&ID.

Supporting information

A brief account of three of the documents which should be produced in conjunction with the ELD is given in "Flowsheeting for Safety" by Wells, Seagrave & Whiteway (1979). These are the materials selection chart, the piping specifications and the line list. Additional documents such as equipment lists, equipment data sheets and layout drawings or plot plans are covered in Rose, Wells & Yeats (1978).

Novel work

Papers on ELDs (excluding those on the use of computer aided drawing) are almost as scarce as those on flowsheets. Care must be taken when looking at older articles as the ELD also used to be referred to as a flowsheet, specifically the 'engineering piping flowsheet', 'control flowsheet' or 'detailed equipment flowsheet' as mentioned earlier.

Three papers have been found which address issues related to ELD drawing: two are from the 1950s and 1960s so use the old names - these are concerned with 'road-mapping' and 'tiering' flowsheets to improve 'findability' (Romeo, 1957) and redrawing flowsheets to improve clarity (Guccione, 1966); the third is a much more up-to-date article by Schwartz & Koslov (1984) which is described as "a brief guide to developing and using P&IDs".

Romeo proposes that the readability of line diagrams can be enhanced by introducing a grid to the drawing and by tiering the information presented so that the top section shows process equipment, the middle one piping and the bottom transfer equipment (fig. 2.10). Though the grid system which he describes is still in use today, the concept of tiering has not been adopted for general process representation. (It is quite commonly used for utilities drawings). This is most probably because rather than improving the diagram in its primary function as a guide to the piping engineer by representing the information fully and clearly, the tiering system tends to overcomplicate the diagram by introducing unnecessary complexity in the representation of pipework. An additional reason for not tiering the diagram is that it prevents the designer from showing equipment at the correct elevation, which is an important feature of an ELD. Though the system has not been adopted for process diagrams in industry, it has certainly been picked up at some point by academics, as the drawing given in the article by Romeo has been used as an example of a "detailed equipment flowsheet" in the 4th edition of Vilbrandt's book.

Guccione (1966) is unimpressed by the lack of clarity in Romeo's method. His article condemns the tiered structure and emphasises the importance of clarity in flowsheet drawing. He writes "...unless they (ELDs) are judiciously drawn up, they will represent a forbidding maze of tortuous lines that defy one's patience and understanding....the only advantage that such garbled [tiered] diagrams offered in the past was that various types of equipment were grouped and lined up in neat rows. For example, all pumps and compressors were shown at the same elevation so that a designer could quickly spot a particular pump". As a remedy, he proposes that in drawing diagrams, designers should show only essential equipment, eliminate as many line-bends and crossovers as possible and dispense with 'gilding the lily', i.e. unnecessarily showing motors, equipment internals etc.

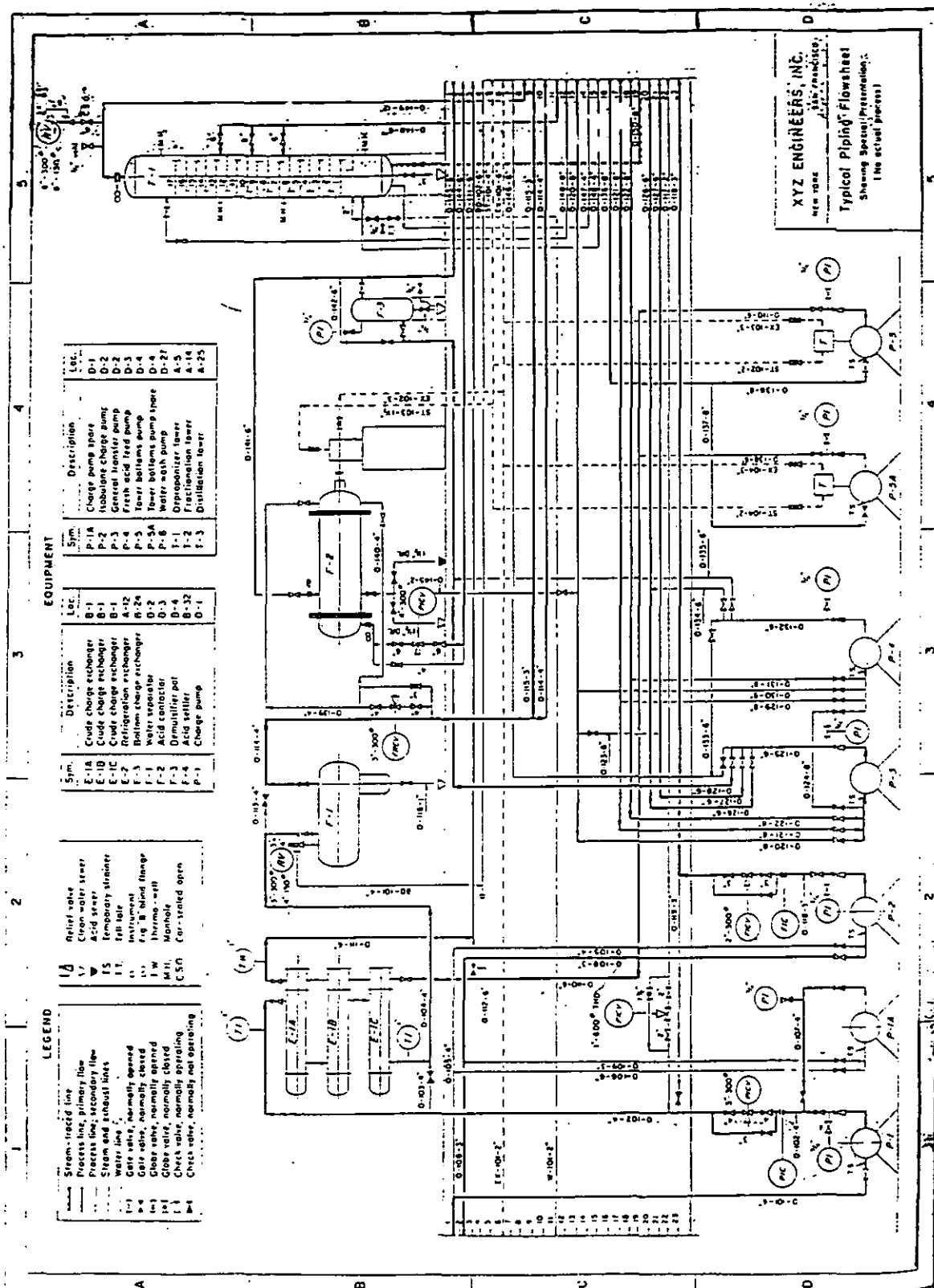


Fig. 2.10 "Roadmap" Flowsheet (from Romeo, 1957)

Schwartz & Koslov (1984) give a comprehensive list of what should be shown on the P&ID and detail how it should be presented and laid out. According to them there are three types of P&ID:

- *systems*, showing the production, utility and pollution control processes and including process, utility generation and environmental P&IDs
- *distribution*, showing how utilities, chemicals and other non-process streams are distributed through the plant and including utility distribution, safety system and chemical distribution P&IDs
- *auxiliary system P&IDs* showing compressor lubrication and cooling systems, hydraulic systems, pump seals [systems] and other auxiliaries related to major process equipment.

Schwartz & Koslov go on to explain about the 'Approval Issue [i.e. version]', the 'Engineering Issue' and the 'Construction Issue' of line diagrams and provide a checklist showing which features each 'Issue' should contain.

Probably the most significant development in the use of computer systems to enhance ELDs is that focusing on the 'intelligent P&ID'. An intelligent P&ID is described by Catena, Dietz & Traubert (1992) as "a computer drawing file created on a CAD system that is electronically 'linked' to a relational database [which] can hold a thorough description of every item of equipment shown on the P&ID...". This new concept in information handling complements existing computer systems for handling drawings which provide the facility for layering as described many years ago by Vilbrandt (1959 - see section 2.3.1).

The types of information which might be held 'behind' the P & ID include component performance, sizing data, operating data, purchasing data and so on. The application of particular interest to Catena et al is the management of Process Hazard Analysis (PHA) data. These authors list the following benefits of intelligent P&IDs which are intended to be used as working documents throughout the plant lifetime rather than just during design:

- simplify process hazard analyses by quickly presenting relevant process and equipment data to key people
- lower cost and increase accuracy and efficiency of PHA

- provide a system to readily share (sic) equipment and process information to multiple users throughout a company
- provide on-line access of PHA information to multiple users during plant emergencies
- provide a system to efficiently and continuously manage change.

Future developments for intelligent P&ID systems are predicted by Catena et al (1992) to include:

- facilities for making PHA results rapidly available to operators at the earliest stages of an emergency
- facilities for suggesting, or even initiating plant shutdown when major problems are predicted
- facilities for capturing and integrating plant reliability and maintenance information.

2.4 Engineering Line Diagram (ELD) Development

ELD development starts, at the highest level, with the generation of ideas and alternatives for realising the process design intentions specified in the process flowsheet and supporting documentation. At the next level, decisions must be made on the best generic means of achieving the desired objectives. Finally, at the lowest level, the precise equipment types and configurations must be specified.

There is a complete dearth of literature addressing the higher level issues of concept generation and evaluation in ELD development. As the design problem becomes more constrained and equipment is introduced to replace concepts, the amount of literature available increases considerably. There are plenty of books (Sandler & Luckiewicz, 1987, Mansfield, 1993, Ludwig, 1984, Rase & Barrow, 1967) detailing what should be shown on an ELD and how the information should be presented. There are also plenty of papers providing detailed information on the characteristics of various items associated with the process (e.g. McGrath, 1995 and Weeks, 1977 on thermal expansion; Britton & Clem, 1991, Irwin, 1991 and Baen & Barth, 1994 on insulation). However, even the coverage of these detailed equipment issues is incomplete - whilst it is not difficult to find guidance on such issues as

insulation or heat tracing, there is very little to be found on the subject of equipment and instrument bypassing for example.

Another area in which the literature on ELD development is lacking is the provision of tools or methods to support decision-making. While there is at least minimal information on this at the detailed end of the spectrum (e.g. how to choose between steam and electric tracing, Lam & Sandberg, 1992), there is none whatsoever at the conceptual or planning level of ELD development. Most literature concentrates on how to work out the particulars once the higher level decision has been made.

Other areas which are important in ELD development are management of data and management of assumptions, uncertainties and constraints. These concepts are addressed in section 2.4.3.

2.4.1 Methodologies for Line Diagram Development

As quoted earlier, a methodology, according to Tanskanen et al (1995), is “an attempt to effectively systematise an activity”. Though process design is often described as an art, there is no escaping the fact that it is also a scientific activity. As such, these authors believe that the need to systematise it can no longer be questioned.

Naturally, a methodology should also support creativity in design, not destroy it. The fear that systematisation kills creativity is partly justified, as Tanskanen et al write, by looking at the way in which we systematise an activity. Typically, this is done by providing a prescribed sequence of tasks to follow, with an associated set of heuristics to support decision-making.

In summary then, Tanskanen et al write that a good methodology for process design should exhibit the following key characteristics:

- it should encourage creative solutions
- it should integrate all the design activities including process engineering, control engineering, mechanical engineering, safety engineering and so on

- it should permit a ‘natural’ way of incorporating the use of computers in decision making and knowledge storage and retrieval.

Though methodologies exist for the conceptual design of processes, as described in section 2.1.1, there are no such tools available for the progression of the design to the ELD stage. There are texts, such as Mansfield (1993) and Scott (1992), which give worked examples of line diagram development in order to illustrate the nature of the procedure. However, the only author who has made any sort of attempt to systematise the activity of line diagram development is Scott (1992). Scott’s method exhibits many of the shortcomings alluded to by Tanskanen et al (1995) and outlined above. However, it is a starting point.

Scott’s method consists of the following sequence of steps:

- 1) Examine the flowsheet to define, for each item, the design objective, the physical and chemical changes taking place and the operating constraints.
- 2) Check that main process variables, including composition, are adequately controlled and that manipulated variables are known.
- 3) Consider the susceptibility of each item to fouling, corrosion or failure and the effect on the system of its possible unreliability. Decide what installed spares are necessary and what can be covered by workshop spares and maintenance policy.
- 4) Consider what provision should be made for interstage storage capacity, to ensure smooth continuing operation in the face of minor malfunctions.
- 5) Consider all operations which have to be performed and draw the necessary pipelines on the diagram. This should be spaciouly drawn using approximately scaled and positioned items.
- 6) Insert all valves, meters, controllers, etc. required for mass flow and control.
- 7) Make similar additions for temperature measurement and control.
- 8) Find what determines the pressure in each plant item and how this might vary in normal or abnormal operation. Consider how valve closures might isolate plant sections containing fluids which could cause overpressure. Make additions for pressure

measurement, control and relief from possible overpressure. Some reconsideration of earlier versions of the diagram may be necessary at this stage.

- 9) The properties of the materials handled at each stage may indicate the need for additions; e.g. hydrocarbon / air mixtures can be flammable and explosive and so need safe pressure relief and venting. Nitrogen purging and blanketing may be required, e.g. in storage tanks.
- 10) Design calculations usually concentrate on operations at flowsheet rate with feeds of specified composition. Lower rates or different feedstock are often used. Examine the ELD to see whether such modes of operation require special provisions to be made.
- 11) Additions may be necessary for a controlled shutdown of the plant, i.e. when enough product has been made, or the plant has to be emptied and cleaned for maintenance. Start-up may require further additions.
- 12) Plant item failure and external events such as fire or mal-operation may require emergency shutdown and the safe disposal of the plant inventory. Additions should be made for any extra vessels and pipelines which this would require.
- 13) Iterate and check that the ELD is still satisfactory for all operating modes. Shade in those valves normally closed. Indicate whether, in the event of air failure, control valves should move to the open or closed position or should stay in their last position.
- 14) Confirm the design and the diagram by completing an operability study.

(Scott & Macleod, 1992)

2.4.2 Support for Decision-Making

Most problems in design involve multiple criteria which may be characterised by both objective and subjective measures (Reid & Christensen, 1994). This is what makes comprehensive support for decision-making so difficult. Reid & Christensen provide an explanation of this in the context of the selection of process improvement projects designed to minimize wastes in chemical processes:

“In making technical decisions, chemical engineers must synthesize various decision criteria and assess the relative value of each alternative project.

The challenge is to integrate such diverse criteria as process yield and public perception to arrive at the best decision.”

The characteristic need to integrate diverse criteria in decision-making is evident at all levels of design from the higher level decisions such as selection of process route through to detailed decisions such as which type of insulation to use.

Methods for supporting decision-making vary tremendously from detailed, quantitative analyses to more superficial, qualitative approaches. The work of Reid & Christensen (1994) is based on a more rigorous approach developed by Saaty (1980) known as the ‘analytic hierarchy process’. This is described as “a method for structuring a complex problem into its component parts, arranging these parts into a hierarchical order, assigning quantitative scores that measure the relative importance of each criterion to the decision goal, and synthesizing the analytical assessments into an aggregated performance measure for each of the competing alternatives”. The method can be used “to enforce a cohesive thought pattern on the part of the engineers and other decision-makers as they seek to identify the best alternative”.

Another example of this more rigorous level of support for decision-making is the use of expert systems to assist in the selection of equipment and materials in design. Bunn & Lees (1988) describe the application of a rule-based expert system to the design of plant handling hazardous materials. This system, like the ‘analytic hierarchy’ approach outlined above, involves a quantitative element, as the composite rules are assigned different strengths.

At the other end of the spectrum, we have much more straightforward methods for analysing a given problem, which are entirely qualitative. Examples of such qualitative methods include semantic networks, decision trees and ‘PMI lists’. Semantic networks provide a method for representing associations between objects and events (Rodgers & Petry, 1995). Decision trees lead the designer through a series of characteristic questions with yes / no answers to a solution which is appropriate based on the answers given. PMI or Plus, Minus, Interesting lists are referred to by de Bono (1996) as “attention directing tools”. By focusing peoples’ attention first towards the plus or good points of a proposal, then towards the minus or bad points, and finally towards any other interesting points, it is possible to overcome bias

towards a particular solution. Consequently, a much more balanced view of the problem can be taken and decisions based on false or oversimplistic assumptions are avoided.

2.4.3 Information Handling

There is relatively little literature on the subject of information handling in design. Most of that which exists concentrates on the development and application of databases for managing physical design data. Such databases are widely used in the field of computer-aided design (CAD), specifically in three-dimensional computer aided software. These systems are capable of doing anything from converting a P&ID into an orthographic model that incorporates a complete 3-D representation of the plant, which in turn can be used to generate dimensioned piping isometrics, to producing datasheets, work orders and hazard analyses (Klement, 1996). Klement writes:

“The benefits of adopting 3-D CAD technology extend beyond the opportunity to automate the generation of isometrics. The most advanced systems typically help engineers manage the design process more effectively by integrating the information contained in the schedules and drawings within a single model. On the one hand the use of such models ensures data integrity and helps optimize work flows.... On the other hand, using such models simplifies the communication process by allowing engineers to enter a change anywhere in the model and thereby automatically update all the relevant documentation.”

Methods for managing other types of design information such as assumptions, uncertainties and constraints are scarce and limited to computer systems such as that described by Chung & Goodwin (1994).

2.5 Conclusions

The most immediately obvious conclusion that can be drawn is that the topic of , as Douglas might put it, “the logic and / or the order in which decisions for developing a first engineering line diagram are made” is relatively unexplored.

Other key conclusions and points of interest from the literature review which will be picked up again in later chapters are listed below under the appropriate section headings.

2.5.1 Process Design

- Consists of three main stages:
 1. Research and development
 2. Process design - including development of the flowsheet and detailed process design
 3. Engineering design and equipment selection.
- Is a multidisciplinary activity.
- Is generally described in the literature in terms of continuous process attributes rather than in a manner which is relevant to both batch and continuous processes.
- Requires a hierarchical approach for development.
- Involves procedural and declarative knowledge.
- Is a cyclic activity.
- Can be considered as a mapping from function space onto attribute space.
- Is vulnerable to errors which result from misuse of knowledge, either through misconceptions (irrelevant or overlooked knowledge) or missing concepts (missing knowledge).

In practice, process design is mostly approached in a modular fashion but in theory, the task needs to be presented systematically in order to illustrate the principles behind it. The key to understanding the philosophy of process design is to understand the structure of the task and how the component methods, tasks, subtasks and domain knowledge are related.

2.5.2 Safety in Design

- Proper consideration requires a systematic approach and early implementation.
- Safety should be incorporated into design in both a proactive and a reactive manner.
- Safety should be addressed continually as a performance driver not left as a performance acceptance criterion.
- Inherent safety and safety may contradict and inherent safety is not always the best option.
- Even in an inherently safe process the overall safety still relies on good technology and good management.
- Safety, health and environmental (SHE) issues should be considered concurrently.
- Hazard studies lose much of their value as a cross check if relied upon as the only formal means of addressing SHE issues.
- Engineered safety can include both software (procedural) and hardware (physical) solutions.

2.5.3 Engineering Drawings

- Writing on drawings is an important way of capturing concepts in design.
- Layering information on drawings is another important practice which can be used to help maintain continuity and consistency in design.
- There is no consensus on the precise meaning of the different terms used to describe engineering diagrams (though particular definitions may be adopted by specific companies or sites)
- The flowsheet should be used to show the design intent, i.e. to show function not form.
- Engineering drawings are communication tools and records to assist memory.

2.5.4 Engineering Line Diagram Development

- Any methodology for line diagram development should:
 - encourage creative solutions

- integrate all the design activities including process engineering, control engineering, mechanical engineering, safety engineering
- permit a 'natural' way of incorporating the use of computers in decision making and knowledge storage and retrieval.
- Support for decision-making is a key component of good design. It can be quantitative or qualitative.
- Information handling is also key: though there is plenty of information on the development and use of databases for engineering purposes there are few published methods for managing conceptual data such as assumptions, uncertainties and constraints.

CHAPTER III - CURRENT PRACTICE

3.0 Introduction

Chapter 2 provided a survey of the literature pertinent to engineering line diagram preparation. One of the conclusions drawn from this literature is that there has been little if any work done in the public domain on the subject of the logic and / or the order in which decisions for developing a first engineering line diagram are made. This chapter is concerned with current industrial practice in chemical engineering line diagram design. In particular, it aims to show whether the gap in the literature referred to above represents an area which has been equally unexplored within industry.

Section 3.1 presents and discusses the results of a survey of current practice in design which was published in 'The Chemical Engineer' for the purposes of the PREMIUM project.

Section 3.2 briefly summarises the outcome of a line diagram development exercise which was produced as a follow-up to the survey and was completed by survey respondents.

Section 3.3 covers a series of 'task analysis' activities which were carried out at ICI in order to try to obtain a better understanding of the day-to-day practicalities of the line diagram development task. The activities described include interviews, observational techniques and activity sampling.

A summary of the overall conclusions which can be drawn on the subject of current practice is given in section 3.4.

3.1 Survey of Current Design Practice

A survey of current practice in engineering line diagram design was generated as part of the PREMIUM project and was published in the June 27th 1996 issue of 'The Chemical Engineer' (TCE). The survey questions were predominantly followed by multiple choice

answers, with spaces left for further comments where appropriate. A copy of the survey as it appeared in TCE is included in appendix A1.

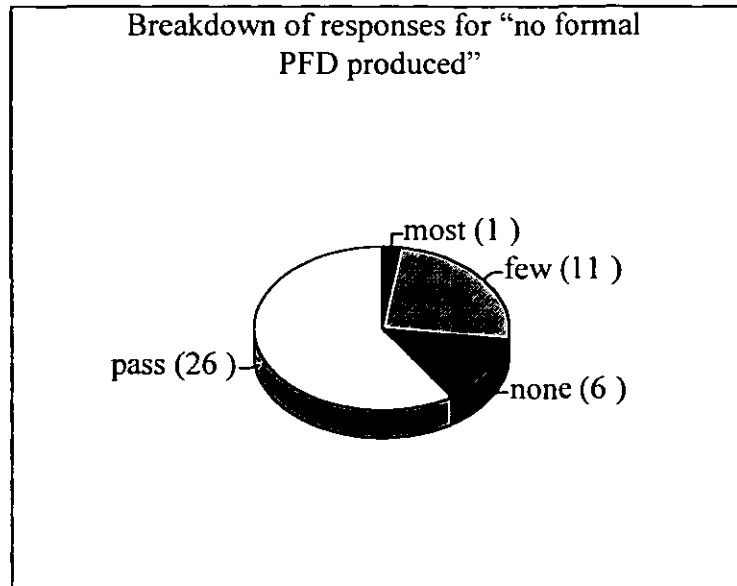
The questions chosen for the survey were intended to provide an overview of the current approach to the preparation of line diagrams within industry. Information on:

- the understanding of the terms ‘process flow diagram’ and ‘engineering line diagram’
- the methods of preparation and development of ELDs
- the methods of acquiring expertise in ELD development
- the weaknesses of the current approaches used

were considered to be pertinent to this subject.

Forty-four people, from a diverse selection of engineering based companies (contractors, food, chemicals, energy, pharmaceuticals), responded to the survey. The collated responses to each question are presented and discussed below. ‘Pass’ is used to indicate either that a respondent has simply left out the question concerned or that a respondent has written a comment (such as “not applicable” or “don’t know”) which indicates that none of the available answer options is appropriate.

Survey of Current Practice Report: Question 1											
Question											
Within my organisation, the source of process flow diagrams (PFDs) for development to engineering line diagrams (ELDs) is:											
Response options											
a) <i>internal</i>	(all / most / few / none)										
b) <i>external</i>	“										
c) <i>no formal PFD produced</i>	“										
Responses											
<p>Breakdown of responses for “source of PFDs is internal” (numbers of responses in brackets)</p> <table border="1"> <caption>Breakdown of responses for “source of PFDs is internal”</caption> <thead> <tr> <th>Response Option</th> <th>Count</th> </tr> </thead> <tbody> <tr> <td>all</td> <td>14</td> </tr> <tr> <td>most</td> <td>25</td> </tr> <tr> <td>few</td> <td>3</td> </tr> <tr> <td>pass</td> <td>2</td> </tr> </tbody> </table>		Response Option	Count	all	14	most	25	few	3	pass	2
Response Option	Count										
all	14										
most	25										
few	3										
pass	2										
<p>Breakdown of responses for “source of PFDs is external”</p> <table border="1"> <caption>Breakdown of responses for “source of PFDs is external”</caption> <thead> <tr> <th>Response Option</th> <th>Count</th> </tr> </thead> <tbody> <tr> <td>all</td> <td>2</td> </tr> <tr> <td>most</td> <td>2</td> </tr> <tr> <td>few</td> <td>23</td> </tr> <tr> <td>pass</td> <td>12</td> </tr> </tbody> </table>		Response Option	Count	all	2	most	2	few	23	pass	12
Response Option	Count										
all	2										
most	2										
few	23										
pass	12										



Discussion

Most respondents are working with internal rather than external PFDs. The balance between the number of companies who use in-house design and those who contract out may well shift in the future as operating companies continue to 'downsize' and become more focused on production rather than new processes.

Around one quarter of respondents say that there are occasions when no formal PFD is produced. Without a formal PFD, more late changes in design can be anticipated as a consequence of not thinking the problem through at the start. The traceability of designs may also be limited, making it more difficult to look back through the development of the design in order to spot mistakes and to make successful alterations.

Survey of Current Practice Report: Question 2

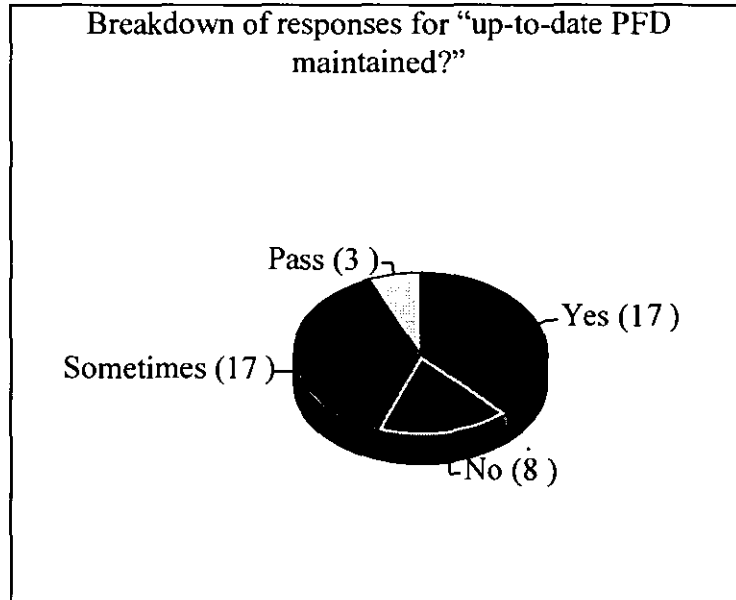
Question

Within my organisation, a formal, up-to-date PFD is maintained in parallel with the ELD.

Response options

yes / no / sometimes

Responses



Discussion

Around three quarters of respondents maintain up-to-date PFDs either some or all of the time. It is considered good practice to have an up-to-date PFD available in order to be able to understand where the line diagram design has come from and in order to help with general project and plant management (induction of new staff, planning modifications, troubleshooting, etc.). However, it might also be important to keep the original PFDs so that these can be referred to throughout the design process. The original PFDs could be needed, for instance, after discovering that a change leads to a modification chain (ref. chapter 1), to enable the original design to be re-instated.

Survey of Current Practice Report: Question 3

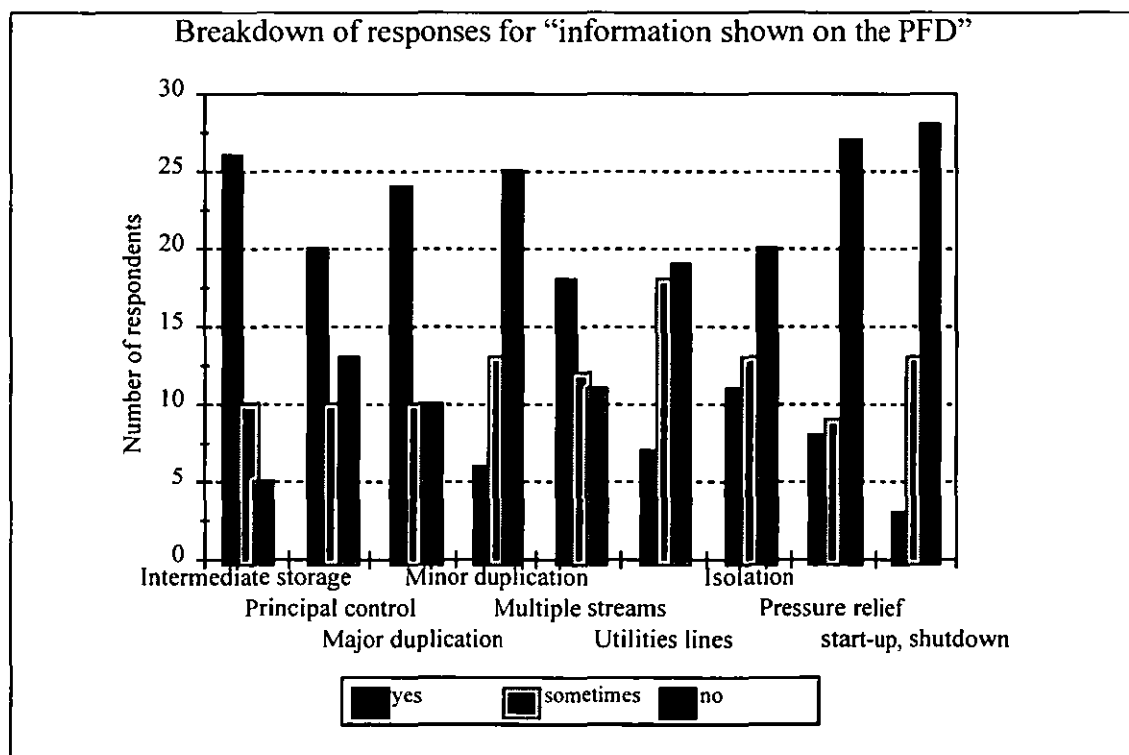
Question

Within my organisation, the following information is already shown on the PFD, rather than being added at the ELD stage:

Response options

- intermediate storage	yes / no / sometimes
- principal control loops / control philosophy	“
- duplicated equipment (major)	“
- duplicated equipment (minor)	“
- multiple streams	“
- utilities lines	“
- isolation valves	“
- pressure relief	“
- hardware associated with start-up / shutdown	“
decontamination / maintenance	

Responses



Discussion

According to the responses given, a typical PFD will represent the following:

- Intermediate storage
- Principal control loops
- Major duplicated equipment
- Multiple streams

but not

- Minor duplicated equipment
- Utilities lines
- Isolation valves
- Pressure relief
- Hardware associated with start-up / shutdown / decontamination / maintenance

Major duplicated equipment would not be shown if it is only to be used as a spare.

Survey of Current Practice Report: Question 4

Question

Within my organisation, expertise in the development of line diagrams (see note 1 below) is provided by:

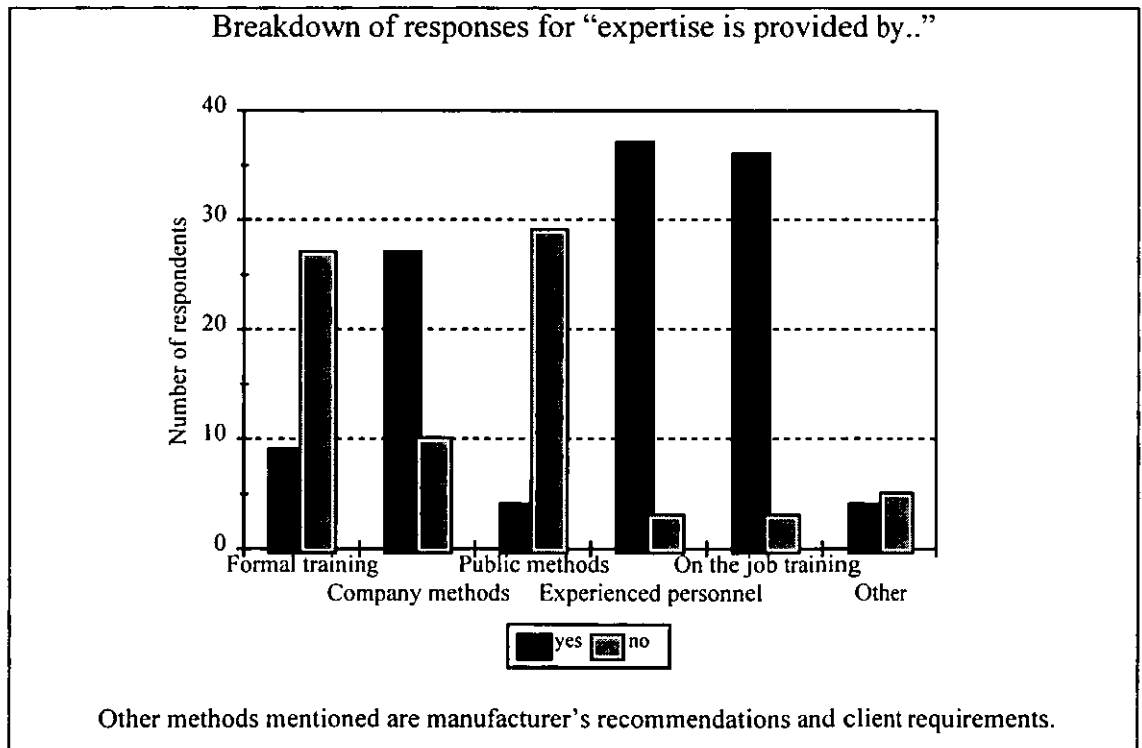
Response options

- | | |
|---------------------------------------|---------|
| - formal training | yes /no |
| - company methods / procedures | “ |
| - public methods / procedures | “ |
| - employment of experienced personnel | “ |
| - ‘on-the-job’ training | “ |
| - other | |

Note 1

The focus of this work is on aiding decision-making in engineering line diagram (ELD) development, not support for the drawing process as such. Thus, for example, company methods / procedures which exist for deciding such things as which equipment to duplicate or where to position indicators and alarms for diagnostic control would be relevant.

Responses



Discussion

Formal training in PFD to ELD development appears to be relatively uncommon. A large number of respondents report that company methods are used to develop expertise in line diagram development. Very few use public methods. The majority of respondents indicate that their companies rely heavily on both employment of experienced personnel and on 'on the job' training.

Whilst experience is often the best form of learning, some thought should be given to the feasibility of these methods as long term sources of expertise in today's working climate. As the trend seems to be towards short-term jobs and contracts, both employment of experienced personnel and on-the-job training could become increasingly unavailable as sources of expertise because people will not remain in one place long enough to build up significant knowledge. (One respondent commented to this effect under question 5.) In addition, learning by on-the-job training rather than from a structured training program could perpetuate some bad practices in design.

Survey of Current Practice Report: Question 5

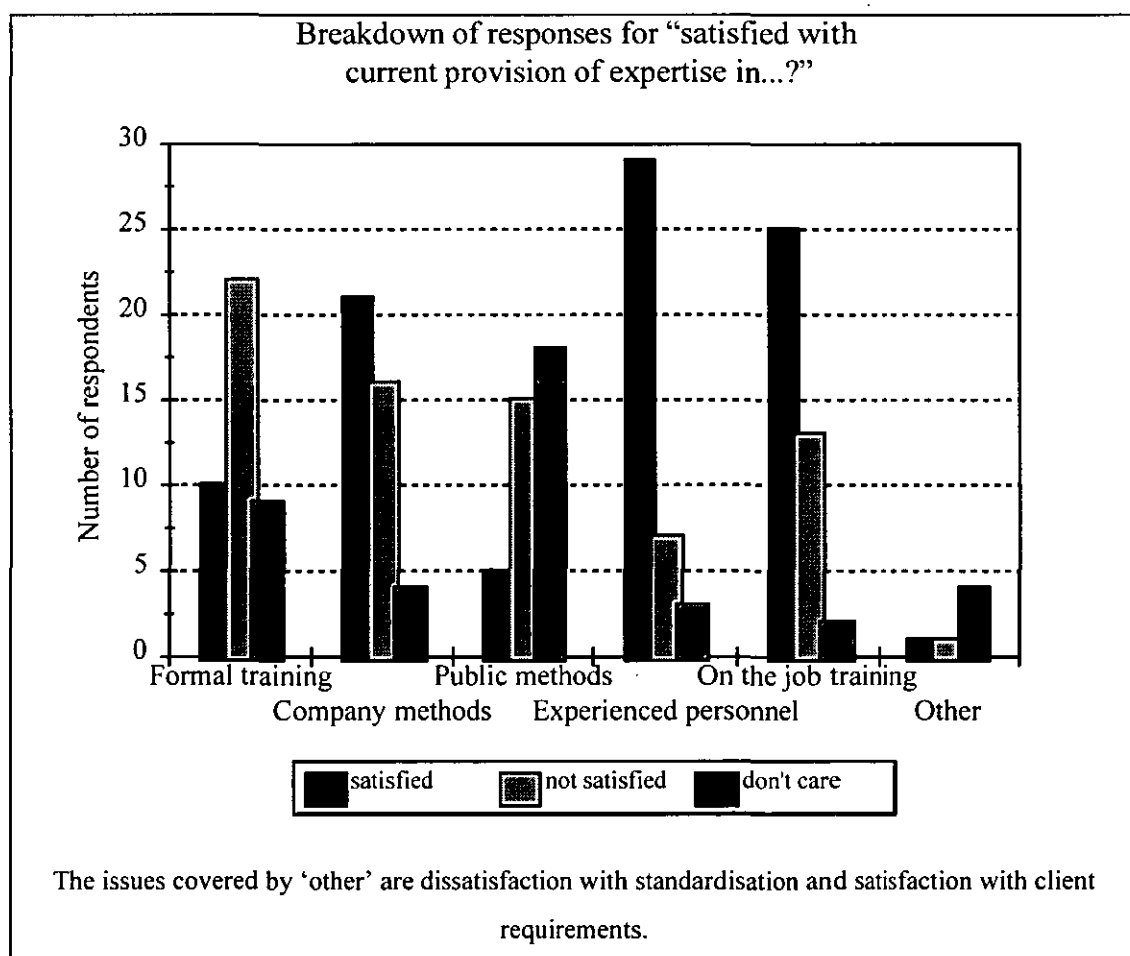
Question 5

Are you satisfied with current provision of expertise for the development of line diagrams in the following areas (regardless of whether or not they are provided by your organisation):

Response options

- formal training	satisfied / not satisfied / don't care
- company methods / procedures	"
- public methods / procedures	"
- employment of experienced personnel	"
- 'on-the-job' training	"
- other	

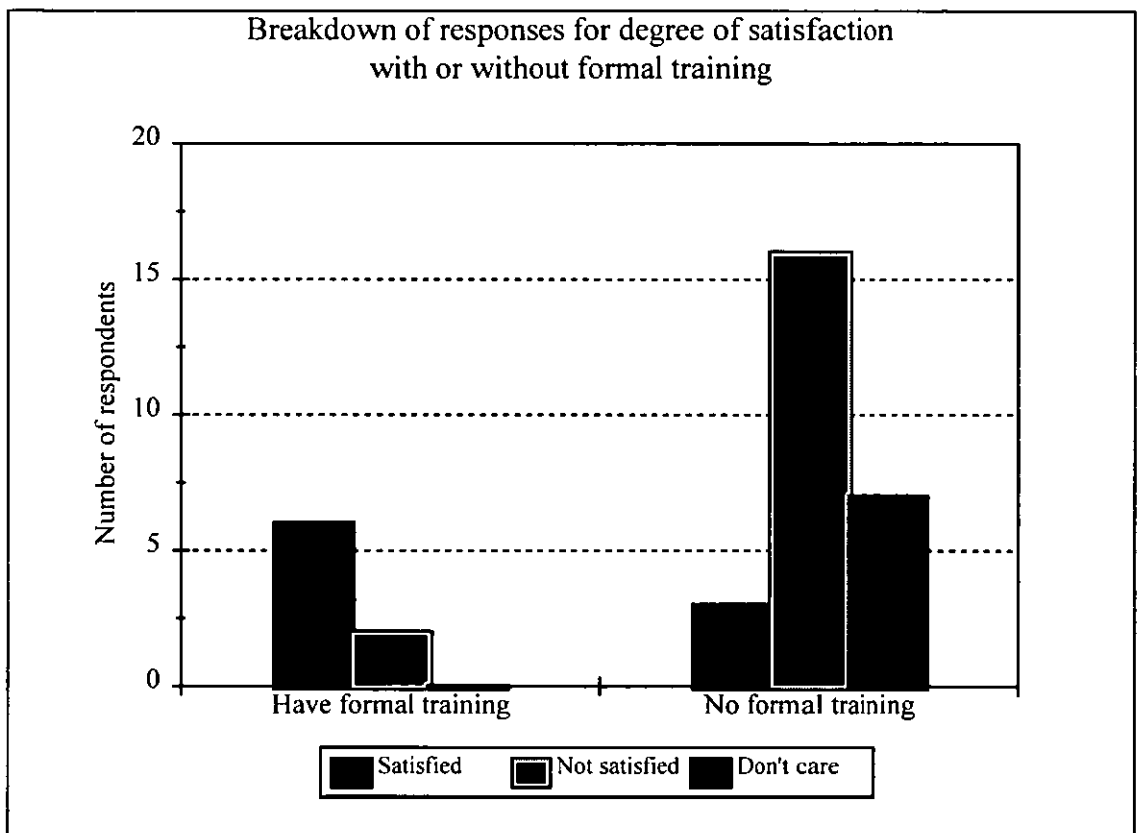
Responses



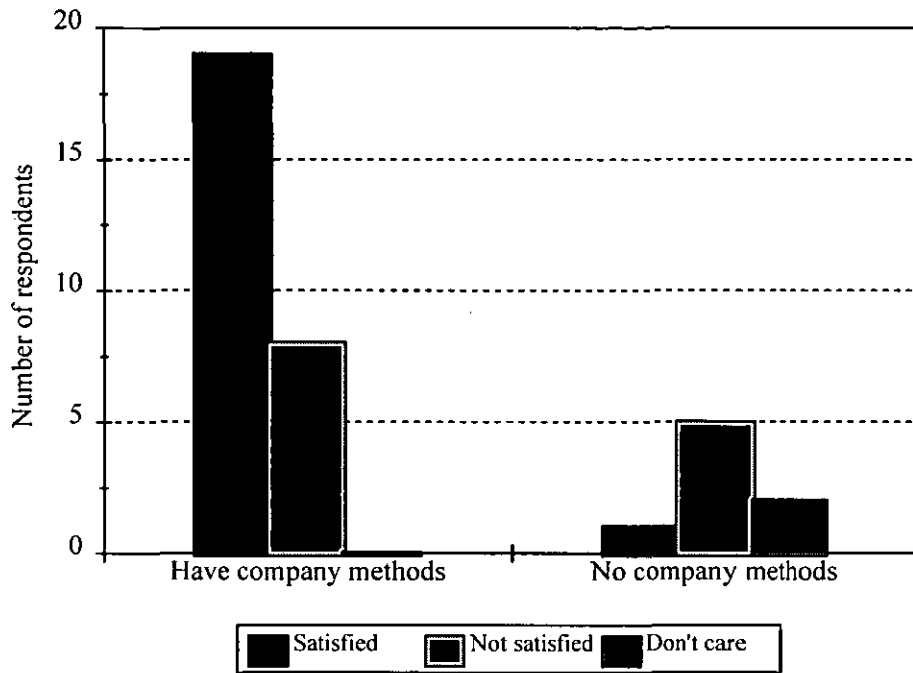
Discussion

It is difficult to interpret the meaning of these responses by looking at them in isolation. For instance, a number of respondents say that they are not satisfied with current provision of expertise through company methods. This could either be because they are not provided with company methods or because they are dissatisfied with the ones they are given. The responses have therefore been correlated with those from question 4 by linking the sources of expertise provided to the degree of satisfaction expressed for each respondent. This serves to clarify the context in which people are or are not satisfied with the sources of expertise described.

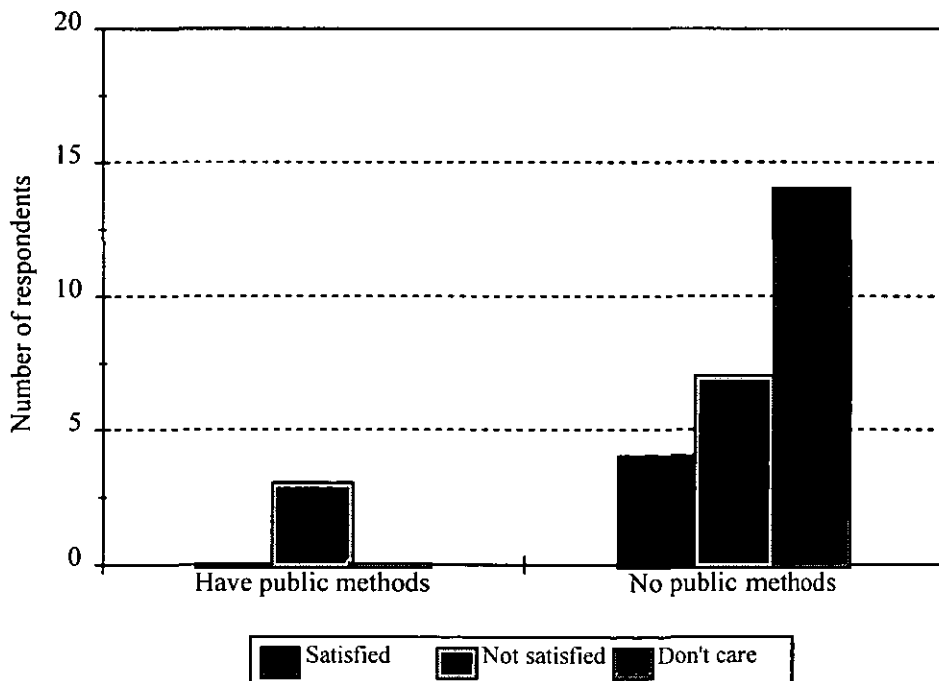
Correlations

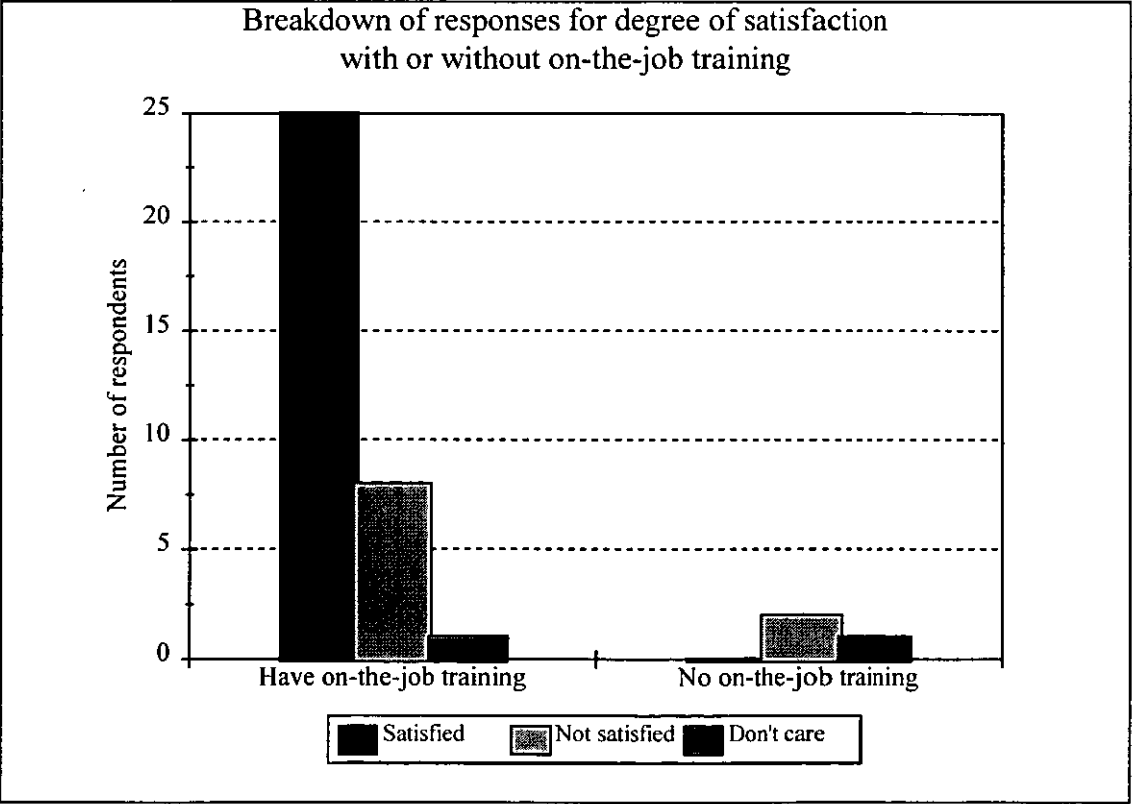
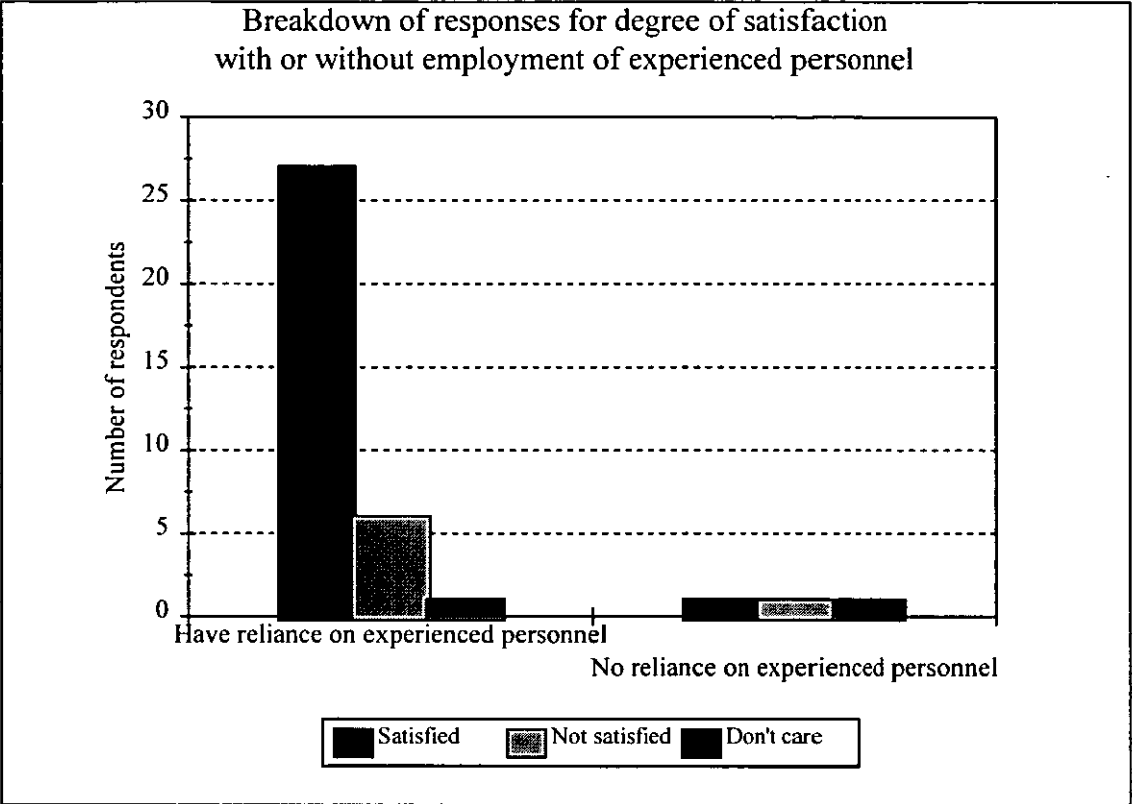


Breakdown of responses for degree of satisfaction
with or without company methods



Breakdown of responses for degree of satisfaction
with or without public methods





Discussion

The correlations reveal that there are a number of respondents who do not have access to formal training and who are dissatisfied with this situation. The majority of respondents who do have formal training are satisfied with it.

Around a third of respondents who say they have company methods are not satisfied with them. A similar number of respondents are not satisfied with having no company methods.

The overall consensus on public methods is a 'don't care' response, though a few respondents did say that they were not happy with the public methods available to them or were not happy in using none. It is unclear whether this general apathy towards public methods is because respondents do not have easy access to them, do not feel they need them, consider them inadequate or consider them inappropriate.

The majority of respondents are satisfied with the provision of expertise through employment of experienced personnel. A few, however, are dissatisfied and one of the comments made was "few stay in engineering long enough to gain thorough experience". This could lead to problems in acquiring expertise in the future as explained under question 4.

Just under a quarter of respondents say that they are not satisfied with current provision of on-the-job training - most of these do have this form of expertise within their company. Two respondents said that they are not satisfied and that they do not have access to on-the-job training.

On the whole, current provision of expertise in line diagram development seems a little unstructured and fragile. This situation is likely to be aggravated by current trends towards shorter term jobs and contracts. More formal training could perhaps help to alleviate some of the dissatisfaction surrounding company methods, employment of experienced personnel and on-the-job training. It would also provide a sounder basis for building design expertise.

Survey of Current Practice Report: Question 6																	
Question Within my organisation, the job titles or roles of the persons responsible for ELD development are:																	
Response options None specified																	
Responses <table border="1"> <thead> <tr> <th>Job titles / roles</th><th>Number of respondents</th></tr> </thead> <tbody> <tr> <td>Process engineers</td><td>25</td></tr> <tr> <td>Project engineers</td><td>15</td></tr> <tr> <td>Piping engineers</td><td>5</td></tr> <tr> <td>Project managers</td><td>4</td></tr> <tr> <td>Process managers</td><td>3</td></tr> <tr> <td>Instrument engineers</td><td>3</td></tr> <tr> <td>Mechanical engineers</td><td>2</td></tr> </tbody> </table> <p>Also mentioned were:- Technical managers, proposals engineers, draughtsmen, preparation engineers, detailed designers, drafting supervisors, specialist engineers, drawing office section leaders, design offices team leaders, production engineers and managers, designers and chemical engineers.</p>		Job titles / roles	Number of respondents	Process engineers	25	Project engineers	15	Piping engineers	5	Project managers	4	Process managers	3	Instrument engineers	3	Mechanical engineers	2
Job titles / roles	Number of respondents																
Process engineers	25																
Project engineers	15																
Piping engineers	5																
Project managers	4																
Process managers	3																
Instrument engineers	3																
Mechanical engineers	2																

Survey of Current Practice Report: Question 7**Question**

Within my organisation, the job titles or roles of the people who contribute to ELD development are:

Response options

None specified

Responses

Job titles / roles	Number of respondents
Electrical / Control engineers	20
Process engineers	15
Project engineers	13
Operating staff	10
Piping / Layout engineers	10
Mechanical engineers	10
Safety representatives	9
Structural engineers	5
Production engineers	5
Maintenance engineers	4
Commissioning engineers	4
Project managers	4
CAD operators	3
Chemical engineers	3
Development engineers	3

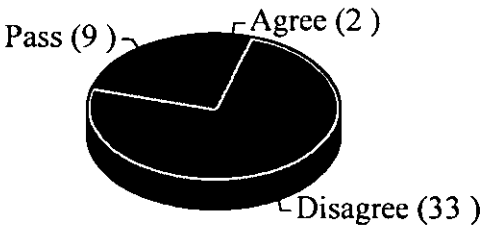
Also mentioned were:-

Technical managers, chemist, designers, technologists, environmental representatives, equipment engineers, HVAC, HUC, HAZOP chair and secretary, discipline engineers, specialist subcontractors, specialists, R & D manager, Q.A. representative, control / Provox engineer, drawing office section leader, technical department, function engineers, production managers, operations managers, production supervisors, design office team leaders.

Discussion

The people most commonly quoted as contributing to ELD development include electrical or control engineers, process engineers and project engineers. Operating staff, piping and layout engineers, and mechanical engineers feature reasonably often, while structural, maintenance and commissioning engineers seem to contribute rarely to ELD development. This should give cause for concern, as poor layout and operability are some of the major causes of late changes in design.

These results suggest that there is probably insufficient interaction between different departments and disciplines during design and insufficient feedback on the success of the design in terms of operability, ease of control and so on. Perhaps some form of guidance on who should be involved in the various design decisions or reviews is required to remind designers that they are not expected to do it all on their own and to ensure that this vital interaction does take place.

Survey of Current Practice Report: Question 8								
Question Within my organisation, there is a distinction between the methods used for ELD development of batch processes and those used for continuous processes:								
Response options <i>agree / disagree</i>								
Responses <div><p>Breakdown of responses for “a distinction is made between batch and continuous ELD development”</p><table><thead><tr><th>Response Option</th><th>Count</th></tr></thead><tbody><tr><td>Disagree</td><td>33</td></tr><tr><td>Pass</td><td>9</td></tr><tr><td>Agree</td><td>2</td></tr></tbody></table></div>	Response Option	Count	Disagree	33	Pass	9	Agree	2
Response Option	Count							
Disagree	33							
Pass	9							
Agree	2							
Discussion The majority of respondents wrote that there is no distinction between the methods used for ELD development of batch processes and those used for continuous processes. Only two respondents reported distinct differences. The first of these wrote "batch is designed using qualitative methods, continuous using quantitative methods" and the second “a process archetype function is used for continuous process”. Though there may not be any formal distinction between design methods used for the two types of process, it is quite likely that in many companies subtle differences in emphasis do exist. These are particularly likely to be found in the nature and organisation of the information recorded in support of the ELD.								

Survey of Current Practice Report: Question 9											
Question											
Within my organisation, the ELD is developed:											
Response options											
a) <i>by computer, using CAD tools</i>	(all / most / few / none)										
b) <i>manually</i>	“										
Responses											
<p>Breakdown of responses for “the ELD is developed by computer”</p> <table border="1"> <thead> <tr> <th>Response Option</th> <th>Count</th> </tr> </thead> <tbody> <tr> <td>all</td> <td>25</td> </tr> <tr> <td>most</td> <td>17</td> </tr> <tr> <td>few</td> <td>1</td> </tr> <tr> <td>pass</td> <td>1</td> </tr> </tbody> </table>		Response Option	Count	all	25	most	17	few	1	pass	1
Response Option	Count										
all	25										
most	17										
few	1										
pass	1										
<p>Breakdown of responses for “the ELD is developed manually”</p> <table border="1"> <thead> <tr> <th>Response Option</th> <th>Count</th> </tr> </thead> <tbody> <tr> <td>few</td> <td>18</td> </tr> <tr> <td>pass</td> <td>15</td> </tr> <tr> <td>none</td> <td>10</td> </tr> <tr> <td>all</td> <td>1</td> </tr> </tbody> </table>		Response Option	Count	few	18	pass	15	none	10	all	1
Response Option	Count										
few	18										
pass	15										
none	10										
all	1										

Discussion

The responses to this question show that virtually all respondents have access to, and rely heavily upon, computer facilities for drawing ELDs. However, some of the comments made by respondents imply that the ELD is often still developed manually and then put on computer as the design reaches the final stages. This suggests that the computer is used as an archiving rather than a developmental tool. More people need to be persuaded to use computers in the actual development of ELDs if the full potential of CAD (for instance in recording decision trails, providing supporting information and so on) is to be realised.

Survey of Current Practice Report: Question 10**Question**

Within my organisation, the following standards for ELD presentation are adopted:

Response options

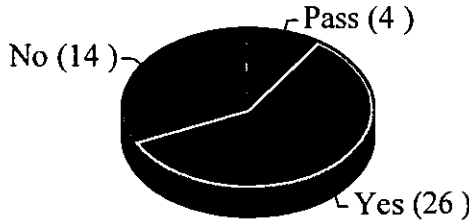
- *BS1553*
- *BS1646*
- *BS5070*
- *ANSI*
- *other*

Responses

Standards for ELD presentation	Number of respondents
BS1553	6
BS1646	6
BS5070	5
ANSI	5
DIN	2
Other - In-house	11
Client's own	9
Don't know	4
Miscellaneous	5

Discussion

In the raw data, just under half of respondents wrote that they use public standards of some sort. A similar number use client or in-house standards and four respondents said that they did not know what standards they were using (if any). This wide use of in-house or client standards somewhat defeats the objectives of the public standards (avoiding the need for translation between different organisations, ease of recognition of symbols, standardised drawing methods and so on).

Survey of Current Practice Report: Question 11								
Question Within my organisation, costs and benefits are taken into account during ELD development:								
Response options <div>yes / no</div>								
Responses <div><div>Breakdown of responses for “costs and benefits are taken into account during ELD development</div><div><table><thead><tr><th>Response</th><th>Count</th></tr></thead><tbody><tr><td>Yes</td><td>26</td></tr><tr><td>No</td><td>14</td></tr><tr><td>Pass</td><td>4</td></tr></tbody></table></div></div>	Response	Count	Yes	26	No	14	Pass	4
Response	Count							
Yes	26							
No	14							
Pass	4							
Discussion <p>The majority of respondents write that costs and benefits are taken into account during ELD development. However, it is evident from the comments made in the raw data that in most cases the costs are not used to drive the process of ELD development continuously - rather they are reviewed at various points in the design. There are a significant number of respondents who say that they do not take costs into account during ELD development.</p> <p>Three comments of interest were “justification of equipment and ancillaries by discussion”, “cost engineering - all aspects are cost orientated” and “value engineering procedure is being developed”. These imply that there are instances when costs are considered in a 'forward thinking' manner as equipment is added to the ELD rather than by eliminating equipment as an afterthought.</p>								

Survey of Current Practice Report: Question 12**Question**

Are you satisfied that the completed design (including, of course, the ELD) provides sufficient record of:

Response options

- | | |
|---|-----------------|
| - <i>the base function of equipment</i> | <i>yes / no</i> |
| - <i>multiple or ancillary functions of equipment</i>
<i>(see note 2 below)</i> | <i>“</i> |
| - <i>constraints on equipment relationships</i>
<i>(see note 3 below)</i> | <i>“</i> |
| - <i>design prohibitions</i>
<i>(see note 4 below)</i> | <i>“</i> |
| - <i>SHE / environmental requirements</i> | <i>“</i> |
| - <i>reasoning leading to design decisions</i> | <i>“</i> |
| - <i>provision for start-up / shutdown /</i>
<i>decontamination / maintenance operations</i> | <i>“</i> |
| - <i>batch and non-steady state operations</i> | <i>“</i> |
| - <i>all other aspects of the design necessary for</i>
<i>subsequent decision-making</i> | <i>“</i> |

Note 2

An example of a multiple function would be where an isolation valve is required for maintenance purposes, but also for start-up. An example of a main and an ancillary function would be that a positive displacement pump is required for transfer of material, but is also incidentally relied upon for prevention of reverse flow.

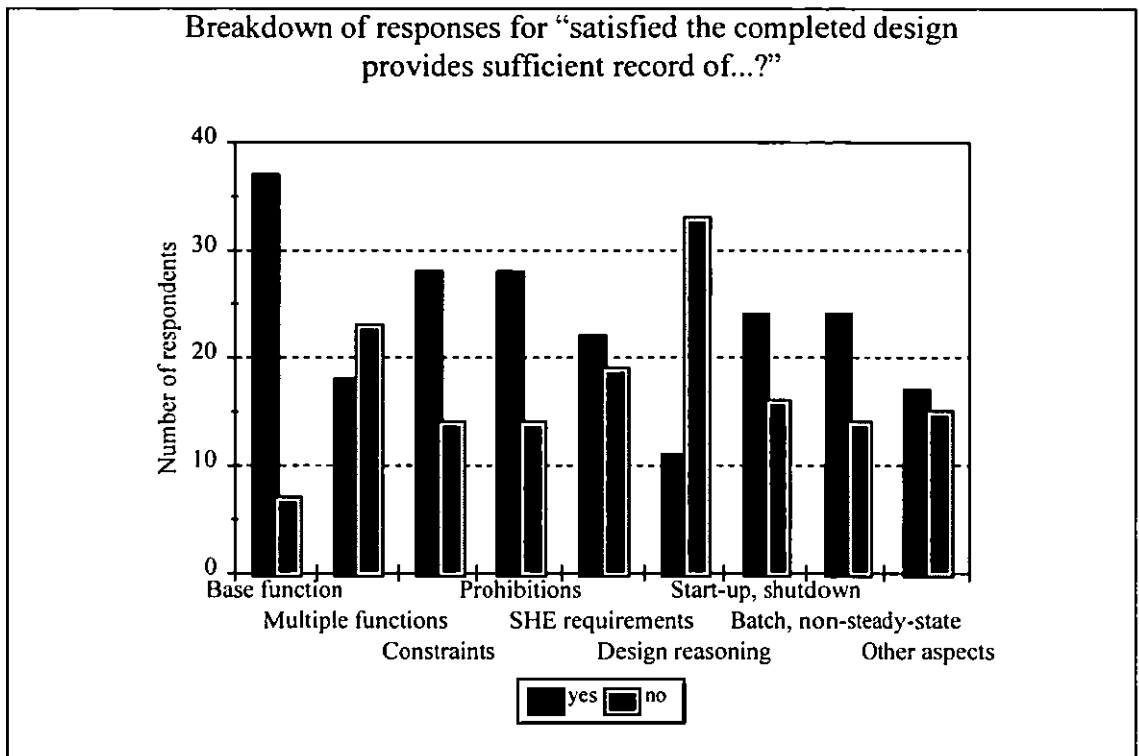
Note 3

An example of a constraint on equipment relationships would be where a pipe must enter another specifically at the top for process reasons.

Note 4

An example of a design prohibition might be “no dead ends permitted”, to prevent water collection, perhaps.

Responses



Discussion

The majority of respondents are satisfied that the completed design (including the ELD) provides sufficient record of most of the types of information listed, though in some cases the majority is only marginal. In all cases other than 'the base function of equipment' there is still a notable amount of dissatisfaction expressed.

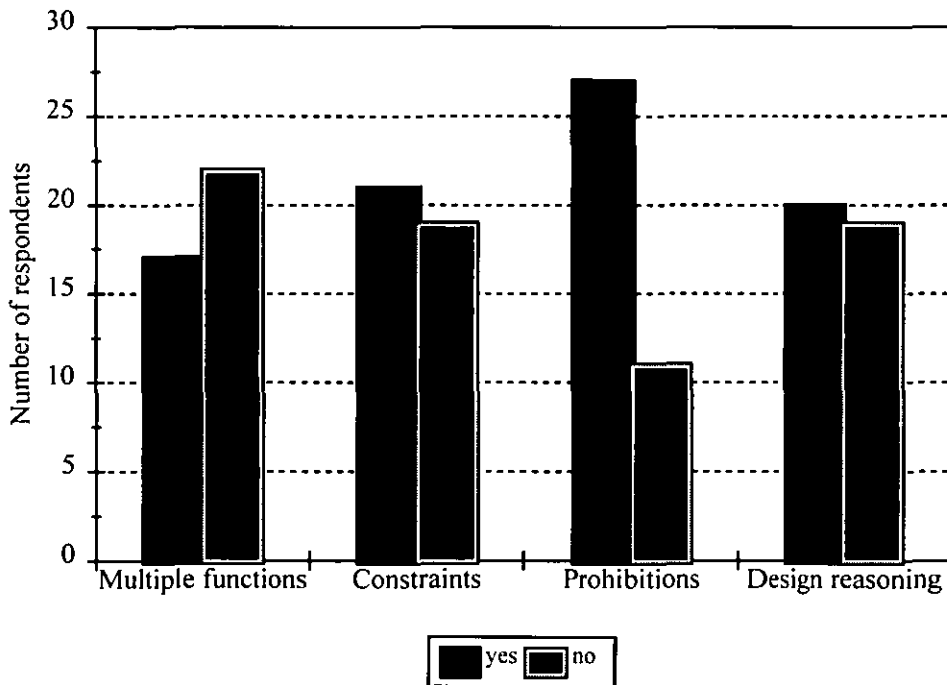
The types of information most commonly reported as not recorded are:

- Multiple or ancillary functions of equipment
- Reasoning leading to design decisions.

There appears to be ample room for improving the recording of all types of information presented with the exception of 'the base function of equipment'.

Further problems associated with current approaches to design and recording which were listed by at least one respondent are:

- late changes during detailed design due to procurement issues usually lost
- control and trip functionality not recorded
- start-up etc. can be late and impact on design
- process capability not adequately recorded
- multiple modes of operation required may not be clear
- control loop settings may only be recorded in software
- all design decisions may be included in meeting minutes, but people looking back don't read them
- economic aspects not adequately recorded
- range of design points not adequately recorded
- functional details of DCS (Distributed / Digital Control Systems) and interlock systems not recorded.

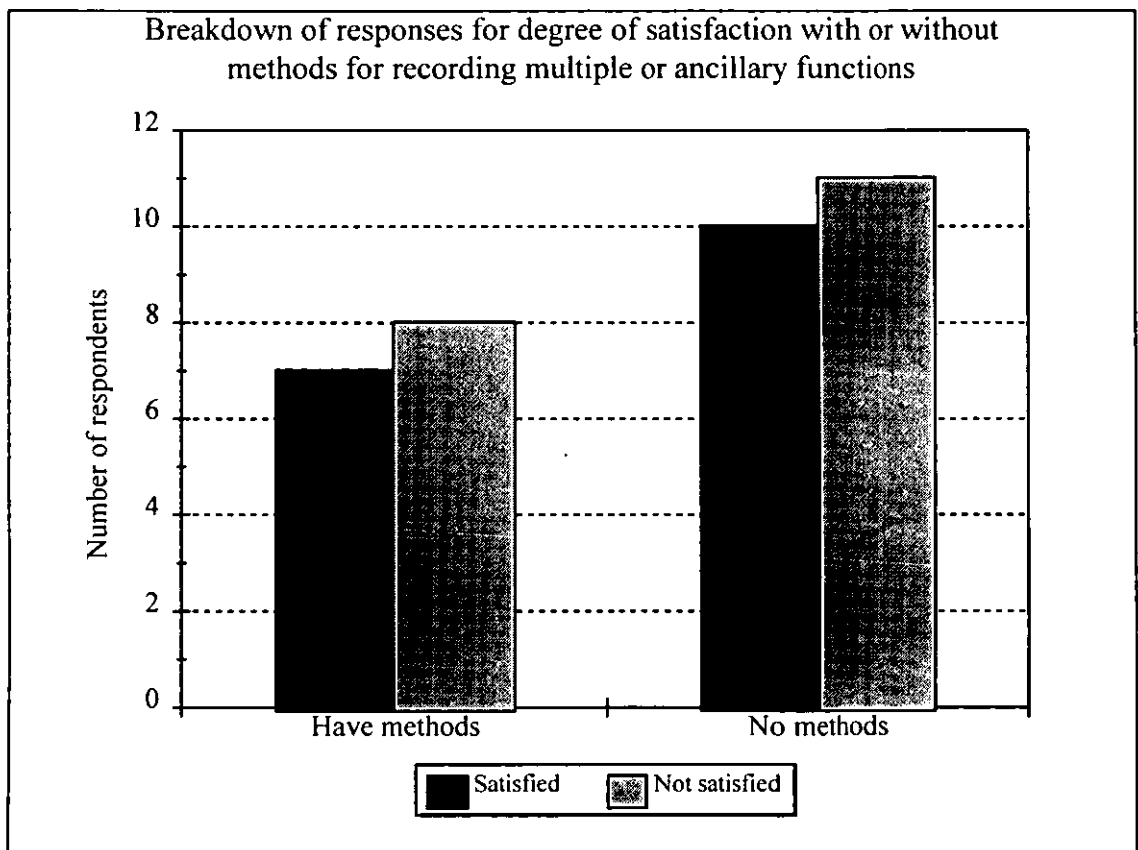
Survey of Current Practice Report: Question 13																
Question																
Does your organisation have specific methods of making records concerning:																
Response options																
- multiple or ancillary functions of equipment	yes / no															
- constraints on equipment relationships	“															
- design prohibitions	“															
- reasoning leading to design decisions	“															
Responses																
<div>Breakdown of responses for “my organisation has specific methods of recording...”</div>  <table><caption>Data for Breakdown of responses for “my organisation has specific methods of recording...”</caption><thead><tr><th>Category</th><th>yes</th><th>no</th></tr></thead><tbody><tr><td>Multiple functions</td><td>17</td><td>22</td></tr><tr><td>Constraints</td><td>21</td><td>19</td></tr><tr><td>Prohibitions</td><td>27</td><td>11</td></tr><tr><td>Design reasoning</td><td>20</td><td>19</td></tr></tbody></table>		Category	yes	no	Multiple functions	17	22	Constraints	21	19	Prohibitions	27	11	Design reasoning	20	19
Category	yes	no														
Multiple functions	17	22														
Constraints	21	19														
Prohibitions	27	11														
Design reasoning	20	19														
Discussion																
The results show that with the exception of design prohibitions, approximately equal numbers of respondents have or do not have specific organisational methods for making records of the types of information listed.																

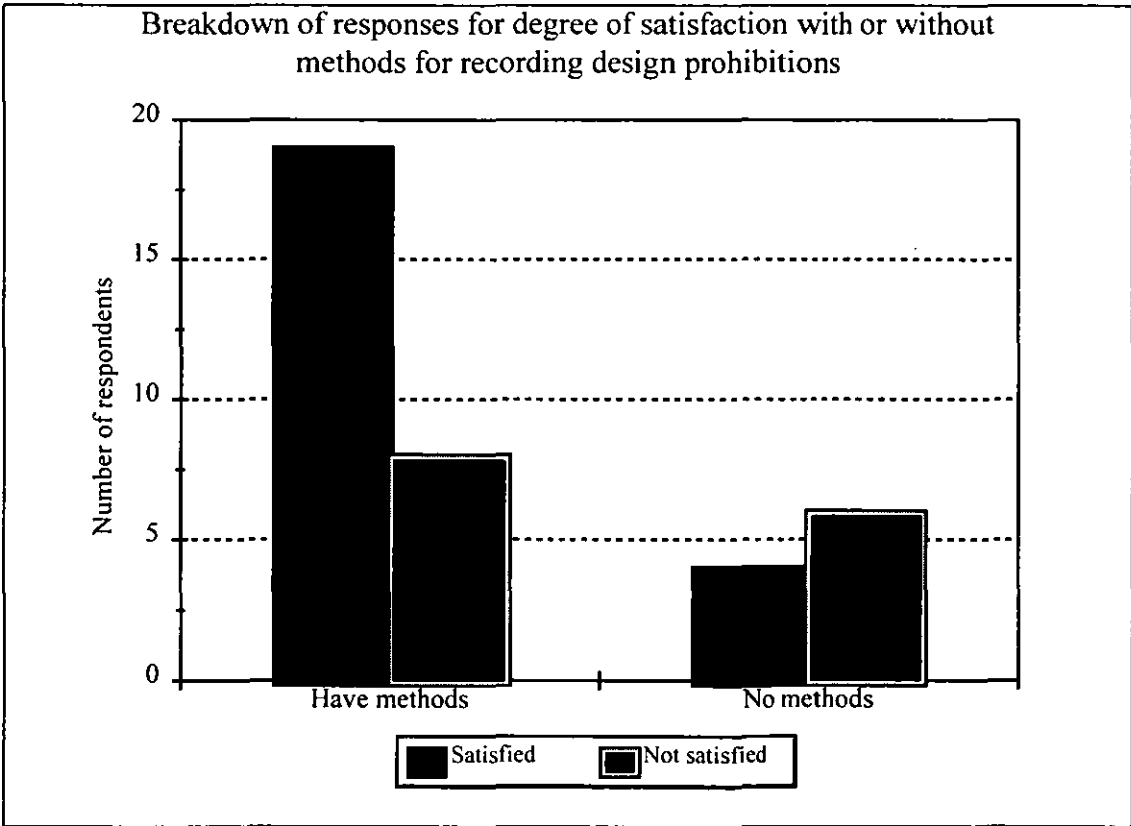
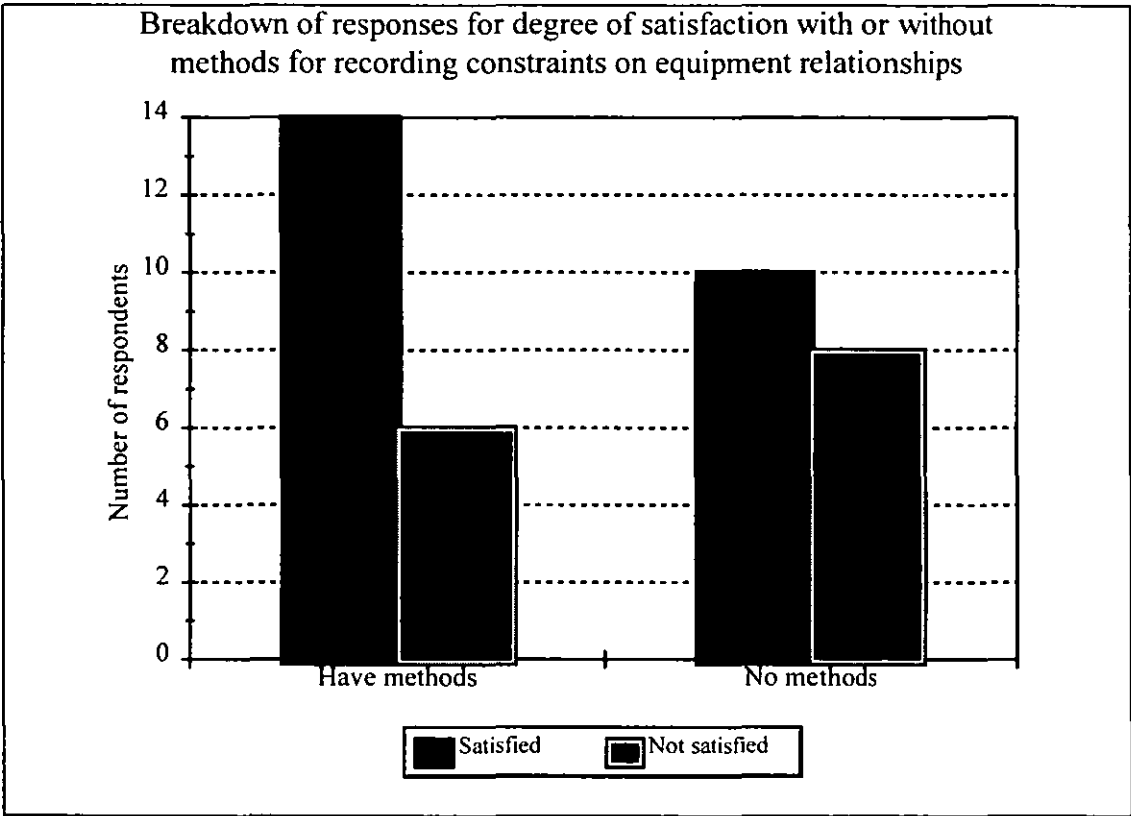
Other information listed as being recorded includes:

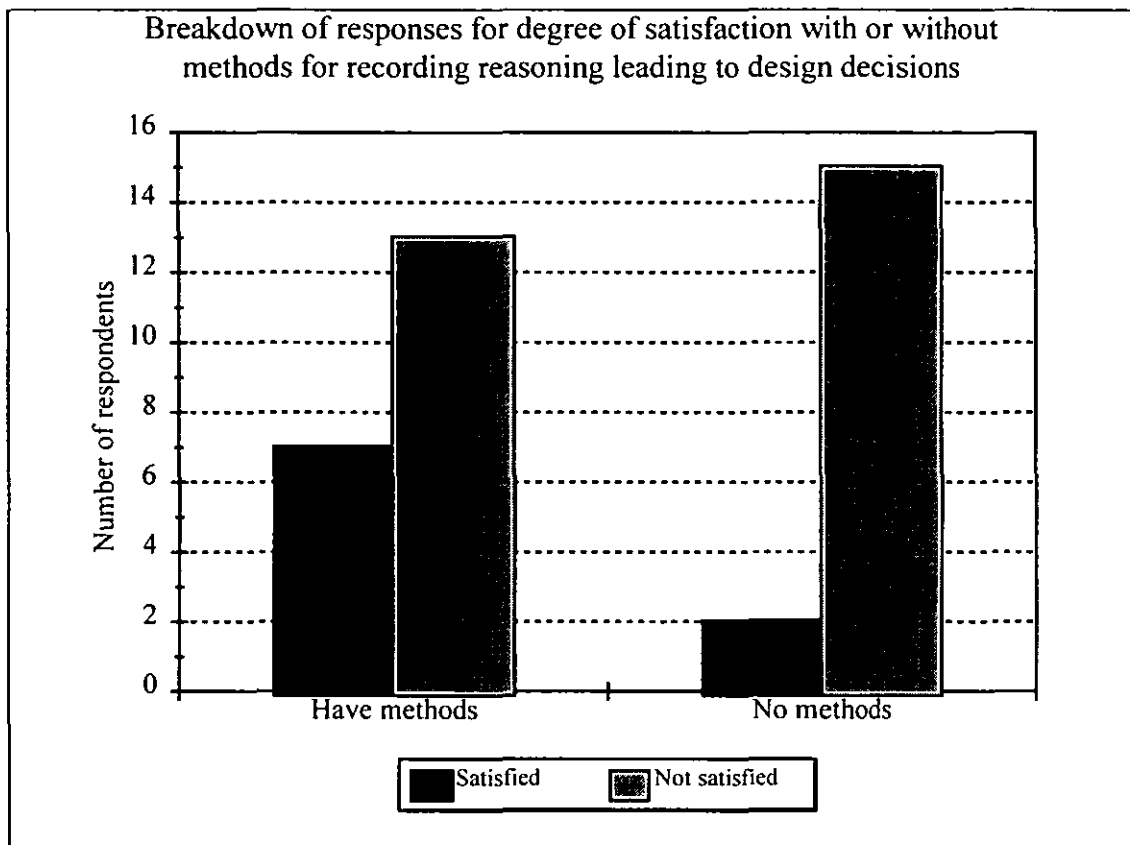
- standard 'module' designs
- design and layout details impacting on maintainability and operability, particularly where these have safety implications.

In order to assess the success of the methods referred to in question 13, the responses have been correlated with the corresponding answers to question 12 (as before with questions 4 & 5):

Correlations







Discussion

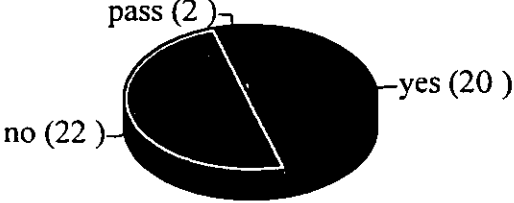
In the case of multiple or ancillary functions, about half of respondents with specific methods of recording are satisfied and about half without methods are satisfied.

For constraints on equipment relationships, the majority of respondents appear to be satisfied. Approximately equal numbers are satisfied whether they have methods of recording constraints on equipment relationships or not. Just under half of the respondents are dissatisfied with the methods used.

The majority of respondents have methods for recording design prohibitions and are satisfied. Approximately equal numbers are dissatisfied whether they have methods of recording design prohibitions or not. Just under half of the respondents are dissatisfied with the methods used.

Finally, in the recording of reasoning leading to design decisions, around two thirds of all respondents are dissatisfied. Half of these have specific methods and half do not. Only two respondents say that they are satisfied with no methods.

The results of these correlations reinforce the observations made under question 12, namely that there is ample room for improvement in recording multiple or ancillary functions of equipment and reasoning leading to design decisions.

Survey of Current Practice Report: Question 14								
Question Do you personally have specific methods of making records concerning any of the above:								
Response options yes (e.g.) / no								
Responses <div><p>Breakdown of responses for “I personally have methods of making records concerning the types of information listed above</p><table><thead><tr><th>Response</th><th>Count</th></tr></thead><tbody><tr><td>yes</td><td>20</td></tr><tr><td>no</td><td>22</td></tr><tr><td>pass</td><td>2</td></tr></tbody></table></div>	Response	Count	yes	20	no	22	pass	2
Response	Count							
yes	20							
no	22							
pass	2							
Discussion Approximately half of respondents have personal methods of making records concerning the information listed in question 12. Methods listed include: <ul style="list-style-type: none">• making notes on drawings prompted by checklists• keeping items such as the following:<ul style="list-style-type: none">- project philosophy notes built up as part of decision-making during conceptual design- design / compliance reviews- process description documents- data summary sheets- technical reports- handover documents- copies of past project ELDs- functional specs								

- notes on rationale for process development
- notes on calculation bases
- memos
- minutes of meetings.

The fact that many designers find it necessary to supplement their company methods with personal methods for recording information suggests that the company methods could be better structured and more comprehensive. Good recording and information management is particularly important for companies working on ELDs for external customers as it enables them to explain their work to the customer if necessary. Moreover, all companies could benefit from the increased efficiency and improved auditability afforded by good recording and information management systems.

Survey of Current Practice Report: Question 15

Question

Supposing a written aid for line diagram development were available, which of the following formats would you prefer:

Response options

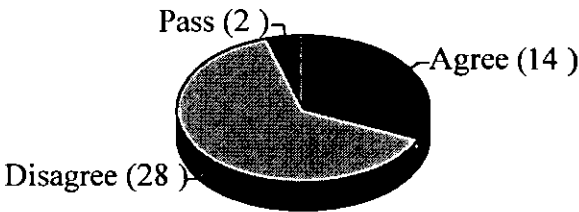
- *decision trees*
- *matrix structures*
- *interactive computer programs*
- *index-linked reference notes*
- *other (e.g.)*
- *no strong preferences*

Responses

Format for written aid	Number of respondents
Decision trees	9
Matrix structures	5
Interactive computer programs	12
Index-linked reference notes	16
Other (ideally provide an example)	1
No strong preferences	17

Discussion

Almost half of the respondents indicated that they had no strong preferences for a format for any written aid for line diagram development. Among those who expressed a preference, index-linked reference notes were the favourite. The general feeling, as expressed by one respondent, seemed to be “whatever works, and is clear to use”. From a development point of view, interactive computer programs or index-linked reference notes would be preferred as they are more widely applicable. It is difficult to produce definitive decision trees, while matrix systems tend to require a certain amount of expertise from the user.

Survey of Current Practice Report: Question 16									
Question									
“Capturing corporate knowledge relevant to line diagram development is <u>not</u> a problem in my organisation”:									
Response options									
agree / disagree									
Responses									
<div>Breakdown of responses for “capturing corporate knowledge is <u>not</u> a problem...” <table><thead><tr><th>Response</th><th>Count</th></tr></thead><tbody><tr><td>Disagree</td><td>28</td></tr><tr><td>Agree</td><td>14</td></tr><tr><td>Pass</td><td>2</td></tr></tbody></table></div>		Response	Count	Disagree	28	Agree	14	Pass	2
Response	Count								
Disagree	28								
Agree	14								
Pass	2								
Discussion									
<p>Two thirds of respondents imply that capturing corporate knowledge relevant to line diagram development is a problem within their organisation. In the light of the current trends in employment and in methods used to acquire design expertise discussed under questions 4 and 5, this result is quite worrying. If companies fail to record corporate knowledge adequately and continue to rely on on-the-job training for developing design expertise in new graduates, then as the number of people with good experience begins to diminish (due to the increased use of short-term contracts), corporate knowledge will gradually be irrevocably lost.</p>									

Survey of Current Practice Report: Question 17

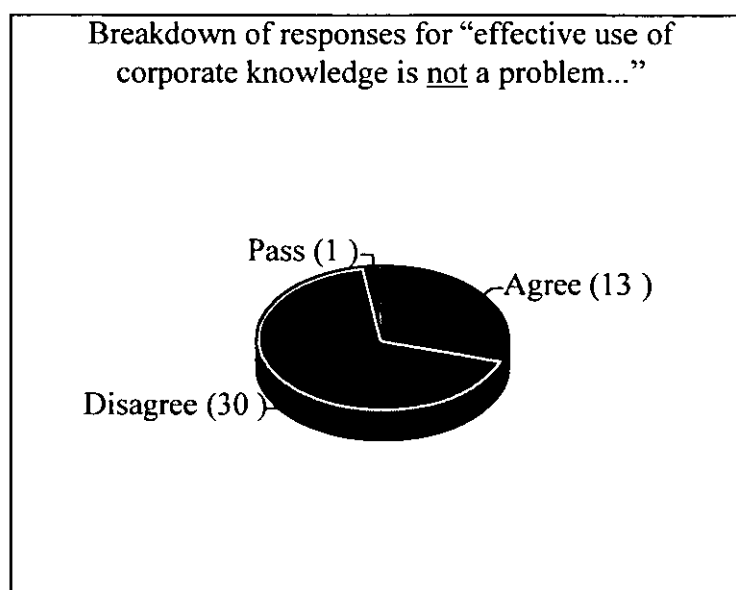
Question

“Effective use of corporate knowledge relevant to line diagram development is not a problem in my organisation”:

Response options

agree / disagree

Responses



Discussion

Two thirds of respondents imply that effective use of corporate knowledge relevant to line diagram development is a problem within their organisation. Again, this problem can only be solved by better information management. This could include development of tools to improve usability of information and provision of more formal procedures for referencing relevant information. In addition, some of the information generated as corporate knowledge could be used to train new recruits, for example in the peculiarities of line diagram design specific to the company.

3.2 Exercise in Line Diagram Development

The final question asked in the survey discussed above was whether respondents would be willing to participate in a small line diagram development exercise in order to provide more comparative data in support of the analysis of this part of the design process. Details of this exercise and a fuller account of the results are included in appendix A2. Despite initial enthusiasm on the part of the respondents, only three solutions to the example problem were obtained. A brief analysis of the responses is given below.

The first point of interest in comparing the solutions to the line diagram development exercise is concerned with the overall approach to the design problem. One of the responses clearly takes a breadth first approach to the design with quite a rigid structure for ELD development. In contrast, another response seems to take a depth first approach with significant amounts of detail being given in relation to one problem before the next is addressed, there being no obvious structure for the stages of line diagram development.

A second point which is immediately striking is the timing of the HAZOP Study. All three responses state that a HAZOP would be carried out on the preliminary ELD, and one specifies a further Hazard Study on the updated ELD. This implies that the HAZOP is being used as a design development tool rather than as a design check. General texts on Hazard and Operability Studies (e.g. Coulson, Richardson & Sinnott, 1991; Skelton, 1997) recommend that the HAZOP is carried out on the firm ELD, and give no mention of a Hazard Study on the preliminary drawing.

Whilst all of the responses demonstrate good practice in terms of early identification of hazards and their effects on design safety requirements, little attention seems to have been paid to environmental considerations such as waste minimisation and effluent treatment. In addition, none of the responses mentions quality control or consideration of transitional operations such as start-up, shutdown (except emergency shutdown) or decontamination. This highlights again the steady-state mindset in process design. Although interactions with other disciplines concerning specifications, control systems and so on seem to be well established, there is no indication of where operating and other procedures should begin to be developed.

Comparison of the responses also demonstrates clearly that although current practice is good at raising the subject of safety, there is considerable subjectivity in its handling and resolution. This characteristic is true of most design issues - raising the appropriate issues is one step in the right direction but resolving the issues effectively relies upon a certain amount of background knowledge. It is relatively straightforward to develop written procedures which can be used to raise important issues but it takes a lot more effort to develop the decision support which is required to handle their resolution consistently.

3.3 Task Analysis

The phrase 'task analysis' is used to describe any process that identifies and examines the tasks that must be performed by users when they interact with systems. The primary purpose of task analysis is to compare the demands of the system on the operator with the capabilities of the operator. The information generated is then used to reduce error and achieve successful performance within the boundaries of the system.

Task analysis can be used to establish task requirements or to carry out task assessments on topics such as:

- allocation of function
- person specification
- staffing and job organisation
- safety management.

More specifically, Kirwan & Ainsworth (1993) write that "...task analysis could also be applied to a particular phase within the design cycle as if this phase was a system to be assessed...This is currently unusual, but in safety terms could be highly beneficial".

There are many different methods of collecting data for the purposes of task analysis. The methods which were considered to be most useful for the analysis of the process flowsheet to engineering line diagram design task were observational techniques, structured interviews and activity sampling.

Observational techniques are most appropriate when information is of a visual or audible form and when skilled performance is such that actions are 'semi-automatic'. Structured interviews are useful for collecting a wide range of information on a particular task situation. Activity sampling involves a simple tally or sequential recording of design tasks which can be used to compute the relative frequencies of each task. The information generated by this technique, though usually very limited, can provide a very useful means of identifying the steps which have to be undertaken during a task (Kirwan & Ainsworth, 1993).

Further information on the practicalities of the line diagram development process was gathered by carrying out task analysis activities on a specific project at ICI Runcorn. The overall objective of these activities was to generate information on how designers engage in the day-to-day task of PFD to ELD development given their current design guidelines. The task analysis was performed at ICI Runcorn within a period of 4 months and involved one three day visit and one one day visit. The following activities were undertaken:

- interviews with design team members
- observation of project meetings
- development and application of a task analysis diary.

Structured interviews of about half-an-hour's duration were held with the following design team members:

- control / instrumentation engineer
- HAZOP / safety engineer
- commissioning engineer / operator
- project engineer.

The questions asked were:

- 1) What are your tasks associated with the Engineering Line Diagram (ELD)?
- 2) What information do you require from process engineers in order to do your job properly?
- 3) What information do you think process engineers rely on you for?
- 4) How do you communicate with process engineers in order to share this information?
- 5) How often do you share the information?
- 6) What shortfalls do you find in your current methods of communication?

- 7) How do you think these could be improved?
- 8) Do you actually use the final ELD? If so, what for?

Informal interviews of a similar time duration were also held with the existing and former project leaders. The purpose of these was to obtain information on the overall approach to the management of the design task.

The observation of project meetings involved attending and making detailed notes on two three hour PFD review meetings and one three hour ELD review meeting. This activity was undertaken in order to obtain information on the types of issues which predominate when the different engineering disciplines are brought together as a group.

Both types of activities described above address the analysis of the design task at quite a high level, and should consequently provide an excellent overview of the design process. The third activity, which was the 'task analysis diary', was developed in order to provide more detailed records of daily design activity in order to complete the picture.

The specific objectives to be met by the combined task analysis activities included identification of the following:

- Whether there are any common patterns in:
 - the order in which the PFD is developed into the ELD
 - the way in which members of other disciplines are brought into the design.
- How much information on decision making is recorded and in what form.
- What information is shared at the start of ELD development.
- How much conscious effort is made to consider all possibilities (as far as reasonably practicable) before coming to a decision and how criteria are agreed and the decision finally reached.
- How much 'chunks' of design are re-used and how this affects the solution in terms of context (location, climate, staff, services).
- How problems are 'packaged' into mini-projects.
- To what extent SHE, operability and cost are considered throughout the design (rather than in reviews).

- Data sources used - where do people get information from and to what extent are they prepared to estimate (any rules of thumb for feasibility etc.).

3.3.1 Interviews with Design Team Members

Informal interviews were held with the present and former design team leaders for a project at ICI. These interviews showed that even within the same company, there are differences in the degree of structure afforded to the design process and in the specific purpose and procedure of reviews. The only thing which is agreed upon is the sequence of design drawing 'issues' (versions) which need to be produced. This follows a defined route of *notional* to *preliminary* to *firm* ELD, with development and/or review meetings being held between each stage. The format or philosophy for handling the design process along this route is very much at the discretion of the project leader.

Structured interviews were also held with other members of the design team, as described earlier. These elicited many useful observations on key aspects of the design task which are summarised below.

Use made of the ELD

The ELD is important to each member of the design team for the reasons given below:

- Control / instrumentation engineers use it:
 - in conjunction with datasheets to specify the instrumentation required to meet the control / diagnostic objectives of the process
 - as an information source if modifications are required
- Hazard Study leaders use it to carry out Hazard Study III (HAZOP)
- Hazard and reliability engineers use it as an information source for calculation of the reliability of protective systems
- Commissioning engineers use it:
 - to develop operating instructions, maintenance procedures, decontamination procedures, etc.
 - to confirm that plant has been constructed as proposed

- Operators use it for troubleshooting
- Project engineers use it:
 - to keep a record of changes made during construction
 - to help produce the process databook
 - for reference
 - as a handover document for contractors.

Information exchange

The following types of information were found to be exchanged between the different team members of a design group in order to produce sound ELDs.

- Advice to process engineers from control / instrumentation engineers on the feasibility of measurement / control systems, identifying safety issues and operability
- Advice to process engineers from commissioning engineers on operability
- Clear definition of control strategy from process engineers to control / instrumentation engineers
- Instrument datasheets and piping and equipment process datasheets from process engineers to control / instrumentation engineers and project engineers respectively
- Process conditions data from process engineers to commissioning engineers.

Information is exchanged between disciplines both formally and informally by a combination of discussions, meetings and documents through a document control procedure. The exchange between process and other engineers is effectively continuous. The exception is the safety engineer who tends to act as an adviser on anything other than very big projects and as such is only called upon when the need is identified. There is no formal guidance on when or why other disciplines should be consulted during ELD development.

Shortfalls in current methods of working

Some of the shortfalls in current design practice identified by the different team members are listed below:

- Late changes made after the formal review procedures have been completed are not always communicated to those who are affected by them
- Difficulty in finding a balance between full recording and 'user-friendly' recording of information
- Too many 'black boxes' on ELDs, such as those representing control systems, making it difficult to interpret them from an operating point of view
- Incomplete understanding of others requirements, illustrated for example by specifying instrument ranges which do not cover the entire range of possible operating conditions
- Communication with site is not always as good as it could be
- Inadequate specification to subcontractors of information required on drawings, leading to inconsistent drawings and often to rework
- Reluctance to ask for safety advice early on.

Discussion

The information generated from both the informal and structured design team member interviews provided a useful insight into the line diagram design process as viewed from the point of view of other related disciplines. Observations made during the informal interviews with the present and former project leaders concerning the lack of consistency in the overall approach to the design problem reinforce those made on the line diagram development exercise covered in section 3.2 .

The information obtained through holding structured interviews with individual team members raised some interesting points and provoked a number of suggestions for improving the design process. These are summarised below.

1. The information on the importance of the ELD to different people could be used to draw up a definition of the ELD in terms of user-objectives to complement the usual equipment definition. This could help to clarify the objectives in PFD to ELD development.
2. The observations made on information exchange also provide important material which could be used to help designers to identify when they should be seeking advice from other

disciplines and when they should be notifying other disciplines of changes made to the design. Though there was no rigid structure to the way in which members of other disciplines were brought into the design, an informal arrangement could be inferred from the information gathered. This is represented in fig 3.1 overleaf.

An interesting point to note is that information exchange between the safety engineer or hazard study leader and the process engineer is largely a one-way process. During the course of the design the safety engineer tends to act purely as an adviser. No information is *required* from the process engineer by the safety engineer until Hazard Study III is reached. This may go some way towards explaining why a number of safety issues are not identified until the Hazard Study III stage. If the safety engineer required information from the process engineer earlier on in the project life-cycle as the other disciplines do then there would be more opportunity for the safety engineer to see and question the design. Consequently, the responsibility for identifying potential problems would not rely solely on the judgement of the process engineer but also on the ongoing contributions of the safety engineer. This should lead to significant improvements in the inherent safety of designs.

The shortfalls in current practice which were identified serve as a reminder of the importance of good communication and of the difficulty in finding a balance between the detail in and the usability of information. The communication shortfalls might be addressed by the development of new procedures or guidelines but the shortfalls in using information will be hard to overcome in the presence of time pressures.

3.3.2 PFD and ELD Review Meetings

The second form of task analysis used was observational techniques. This was applied by me acting as a bystander during some of the project meetings as described earlier. The meetings enabled me to witness the interaction between the different engineers and to clarify my perception of their concerns and their roles. They also gave me an insight into how the PFD / ELD methodologies which already exist in ICI are applied and used.

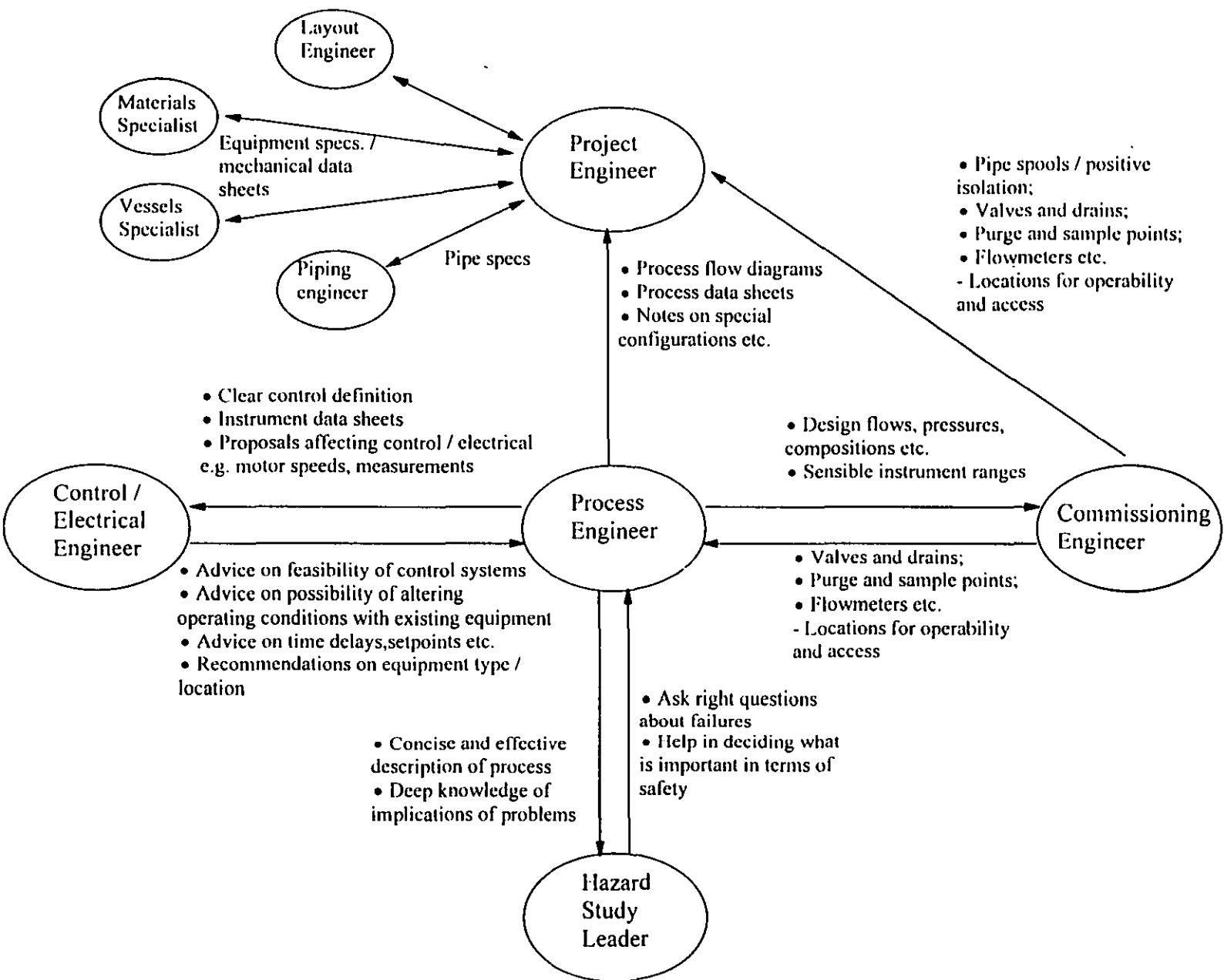


Fig. 3.1 - Network of information flow in line diagram development based on task analysis at ICI

During the review meetings, any actions, key aspects of discussion and conclusions are minuted. However very little information on decision-making is recorded. The minutes tend only to pick up actions to be completed, so that a lot of important points arising from discussions and questions are lost. In addition, there is no structured method of recording issues raised in between the meetings and the process description does not include information on decision making. This means that the only way decision making is likely to be traceable is through the notes on design proposals which are passed around under the formal document control procedure.

A reasonable amount of discussion of design alternatives takes place both within and outside project meetings. The extent of the investigations are obviously limited by time constraints. However, again there is no formal recording of the alternatives discussed, so that the whole basis of the arguments, with issues for and against, is not readily available. As before, some of the history of the discussions could probably be traced via the document control procedure if necessary.

Discussion

The information obtained through the observation of the design review meetings on the nature of the interactions between the different engineers reinforced that generated by the design team interviews and contributed to the development of the network of information flow shown in fig. 3.1 above.

Other significant general observations made are:

1. People ask questions but nobody notes down the response so there is no record of the information which permitted the design to continue. The minutes which are taken relate mostly to issues which have generated actions on the various team members.
2. The structure of the meetings is not very formal. Many useful points are raised and much information is generated by allowing thoughts to flow and minds to wander somewhat away from the immediate topic. However I had the impression that a number of issues

could easily be overlooked due to the use of such an informal structure. This is perhaps one of the weaknesses of running the meetings as development and review meetings combined, rather than purely as design reviews.

3.3.3 Task Analysis Diary

The last task analysis approach adopted was activity sampling. A timesheet for a task analysis diary was developed for this purpose. The intention was that design engineers would fill this in as they worked. Steps of design objectives from an early version of the PREMIUM methodology (see chapter 4) were used as the basis for the list of design activities shown on the diary record sheets. The format for the diary and record sheets was developed with the assistance of Dr Andrew Shepherd - a task analysis expert at Loughborough University.

The aim of the study was to obtain the following information on design practice:

- the main design activities undertaken
- the amount of time spent on the different activities
- reasons for moving between the different activities
- methods of communicating in order to progress the design.

The record sheets were produced to help the designer to record such information. A number of these sheets were to be bound together in a booklet, along with instructions on how to use them. An example of the instructions and record sheet are given in appendix A3. The input required of the designer was to keep the booklet to hand and to keep it up-to-date, preferably by adding the required information concurrently with their work. The booklet was then to be returned to us either when the project on which the designer was working had been completed or when the designer had used all the record sheets provided.

After a trial run, it was concluded that the diary was an inappropriate way of gathering information on the line diagram design process. The reasons for this are described below.

Discussion

One of the main objectives in developing the task analysis diary was to enable information on how engineers progress through design from one issue to the next to be produced. When the record sheet from the diary was trialled, it was found to be completely incompatible with the usual method of working. The reasons attributed to this are as follows:

1. The time sheet was designed to be completed with reference to one ELD. In practice, a number of design tasks undertaken during PFD to ELD development impact on several ELDs at once.
2. The time sheet was designed to allow the reader to follow the designer's train of thought regarding how they move from one task to another. In practice, tasks are packaged and actions arise through requests from other people and through identification of new problems so that it is difficult to prescribe a fixed pattern of response. The order in which problems are addressed is generally driven by priorities which are set by the project program. This means that the design activity can be considered to be reactive rather than proactive from the point of view of the individual designer.
3. The time sheet lists quite discrete areas of work. In practice, a number of activities will be undertaken simultaneously, so that problems are considered in groups rather than in isolation.
4. The time sheet is aimed at the individual designer. In practice, design is a team activity, so it is not appropriate to try to understand why the individual designer moves from one problem to the next. The different problems are allocated amongst the team so while they may not necessarily be related on an individual scale, they may follow some sort of pattern at the wider team scale.

A member of the ICI team provided the following list of typical work carried out over ten days to illustrate the true nature of the design task:

- relief review - checking adequacy of previous design
- sampling / analysis
- instrument data sheets
- programme for characterising plant performance
- troubleshooting
- planning future work programmes
- layout review
- materials of construction review
- design studies (with functional experts) on specific equipment items
- nitrogen supply.

Although it was not possible to infer a pattern in the specific design activities undertaken by the individual designer, the information generated by the task analysis as a whole made it possible to compile a crude flow diagram of the design tasks and activities in process flowsheet to line diagram development. This is shown in fig. 3.2.

3.3.4 Summary notes on remaining task analysis objectives

The task analysis activities described above have addressed the issues of: patterns in the approach to ELD development and the way in which other design team members are brought into the design; recording of information on decision-making; the extent to which design alternatives are explored and the manner in which decisions are reached. This section gives a brief summary of the observations made with respect to the remaining task analysis objectives outlined in section 3.3.

- The only documented information shared at the start of ELD development at ICI is the process flow diagram and tabular data indicating:
 - stream / batch quantities
 - temperatures
 - pressures
 - compositions

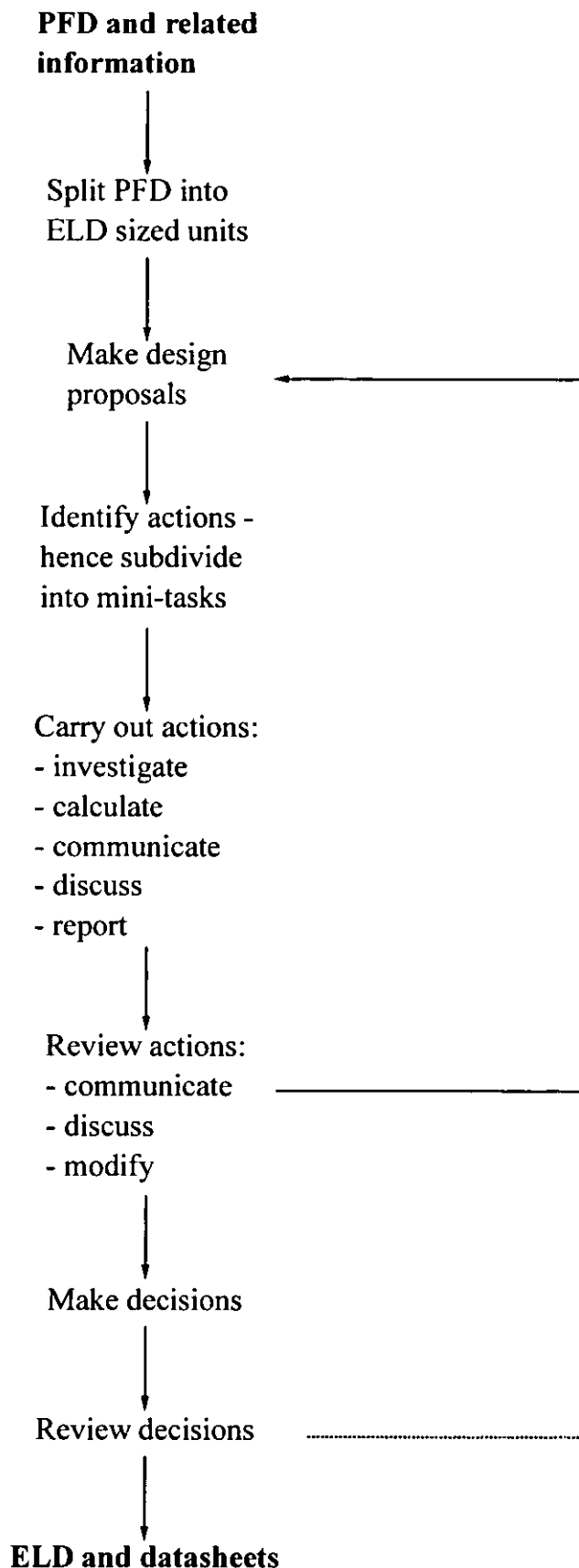


Fig. 3.2 - Flow diagram of design tasks and activities in PFD to ELD development

- energy [flows]
- outline size of main plant items
- main instruments
- principal control loops.

(ICI doc't 'Methodology for PFD review', 1997)

NB The results of Hazard Studies 1 and 2 would also have been distributed to project members as they were generated.

- It was not possible to ascertain to what extent 'chunks' of design and of plant are reused because the project used for the task analysis was a modification.
- No formal method for packaging problems into mini-projects was identified. Work just appears to be allocated as problems arise during meetings or discussions.
- It was difficult to establish how much SHE, operability and cost are considered throughout the design on an individual basis as no work-shadowing was done. However, the evidence certainly points towards a degree of ongoing consideration of these issues through the described interactions with other disciplines.
- It was not possible to identify the types of data sources used within the project as no work-shadowing was done. The extent to which people are prepared to estimate depends very much on their experience and on the criticality of the data in question.

3.4 Conclusions

The overall conclusion which can be drawn from the analysis of current practice in line diagram design is that the lack of a formal definition of the logic and / or the order in which decisions for developing a first engineering line diagram are made is not confined to the public domain. Within industry, there is a similar climate of ambiguity and vagueness to that portrayed in the literature review.

Other key conclusions from perceptions within industry are listed below.

3.4.1 Engineering Drawings

- The PFD would generally be expected to show:
 - intermediate storage
 - principal control loops / control philosophy
 - major duplicated equipment
 - multiple streams

but not

- utilities lines
- isolation valves
- pressure relief
- hardware associated with start-up / shutdown / decontamination / maintenance.

More complete definitions of the process flowsheet, PFD and ELD in the context of this work will be given in chapter 5.

- Computers are used almost universally for preparing engineering drawings but a significant part of line diagram development work is still done without computers.
- The public standards for engineering drawings are somewhat redundant as they are not widely used.

3.4.2 Line Diagram Development

- There is no clear agreement on the general approach to line diagram development beyond the need to produce notional, preliminary and firm issues (versions) for each drawing.
- Though many companies do take an interdisciplinary approach to design there is still a need to improve understanding and communication between the different disciplines. Provision of some form of guidance on who to speak to and when could improve the effectiveness of interaction between different disciplines.

- Information exchange needs to be driven by some form of incentive for all parties involved otherwise commitment to it is lost.
- There seems to be some confusion in industry over the precise purpose of the HAZOP, with some companies appearing to use it as a development tool in line diagram design.
- The steady-state mindset in design is very evident in the responses to the survey line diagram development exercise.
- Line diagram design is still very much a 'pen and paper' process, with computers mostly being used as a means to generate the final drawings.
- There are no significant differences in the general approach to line diagram design for batch or continuous processes.
- Costs are largely taken into account during reviews, rather than being used as a driver in design.
- The importance of safety in design is widely recognised, but attention paid to environment and quality control still seems to be limited.
- At the individual level, the order of actions in line diagram development tends to be reactive rather than proactive. Designers are driven by changing priorities which arise through the interconnected actions of the team as the project progresses.

3.4.3 Problems in Design

The problems commonly faced in line diagram design can be grouped into the following classes:

- problems due to late changes
- problems due to a lack of understanding between different disciplines
- problems due to compromises between detail and usability of information
- problems due to a general reluctance to record design details, even when they are important.

3.4.4 Acquiring design expertise

Companies rely on company methods, on-the-job training and employment of experienced personnel for provision of design expertise. Many designers are not satisfied with the lack of formal training in design. Formal training could be used to bridge the gap caused by a shortage of experienced personnel which is likely to arise as a result of the increased use of short-term contracts and the tendency of designers to move into other areas of work. Formal training could also be used as a means of perpetuating corporate knowledge.

3.4.5 Information handling

- The ability to raise important design issues and the ability to handle them effectively and consistently are quite different. Procedures or methods can be used to raise important issues but these will not give guidance on the resolution of the issues. Some form of decision support is required to ensure that issues are handled as thoroughly as possible.
- Recording of information pertinent to line diagram design is generally not very satisfactory, particularly in the areas of multiple or ancillary functions and reasoning leading to design decisions.
- Capture and effective use of corporate knowledge poses a significant problem.
- The preferred form of support for line diagram design is index-linked reference notes. The usability of support tools is the main concern and so other forms should not be discounted if these are more appropriate.

CHAPTER IV - EVOLUTION OF THE METHODOLOGY

4.0 Introduction

Chapters 2 and 3 of the thesis illustrate that there is a lack of any formal procedure or method which captures the logic for the order in which decisions for developing a first line diagram should be made. Consequently, there is a need to generate such a method in order to provide a framework for the systematic and proactive consideration of safety, health and environmental (SHE) issues in detailed process design.

This chapter describes the generation of a methodology which is intended to explain fully the activities and objectives of ELD development and to capture the logic for the order in which these activities and objectives are addressed.

Section 4.1 defines the objectives for the new methodology and outlines the general approach taken to its formulation.

Section 4.2 describes the research which was done to generate the first draft for the new methodology. This includes the application of Scott's method to a particular design problem and the establishment of the concept of intermediate representation.

Section 4.3 discusses the work which contributed to the development of the second draft of the methodology. The idea of incorporating a separate section at the front of the methodology to handle higher level issues such as the type of effluent treatment required is introduced. Some of the logic behind the order of the steps is also explained.

Section 4.4, which is concerned with the third draft of the methodology, describes the generation of a matrix of design objectives and solutions and discusses its impact on the structure of the methodology. The grouping of the methodology steps into different sections is also covered.

Section 4.5 elaborates on the concept of design hierarchies in line diagram development (introduced in section 4.3) and shows how these contributed to the framework of the methodology .

Section 4.6 discusses the changes which were made leading to the fifth draft of the methodology. These changes were largely concerned with the presentation of information within the methodology.

Section 4.7 describes how the focus of the methodology changed in response to the findings of the task analysis work, carried out at ICI, and in response to the feedback generated from application of the method in a ‘Masterclass’ with engineers from ICI.

Section 4.8 gives a brief summary of the key stages in the development of the methodology.

Section 4.9 presents the conclusions for the chapter.

4.1 Methodology Objectives

The basic objectives in developing a methodology for line diagram development were:

- to provide a framework for capturing the logic and / or order in which decisions for developing a first line diagram are made
- to provide a detailed account of all the necessary contributory activities in order to minimise the frequency with which design objectives are overlooked
- to ensure that the method is adaptable, so that it can be used by designers with different degrees of experience, from different backgrounds and with different approaches to the design problem
- to ensure that the method is ‘open’, so that it can be used for a variety of design tasks ranging from plant modifications right through to complete design of batch or continuous processes.

Before elaborating on the key stages in the development of the methodology, it is worth saying a little about the overall approach to the problem. The approach taken, much like the one used for design itself (see section 2.1.2), was to perform a series of synthesis and evaluation steps. The starting point for this was the basic Scott (1992) method. Synthesis, in which a refined method is created, entailed the collection and integration of information, initially from the open literature. Evaluation was achieved by applying each version of the method to various hypothetical design problems.

4.2 Methodology #1

The literature review on methodologies in engineering design revealed that Scott's method was the only available piece of work attempting to formalise the process flowsheet to line diagram design task. Since Scott's method does not attempt to capture the logic for the order of decisions to be made in ELD development, there is scope for a new methodology which does.

4.2.1 'Lawley' Exercise

Scott's attempt to systematise line diagram design is given in section 2.4.1. The method developed was intended purely for use by undergraduates in their final year design projects. It comprises a series of steps giving instructions which are intended to be addressed successively, with the specific call for iteration, if necessary, at step 13 of 14 (see section 2.4.1).

The first logical step in the generation of a new methodology was to apply Scott's method to a specific design problem in order to discover its particular strengths and weaknesses. The design problem chosen was one based on a well-known case study by Lawley (1974) on alkene dimerization. The problem is presented in Scott & Macleod's (1992) book "Process Design Case Studies" along with Scott's method. The details are outlined in appendix B1.

The aim of performing this alkene dimerization exercise, henceforth referred to as the 'Lawley' exercise, was to determine how useful Scott's step-by-step approach is as a basis for a new methodology, and whether the steps listed capture all of the objectives of detailed process design. Detailed notes were recorded on the thought processes which were initiated by each step in Scott's method and on the reasons for the answers given and / or the equipment added to the line diagram. A full account of this reasoning is included in appendix B2, along with the diagrams generated in the course of the exercise.

Meanwhile, an engineer from ICI undertook the same line diagram exercise, using his own expertise rather than Scott's method. The record which he made of the exercise was similar in that it documented the overall purpose of each item of equipment added. However the record did not explain the reasoning behind each decision nor did it explain the order in which the decisions were made. A copy of the record and diagram which were produced is provided in appendix B2.

The line diagrams which were generated for this exercise were compared with a worked solution which is available in the form of a 'plant design workshop' in a departmental course manual written by Scott (1992). The end result in this workshop, i.e. the final line diagram, closely resembles that given by Lawley (1974) in the original paper. It was found that while all the diagrams examined, that is mine, the ICI engineer's, Lawley's and Scott's, exhibited the same major control characteristics, the details of such features as duplication of pumps, position of kickback lines, position of diagnostic instrumentation and so on were quite varied.

These results were encouraging. Though many of the details of the design varied in form, the drawings all exhibited the same types of key information. This showed that Scott's method conveys the right design objectives, it just does not provide enough supporting information to ensure that these are resolved consistently and effectively.

The main strength of Scott's method was found to be the use of a series of steps for breaking down the line diagram design task and introducing system and structure. The weaknesses of this method are that:

- it is too prescriptive (it tells you what to do rather than suggesting what may need to be done and why)
- it implies that the design can be achieved in a straightforward sequential manner with minimal recycles and iterations
- it implies that controls of flow, temperature and pressure are not inter-dependent and can be addressed separately
- it does not allow for the hierarchy of decisions which must be addressed in the design process (see section 4.3 for an explanation of these)
- it does not indicate where interaction with other disciplines will be required
- it does not detail how costing, safety, health and environment (SHE) and operability issues must be incorporated into the design, nor does it detail what effects these might have on the design decisions.

These weaknesses can be translated into qualities required for a successful methodology for line diagram synthesis. Combined with Tanskanen et al's (1995) key characteristics for any methodology, outlined in section 2.4.1, these give the following requirements for the methodology under development:

- it should encourage creative solutions
- it should integrate all the design activities including process engineering, control engineering, mechanical engineering and safety engineering
- it should permit a natural way of incorporating the use of computers in decision making and knowledge storage and retrieval
- it should be supportive without being prescriptive
- it should accommodate iteration / recycle between the different steps of activities and issues
- it should take account of the interdependence of issues raised in different steps where necessary
- it should accommodate the hierarchy of decisions which exists in the design process

- it should incorporate activities and issues associated with cost, SHE and operability.

4.2.2 Intermediate Representation

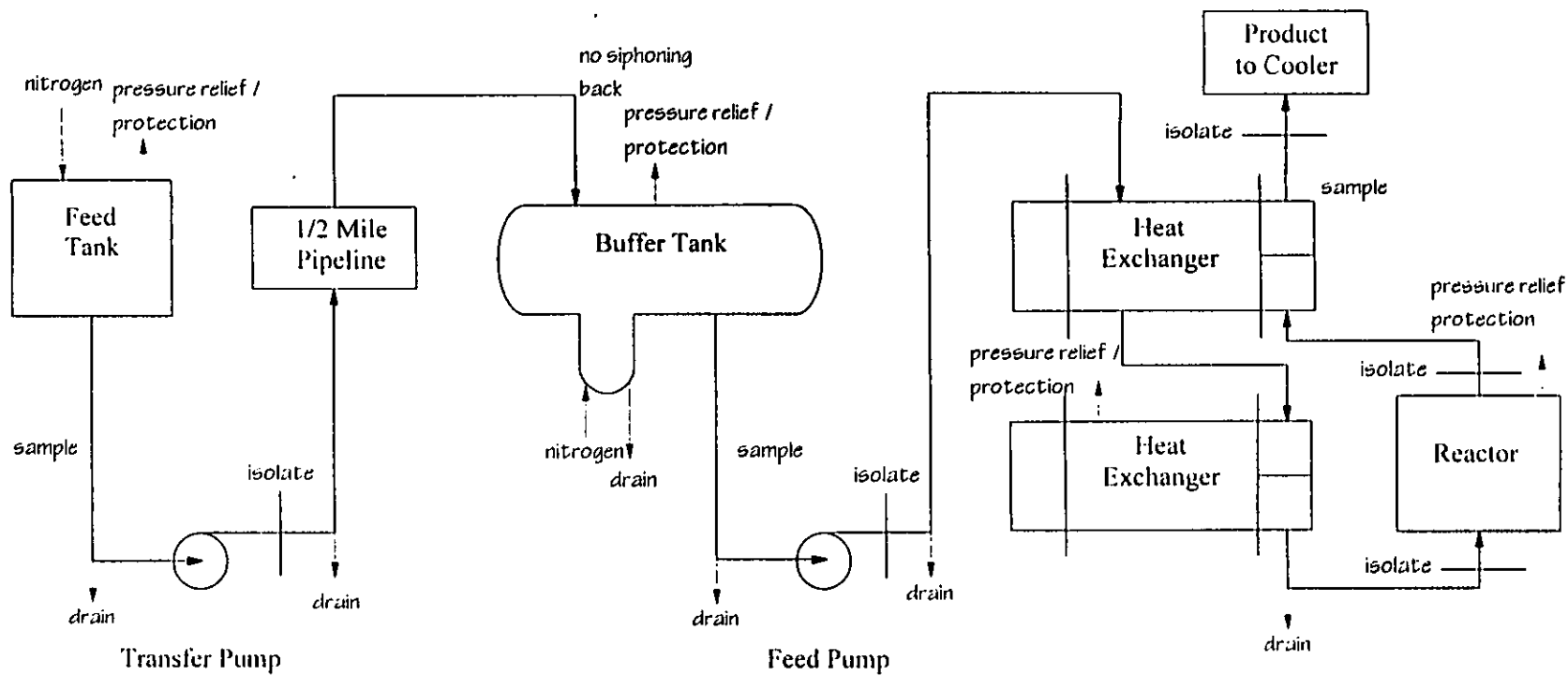
One of the most important concepts arising from the ‘Lawley exercise’ and illustrated in fig. 4.1 below, is that of ‘intermediate representation’. This term has been adopted to describe the elaboration of the process flowsheet in terms of functions, rather than equipment. Notice how the drawing indicates the need for such functions as isolation and reverse flow protection without specifying precisely what facilities are required to achieve these and where.

The conception of ‘intermediate representation’ arose through my limited knowledge of the many solution options available for each specific design problem. In working through the ‘Lawley exercise’ I was relatively clear on *what* I wanted to achieve, but lacked the necessary information to be able to specify *how* to achieve it. The ‘intermediate representation’ idea can be considered to be an extension of the concept raised by Hill (1968) and discussed in section 2.3.2 of the literature survey. Hill (1968) emphasises the importance of the flowsheet as a *statement of process objectives* and implies that the unnecessary inclusion of too much detail early on in the design may lead to the formulation of assumptions which might foreclose the best solutions.

Annotating an engineering drawing by outlining all the functional requirements for the process before any specific design objective is looked at in detail is considered to be important for the following reasons:

- it enables the designer to produce an overall picture of the salient safety and operability features for the plant in a very short space of time
- it delays the need to provide specific (hardware) solutions until such time as all possible interactions with neighbouring equipment have been identified
- it precludes the need to make unnecessary assumptions early on in line diagram development

Fig. 4.1 - 'Intermediate representation' in the Lawley design exercise



- it encourages the designer to identify where hardware can be used to achieve multiple objectives, and where it would be redundant
- it encourages the designer to consider alternative solutions for a particular problem rather than opting for the most common choice (e.g. always using pressure relief valves to handle pressure relief when other methods exist).

The manner in which this concept of intermediate representation has been incorporated into the final methodology is described in section 5.4.1.

4.2.3 Development of Preliminary Methodology

Having applied Scott's method and identified its strengths and weaknesses, the next focus of the research was to expand on the list of steps in the method to ensure that it was, as far as possible, complete. This was achieved by revisiting the general design literature. Once a complete list of steps had been produced, these were organised into an algorithm. The algorithm was constructed by considering, for each step, the dependence of the component activities and issues on information generated by other steps. In this way, the algorithm was intended to minimise the need for iteration within the method. The list of steps for this first draft methodology are given in table 4.1 below and the algorithm is shown in fig. 4.2.

Table 4.1 - Steps in Methodology #1

Steps	
1)	<i>Check that the control system given on the PFD is adequate (if shown) and add any other automatic control loops as necessary.</i>
2)	<i>Consider isolation for safety - indicate the need for isolation between major plant sections.</i>
3)	<i>Consider start-up: add any extra heaters required, rework / recirculation loops, extra tanks, purge connections, etc.</i>
4)	<i>Consider any facilities which may be required for out of spec. product.</i>
5)	<i>Consider shutdown: safe disposal, decontamination, action in the event of fire, etc.</i>
6)	<i>Consider specific needs, e.g. nitrogen blankets, eliminating air from the system, etc.</i>
7)	<i>Consider cleaning requirements: connections, storage / disposal facilities etc.</i>
8)	<i>Consider any facilities which may be required for product switches to be carried out</i>

- effectively.*
- 9) *Consider the need for interstage storage capacity.*
 - 10) *Consider which equipment should be 'spared' for maintenance.*
 - 11) *Consider the positioning of sample points, plus the need for special connections and any other specific requirements.*
 - 12) *Consider fire protection of vessels.*
 - 13) *Consider temperature protection of vessels (i.e. protection against over- or under-temperature).*
 - 14) *Indicate the need for fire and over-pressure relief.*
 - 15) *Indicate the need for vacuum relief.*
 - 16) *Consider the destination of outlets for environmental acceptability.*
 - 17) *Add automatic control for minor vessels / equipment not considered critical to the steady-state operation of the process, plus any manual control valves required.*
 - 18) *Add vessel overflows, non-return valves as required.*
 - 19) *Add vents, drains on low points, steam traps and flame traps as required.*
 - 20) *Indicate isolation required for maintenance of small items of equipment which are likely to require frequent, but short, attention, including isolation for calibration.*
 - 21) *Add instrumentation for diagnostic purposes, trips and alarms.*
 - 22) *Decide which information is needed in the control room and which should be displayed locally.*
 - 23) *Add kickback lines as necessary.*
 - 24) *Add filters to protect instruments, etc.*
 - 25) *Denote valves normally open / closed and indicate their preferred failure modes.*
 - 26) *Consider hydraulic pressure relief: add any valves / vents as necessary.*
 - 27) *Consider line sizing, classifications and spec.*
 - 28) *Consider the need for lagging, heat tracing etc.*
 - 29) *Indicate which automatic valves need to be remotely operated.*
 - 30) *Add any necessary comments, e.g. "gravity feed", "line entering at top", etc.*

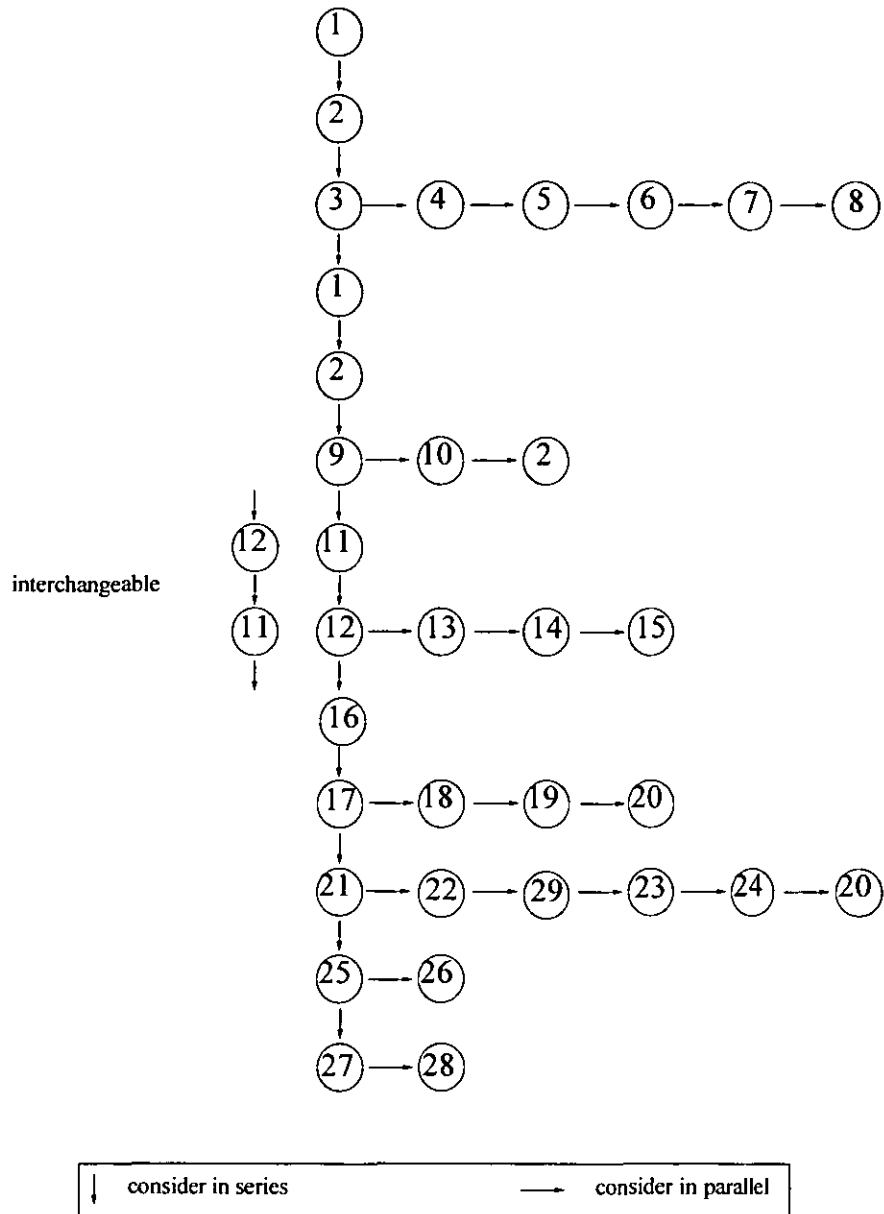


Fig. 4.2 - Algorithm for Methodology #1

Numbers refer to steps as listed in Table 4.1.

Step numbers 29 and 30 do not appear as they were never placed in the algorithm.

4.3 Methodology #2

The preliminary version of the new method was again applied to the 'Lawley' design exercise in order to assess its performance. Some of the key observations made as a result of this are listed below:

- the methodology steps are of varying degrees of importance; some steps warrant significant amounts of time and some do not
- it is important to keep a record as items of equipment and / or instrumentation accumulate functions, so that it is possible to ascertain at a later date whether it matters if the equipment is moved or removed
- a significant number of design issues are either dependent on size or on timing with respect to number of hours on-line, so it is important to establish parameters such as inventories and target availabilities and reliabilities early on in the decision process
- the subjects of control, trips, alarms and isolation should not be considered one by one but rather concurrently, in association with operating strategies.

In order to redress the imbalance of divisions between the steps, a list of equipment likely to be added with each step was drawn up. This was complemented by a list showing how each step depends on certain equipment being present. These lists were intended to help clarify the interrelationships between the steps so that a better distribution and order could be introduced to the method. A document detailing the logic for addressing certain design activities or objectives in a particular order was drawn up. The contents of this document are reproduced below.

Reasons for introducing a particular order to the steps

1. *Fire / over-pressure relief should be considered after isolation, fire protection and outlet destination because: a) the position of isolations will affect the position of relief valves; b) they may be affected by what other forms of fire protection are used and c) if there are limitations on flare capacity etc. then high integrity trip systems might be preferred to greater pressure relief capacity.*
2. *Isolation for maintenance should be considered after start-up, shutdown, cleaning, 'specific needs' and facilities for out of spec. products because these may all introduce extra lines / bypasses etc. which could also need to be shut off.*
3. *Sample points should be considered after start-up, shutdown and out of spec. product as the sample point locations required for these modes of operation are likely to be different from those needed during the steady state operation of the plant.*
4. *Control for minor vessels, utilities etc. should be considered after start-up, shutdown, 'needs', cleaning, spares, product switches, out of spec. product, destination of outlets and major control. All the steps listed may add new lines which could need flow or other*

control and diagnostics, however this type of control is unlikely to interfere with the overall plant control scheme already specified.

5. Kickback lines should be considered after spares, start-up, shutdown, 'needs', cleaning, sample points, product switches, out of spec. facilities and outlet destinations because there may be extra vessels / pumps added for some of these.
6. Isolation of minor items should be considered after spares (which may introduce new lines / pumps etc.), minor control additions (which may need isolation / bypass on control valves), instrumentation (which may need isolating for maintenance / repair), filters (which may need isolation) and major isolation (which may be able to share the same valves).
7. Addition of filters should be considered after start-up, shutdown, 'needs', cleaning, spares and minor control because coarse filters may be needed to protect sensitive equipment on start-up and protective filters may be needed on pumps, control instruments, etc. and to keep purge lines clean. NB Filters may also be needed on outlet destinations.
8. Diagnostic instrumentation should be considered after kickback lines (and associated steps which go before).
9. Vents, drains, steam traps and flame traps should be considered after diagnostic instrumentation (and associated predecessors) because then all relevant lines, equipment and instrumentation should be present. NB Flame traps should be part of fire protection.
10. Hydraulic pressure relief should be considered after vents, drains etc. because these may be able to double for two or more purposes (i.e. be used to provide relief) and after line sizing when it will be known whether dedicated valves / vents are required or if expansion will be significant.
11. Control room / local indication should be considered after diagnostic instrumentation has been added because this is what it refers to.
12. Comments - slopes, gravity feeds, etc. should be added after start-up, shutdown, 'needs', cleaning, product switches, out of spec. facilities and outlet destinations because then all relevant lines should be present.
13. Line sizing should be considered after minor isolation when all lines should be present. Also after bellows / vessel connections. (Rough sizing of major lines may already have been done at the flowsheet stage.)
14. Lagging and heat tracing should be considered after line sizing because they are affected by diameters, fluid velocities and so on. NB Consider these together (i.e. line sizing and insulation).
15. Fire protection of vessels should be considered after start-up, shutdown, 'needs', cleaning and isolation because all vessels and lines should be present and isolatable sections shown.
16. Valves normally open / closed and preferred failure modes should be considered after diagnostic instrumentation etc. has been added because all valves should be shown by then.

- 17. Remote operation of valves should be considered after fire protection, because fire conditions are among those in which remote operation is likely to be needed, and after trip systems, as these may also incorporate remotely operated valves.*
- 18. Vacuum protection should be considered after isolation because the number of devices required will be affected by the number of isolatable sections present.*
- 19. Facilities for out of spec. product should be considered after start-up, shutdown and cleaning because any vessels introduced by any of these may be used for multiple purposes.*
- 20. Destination of outlets should be considered after fire protection and its associated predecessors because all outlets should then have been identified. NB Hydraulic pressure relief and sample points generate effluents also.*

Given this list of criteria for the order in which the design activities and objectives should be addressed, a second draft methodology was generated. The number of steps was reduced by linking some of the ‘smaller’ steps into some of the ‘larger’ steps to make the method more balanced. Following further research into the details of the different design problems in line diagram development, each step was also elaborated to include an explanation for:

- why it needs to be carried out
- what specific tasks are involved
- what issues might affect the decisions which need to be made
- what actions need to be taken in terms of addition of information to the ELD.

A further amendment made in this version of the methodology was the introduction of a section entitled ‘Preliminary Considerations’. This was intended to facilitate the incorporation of design hierarchies within the methodology. Hierarchies exist in many design areas. Pressure relief is a prime example. At the highest level of abstraction, the pressure relief issue is of the form: ‘where pressure relief is likely to be needed, can the process fluids be vented to atmosphere or is a dedicated treatment plant required? If so, what type of treatment will be needed?’. At the next level, the relief issue becomes: ‘which vessels and / or equipment require relief?’. At the most detailed level, the type and configuration of relief devices is then specified.

The ‘Preliminary Considerations’ section initially addressed three main design areas: pressure relief, effluent treatment and availability. An explanation of these is provided below in table

4.2, along with the steps for this second draft of the methodology. The accompanying algorithm is given in fig. 4.3.

Table 4.2 - Steps for Methodology #2

<i>Preliminary considerations</i>	
1)	<i>Availability</i> <i>Before the design commences, a statement should be drawn up which gives guidance on the proposed operating philosophy for the plant. This should be explained in terms of hours on-line per year, hours on-line per day, maintenance strategies, allowable downtime, etc.</i>
2)	<i>Effluent treatment</i> <i>A global decision should be made in the preliminary stages of detailed design on the destination of effluent and the need for any dedicated effluent treatment plant.</i>
3)	<i>Pressure relief destination</i> <i>A decision should be made on the treatment of effluent produced by the action of pressure relief devices. Can vessels be relieved to atmosphere or will a flare system or scrubbing system be required? Are the expected quantities of effluent from relief valves in particular scenarios sufficiently small to warrant consideration of alternative measures which will enable a dedicated treatment system to be avoided?</i>
<i>Steps</i>	
1)	<i>Consider steady-state control and monitoring</i>
2)	<i>Consider line sizing and materials of construction</i>
3)	<i>Consider interstage storage capacity</i>
4)	<i>Consider spares required for maintenance</i>
5)	<i>Consider isolation of large inventories for safety purposes</i>
6)	<i>Consider any additional facilities required for start-up</i>
7)	<i>Consider facilities for out of spec. product</i>
8)	<i>Consider additional facilities required for shutdown</i>
9)	<i>Consider additional facilities required for purging and blanketing</i>
10)	<i>Consider additional facilities required for (liquid) plant cleaning</i>
11)	<i>Consider additional facilities required for operating flexibility</i>
12)	<i>Consider non-steady state control and monitoring</i>
13)	<i>Consider isolation for maintenance</i>
14)	<i>Consider valving arrangements</i>
15)	<i>Consider the location of protective devices required to alleviate over- / under-pressure</i>
16)	<i>Consider any protection required for over- / under-temperature</i>

- 17) Consider the destination of all outlets
- 18) Consider unsteady-state control
- 19) Consider the location of information
- 20) Consider the location of remotely operated valves
- 21) Consider preferred failure modes and normal operating positions for valves.

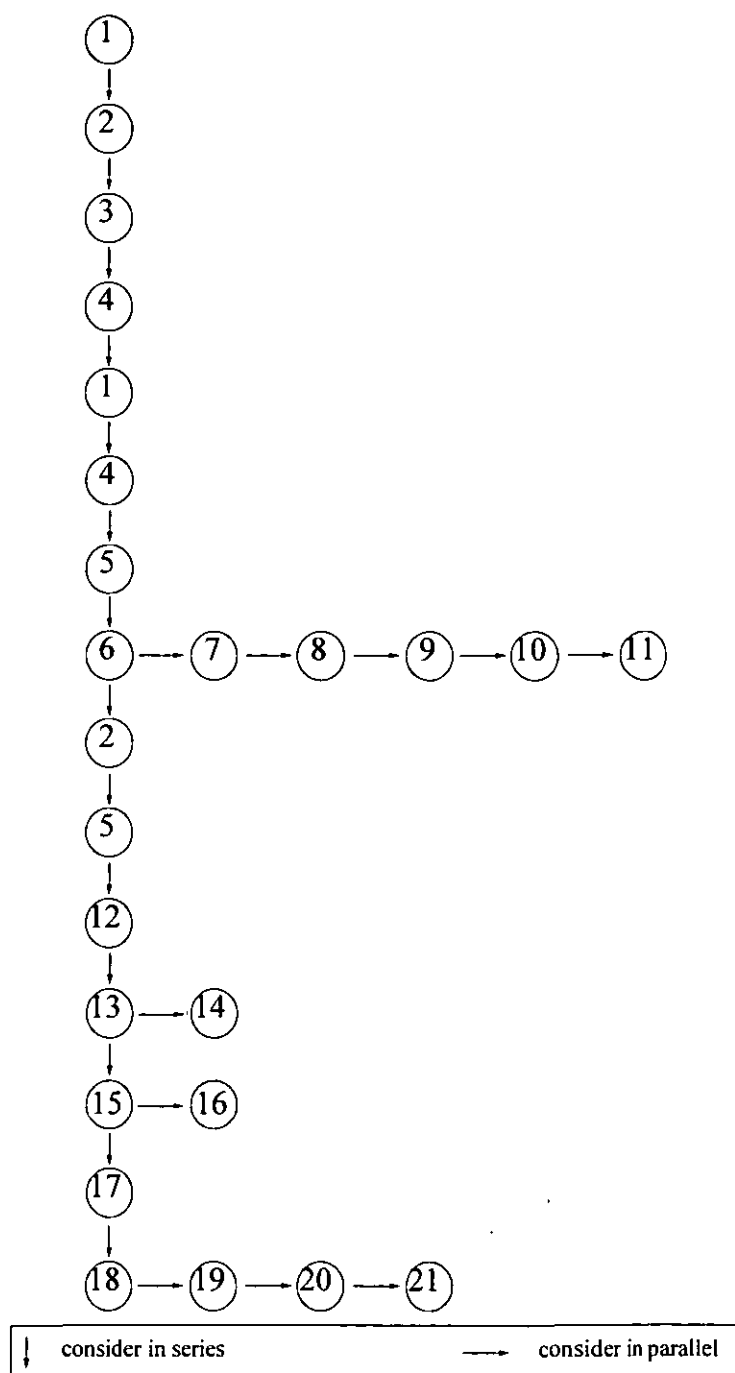


Fig. 4.3 - Algorithm for Methodology #2

Numbers refer to steps as listed in table 4.2

4.4 Methodology #3

At this stage in the methodology development, it was observed that some of the steps in the method were concerned with design objectives while others were written in terms of design solutions. For example, 'steady-state control and monitoring' is an objective, while 'inter-stage storage capacity' is a solution to the problem of availability. This observation prompted the idea of representing the activities which contribute to ELD development in a matrix consisting of a set of design objectives and a set of corresponding design solutions. An extract from this matrix is shown in table 4.3. The objectives are listed horizontally along the top of the matrix and the solutions are given vertically down the side. The ticks represent the equipment cells which should be visited with each design objective. So, for instance if the objective is to provide facilities for maintenance, then it is likely that you will need to consider the provision of isolation valves, blinds, drains and vents, and so on. The complete matrix is included in appendix B3.

Table 4.3- Extract from matrix of objectives and solutions

	Control	Start-up	Maintenance
.....					
Valves		✓	✓	✓	
Blinds				✓	
Drains				✓	
Vents			✓	✓	
.....					

A new version of the methodology (#3) was generated using the structure defined in the matrix (table 4.3). Each design objective in the matrix was used as the subject of a step in the method, while the possible solutions in terms of equipment were used to provide explanations to accompany the steps.

The benefits of viewing the design activity in this way are that the matrix provides a logical justification for the design requirements and a complete definition of the problem in terms of the equipment represented in the ELD. Consequently, it is possible to adopt a closed approach to decision-making. If all the marked cells in the matrix have been visited (or revisited where necessary) then the design should be complete.

The representation of the PFD to ELD development problem as a matrix of design objectives and solutions affected the arrangement of ideas within the core method in two important ways. First, it initiated the concept that all the steps in the methodology should, for consistency, be statements of design objectives rather than a mixture of objectives and solutions. Second, as a result of renaming the steps, it led to a natural breakdown of the steps into sections addressing, in turn, steady-state, 'changing-state' and emergency operations.

At this point in the methodology development, a new document explaining the logic behind the current order of the steps was produced. The contents of this document are reproduced below, following the steps and algorithm for the third draft of the methodology which are given in table 4.4 and fig. 4.4 respectively.

Table 4.4 - Steps for Methodology #3

<i>Preliminary considerations</i>		
<i>(as before)</i>		
<i>Steps</i>		
1)	<i>Steady-state control and confirmation of steady-state operation</i>	<i>(Steady state)</i>
2)	<i>Plant scale and integrity for normal operating conditions</i>	"
3)	<i>Availability and reliability</i>	"
4)	<i>Safe handling of failure with respect to inventory</i>	"
5)	<i>Start-up</i>	<i>(Changing state)</i>
6)	<i>Operating flexibility</i>	"
7)	<i>Shutdown</i>	"
8)	<i>Establishment of a safe internal environment</i>	"
9)	<i>Cleaning</i>	"
10)	<i>Control and monitoring for changing state operation</i>	"
11)	<i>Maintenance</i>	"

12)	<i>Operability</i>	“
13)	<i>Safe handling of failures with respect to pressure</i>	(Emergency)
14)	<i>Safe handling of failures with respect to temperature</i>	“
15)	<i>Environmental acceptability of outlets</i>	“
16)	<i>Control and monitoring for response to failures</i>	“
17)	<i>Location of information</i>	“
18)	<i>Designation of remotely operated valves</i>	“
19)	<i>Designation of preferred failure modes and normal operating positions for valves</i>	“

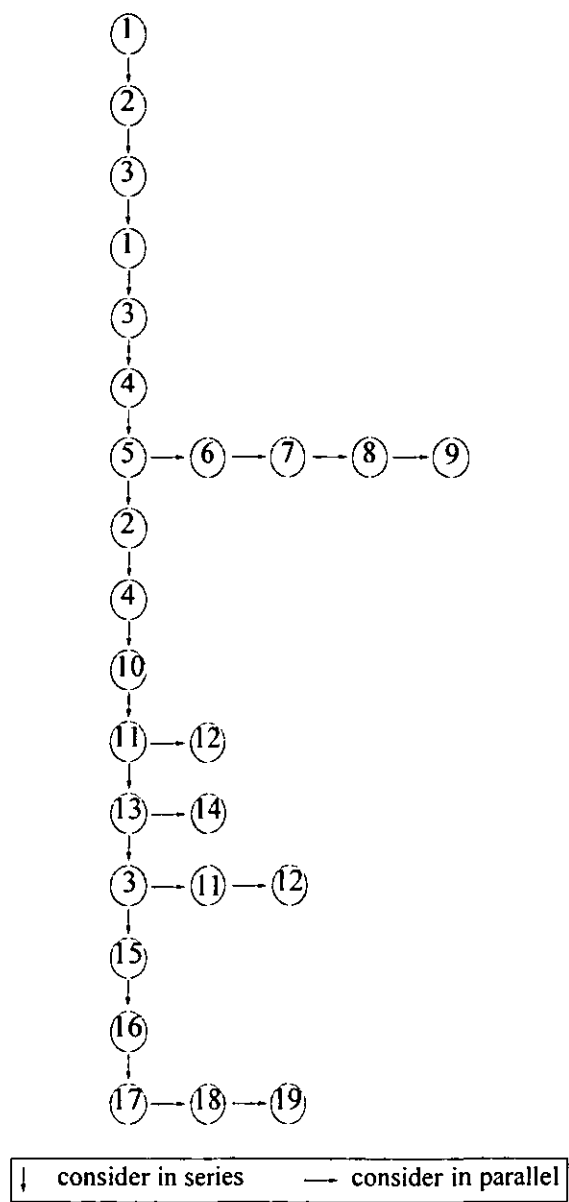


Fig. 4.4 - Algorithm for Methodology #3
 Numbers refer to steps as listed in table 4.4

Reasons for the order of the steps

The basic underlying principle of the methodology is as follows:

- a) Since the PFD is concerned with the process under steady state conditions, the first concern is to ensure that all objectives for the complete steady state operation of the process can be achieved.*
- b) Once the steady state requirements have been finalised, the design procedure moves on to address changing state operations such as start-up, shutdown and preparation for maintenance.*
- c) Finally, the methodology covers emergency operations and response to failure.*

A further general principle is to ensure that any steps which might lead to the specification of additional large items of equipment are included early in the decision process, so that sufficient time is allowed for purchase requisitions to be made and so that layout arrangements can be modified before too much time has been spent on them.

There are various 'levels of consideration' associated with certain objectives, e.g. for pressure relief - a) where should the relief stream be vented to

b) where is the relief device to be situated

c) what type of relief device should be used.

Due to the occurrence of these, the need has been identified for a few preliminary decisions to be made before the algorithmic design procedure is undertaken. This should prevent the designer reaching a certain point in the step algorithm and realising that a complete new system is required to deal with one of the consequences created by the proposed addition of equipment.

The section 'Preliminary Considerations' deals with such early decisions. It covers availability, pressure relief destination and effluent destination.

- A statement on the availability of the plant is important, as factors such as number of hours on line, number of hours for maintenance, cost of loss of production will have an effect on the overall approach to the design and will directly affect decisions in a number of the methodology steps.*
- The destination of material vented during pressure relief should be considered early on as a dedicated treatment system may be required, and this will have significant effects on the cost and layout of the plant. Any such treatment system may also necessitate the generation of its own ELD, purchase requisitions etc.*
- Similarly, the destination of effluent streams should be considered early, as a dedicated effluent treatment plant may be required.*

The reasons for the specific position of each step within the methodology are given below:

STEADY STATE OPERATION

1) *Steady state control and monitoring*

- *This is often considered at the PFD stage, so seems a logical first step in the conversion process.*
- *The basic steady state control system should be finalised before any steps concerning changing state operation are addressed.*

2) *Plant scale and integrity (sizing and materials of construction)*

- *Vessel sizes and headspace may be affected by the steady state control strategy chosen for the plant, so this step should come after the steady state control step.*
- *Line sizes and materials of construction may affect decisions such as location of valves and specification of spares, so this step must come before any which may lead to the addition of such equipment.*
- *Vessel sizes may affect the need for and location of interstage storage capacity, so this step must come before the step on availability and reliability.*

3) *Availability and reliability (interstage storage capacity and spares)*

- *The need for interstage storage (ISS) capacity may be affected by the steady state control strategy chosen for the plant, so this step should come after the steady state control step.*
- *The need for ISS capacity will also be influenced by the size of the vessels in the process, so this step should come after the step concerned with plant scale and integrity.*
- *Spares and ISS capacity are interrelated because there are instances where one will be used to eliminate the need for the other.*
- *If extra capacity is required in any of the major process vessels, this should be identified at an early stage.*
- *The extra capacity provided by ISS vessels may eliminate the need for extra vessels to be specified for start-up etc., so this step should come before the section on changing state operation.*

Repeat step 1) - Control and monitoring may be needed on ISS equipment added in step 3.

Repeat step 3) - Spares may be needed for any pumps, control valves etc. added in association with ISS vessels

Note: It was proposed that the need to iterate would later be formalised in the algorithm, using statements such as "If you have added a vessel at step x then return to step y".

4) *Safe handling of failure with respect to inventory (isolation, reverse / excess flow prevention)*

- *This step should be addressed once all requirements for the steady state process (including sizing and ISS) have been finalised.*
- *The location of reverse flow prevention facilities may affect the number and location of connections / lines which need to be added for changing state operations such as purging, therefore this step should come prior to the section on changing state operation.*

CHANGING STATE OPERATION

5) - 9) Start-up, Operating flexibility, Shutdown, Establishment of a safe environment, Cleaning

- The steady state requirements of the plant may lead to the addition of major items of equipment not shown on the PFD. This equipment must obviously be included in the changing state procedures along with all other equipment already shown on the PFD. It may also be possible to utilise any vessels added in the steady state section to assist in the changing state operations, thus avoiding the need for further additional equipment. Therefore, these steps should come after the steady state steps.*
- These steps should also come after the step on safe failure with respect to inventory (step 4) as the latter may introduce reverse flow prevention equipment which affects changing state operation requirements.*

Repeat 2) - Size and specify materials of construction for any new lines or vessels added.

Repeat 4) - Ensure that isolation of inventory around new equipment is adequate and add any new reverse flow prevention facilities as required.

Note: Iterations were to be formalised later, as mentioned above.

10) Control and monitoring for changing state operation

- This can be added once the strategies / operating procedures and equipment for changing state operations have been defined, so comes after steps 5) - 9).*

Note: Could alternatively have been treated individually after each section.

11) Maintenance

- Now that all major equipment is in place, maintenance requirements can be defined, so this step must come after steps 5) - 9).*

12) Operability (finalising valving arrangements)

- This step must come after all other steps which include the specification of valves. Therefore, this step must follow step 10).*

EMERGENCY OPERATION AND RESPONSE TO FAILURE

13) Safe handling of failure with respect to pressure

- Pressure relief requirements will be affected by the location of isolation valves, so this step must come after the step which finalises valving arrangements.*

14) Safe handling of failure with respect to temperature

- This may be related to over-pressure so should be considered at the same time as step 13).*

Repeat step 3) - Spare relief equipment may be considered necessary.

Repeat step 11) - Add equipment to enable relief equipment to be maintained.

Repeat step 12) - Ensure operability of relief equipment during maintenance.

Note: See above.

15) Environmental acceptability of outlets

- *Once steps 11), 12) and 13) have been completed, every outlet in the process has been defined. Now suitable destinations for each of these outlets can be ensured.*

16) Control and monitoring for response to failures

- *This may be addressed following step 15), by which time all the major equipment items, lines and destinations have been completely specified.*

17) - 19) Location of information, Designation of remotely operated valves, Designation of failure modes and normal operating positions for valves

- *Once control strategies for each mode of operation have been finalised, steps 17)-19) may be carried out.*

4.5 Methodology #4

The existence of hierarchies within the design decision process was touched upon in section 4.3. This realisation led to the identification of the need for a separate, higher level section in the methodology addressing 'preliminary considerations'. Having started along this line of thought, it became clear that there were more than a few design topics which could benefit from such structuring of the decision procedure. The work on 'intermediate representation' indicated that further decomposition of the decision process might also be appropriate, so that a distinction is made between the functional objectives for the process and their hardware solutions. This concept was introduced in section 4.2.1.

These ideas were put into practice by generating a 'table of design hierarchies' which shows the different levels of decision-making required for some of the key objectives in ELD development. Table 4.5 gives the complete set of hierarchies identified.

Table 4.5 - Table of design hierarchies

Subject	Global	Local	Specific
Control	Strategy - degree of automation, staffing	Control flow here, control level there etc. plus diagnostics	Equipment / instruments used , local / control room, trips and alarms, failure modes
Availability	High / low, cost of lost product, which conditions mean shutdown is acceptable	Specification of extra storage capacity, duplicated equipment and spares	Designation of local / warehouse spares
Start-up / shutdown	Strategy - intermediate products bought in for start-up? Degree of effort into preventing wasted product? etc.	New connections / equipment required, low flow (controllable etc.), rework facility / feasibility, heat exchanger start-up, catalyst in place etc.	
Operating instructions	Order of start-up / shutdown (sections)	Order of start-up / shutdown (equipment)	Order of start-up / shutdown (valves)
Effluent treatment	Specific treatment plants required / strategy for removal for treatment	Allocate all effluent lines to treatment system	Specify any monitoring equipment required on effluent lines
Venting and pressure relief	Specific treatment plants required	Specify where pressure relief will be required and destination	Specify equipment and configurations required

Subject	Global	Local	Specific
Safety	<p>What to do in the event of a major loss of containment (e.g. instructions to local residents etc.)</p> <p>Any prohibitions in design, e.g. water must be prevented from entering the system at all costs.</p> <p>Minimizing size of vapour clouds by valve isolations / limiting inventory</p>	<p>Safety equipment required locally e.g. eye baths, showers etc.</p> <p>Isolation, temperature protection, reverse flow prevention, excess flow prevention</p>	<p>Remotely operated valves, accessibility of valves, sample points etc.</p> <p>Alarms and trip systems, shutdown switches etc.</p>
Services	<p>Services required, e.g. high / low pressure steam, air, nitrogen, water etc.</p> <p>Provision for failure (backup and safe shutdown)</p>	<p>Location of service connections.</p> <p>Temporary / permanent connections</p>	
Maintenance	<p>Strategy of repair and inspection</p>	<p>Isolation for maintenance, access</p>	<p>Configurations of isolation valves etc.</p> <p>Normally open / closed.</p>
Quality	<p>Quality control systems, possibility for rework, other uses of off-spec. product etc.</p>	<p>Sample point locations, re-routing where rework is a possibility</p>	<p>Sampling instruments and configurations required</p>
Layout	<p>Grouping of plant sections</p>	<p>Elevations and access</p>	

Subject	Global	Local	Specific
Plant scale and integrity	Minimize inventory? Minimize cost? Minimize leak sources? Simple and robust versus efficient and high maintenance	Materials of construction, line sizes, vessel sizes	
Operating flexibility	Likelihood of different throughputs, different raw materials etc.	Line sizes, equipment sizes, equipment design	
Cleaning	On-line, fluids / systems, effluent treatment systems	Extra connections, extra vessels, effluent destinations	
Location	Implications of weather and type of labour available	Heat tracing, insulation, cooling water	

Taking control as an example, we see that at the highest level or 'global' level, the relevant issues are such things as how much automation is required, what staffing levels are required and so on. At the next 'local' level the control strategy is considered in a little more detail with the designation of flow or level control and so on. Finally, at the 'specific' level, the type and location of equipment required is detailed together with any necessary supporting information such as preferred failure modes. By setting the design objectives out in this manner, it becomes clear that the hierarchies are not only important in breaking down the tasks for each objective, but that they are also important in linking the objectives together at corresponding levels. So, for instance taking control and utilities, at the global level the type of control system chosen may affect the list of utilities required on the plant (or vice versa). At the next level, the location of the different forms of control will influence the routing of the various different utilities required (and vice versa). At the most detailed level, the two objectives come together as the control equipment must be connected in some way to the appropriate utility.

Because there are interactions between the different design objectives at each level of the hierarchy, it was concluded that the logical approach to handling these interactions would be to tackle them 'breadth first', i.e. to consider all objectives at a 'global' level, then all at a 'local' level and finally all at a 'specific' level. This highlighted the need for a corresponding structure to the methodology. Consequently, the methodology objectives were divided into three separate levels, each addressing the different levels of detail encountered in design. These levels were given the titles 'design strategy', 'design intent' and 'design resolution'. The purpose of each of these levels is described below.

Level 1 - Design Strategy

The first level of the method allows the designer to summarise the specific objectives of the design and to ensure that all the relevant information (needed to progress to the next level of the method) has been collected.

Level 2 - Design Intent

The second level of the method allows the designer to expand the functional requirements of the plant (i.e. specify what the plant needs to do but not how it is to be done).

Level 3 - Design Resolution

The third level of the method allows the designer to resolve the functional requirements of the plant by choosing specific equipment.

By ensuring that every design objective is addressed at each of these levels it is possible to produce a methodology that is not only complete but also one that is continually encouraging the designer to think ahead and to progress with minimal iterations.

The structure of the methodology was further modified at this time by grouping together design objectives requiring similar types of information so as to minimise the number of 'steps' listed. The title of each section was also changed from 'steady-state operations', 'changing state operations' and 'emergency operations and response to failures' to 'routine operations', 'non-routine operations' and 'failures' respectively. The steps for each level are given in table 4.6.

Table 4.6 - Steps for Methodology #4

Level 1		
<i>Safety</i> <i>Pressure and fire relief</i> <i>Materials of construction</i> <i>Layout</i> <i>Location</i> <i>Services</i> <i>Import and export</i> <i>Product storage</i> <i>Control</i>		<i>Operating flexibility</i> <i>Quality</i> <i>Maintenance</i> <i>Cleaning</i> <i>Availability and reliability</i> <i>Start-up and shutdown</i> <i>Effluent treatment</i> <i>Venting</i> <i>'Other'</i>
Level 2		
<i>Routine operations</i>	<i>Non-routine operations</i>	<i>Failures</i>
<i>Elevations</i> <i>Services</i> <i>Control</i> <i>Plant scale and integrity</i> <i>Availability and reliability</i> <i>(Operating instructions)</i>	<i>Start-up and shutdown</i> <i>(Operating instructions)</i>	<i>Inventory</i> <i>Pressure</i> <i>Temperature</i> <i>'Other'</i> <i>(Operating instructions)</i>
Level 3		
<i>As for level 2.</i>		

By this stage, the methodology is starting to take on its final form. It consists of three different levels, the latter two divided into three different sections (see section 4.4), characterised by a list of objectives with supporting information on the tasks encompassed by these objectives.

4.6 Methodology #5

At this point, attention was given to the presentation of the information within the methodology. A tabular format was adopted, with each page giving the 'classification' or section name, the design objective, and a list of 'thought prompts' with accompanying

explanations in support of these objectives. An outline of the format is shown in table 4.7. In the process of this transformation, the number of objectives increased once again as more information was added and the objectives were given clearer definition.

Table 4.7 - Format for methodology presentation

Classification

Objective

Thought Prompt	Explanation	Interactions
1.		
2.		

The sets of tables were related to the three different levels described in section 4.5 above. The purpose and outcome for each of these levels is defined in table 4.8. The first level differed from the other two levels in three ways:

- 1) it was not divided into three sections
- 2) it contained a different set of thought prompts
- 3) it did not cover interactions (see below).

Table 4.8 - Purpose and outcome of each of the levels in the methodology

Level	Purpose	Outcome
1	Summarise PFD and agree that it is suitable as a basis for developing ELD Collect necessary background information to assist in developing ELD Summarise assumptions made where information is considered unnecessary or where it is unavailable	Tables detailing aims, comments and actions for each design objective listed in the method
2	Develop a more detailed picture of the functions which must be represented on the ELD without introducing specific equipment	Line diagram marked up with comments, sketches, possible solutions and so on for personal use and discussion with others
3	Determine how all the necessary functions will be achieved by specifying precise equipment types and locations	Final line diagram

Two further amendments to the methodology were made. The first was the renaming of the three sections. This was done in order to move away from the steady-state mindset common in design and discussed in sections 2.1.3 and 3.2. The section headings were changed to 'Process Plant and Materials', 'Process Plant Operations' and 'Process Plant Failures'.

The second amendment was the incorporation of a column in the methodology table for 'interactions'. This column was used in levels 2 and 3 to note where a given thought prompt might interact with the other thought prompts listed.

4.7 Methodology #6

Having reached the stage where a reasonably well-structured and complete draft for the new methodology had been developed, the next step was to trial the methodology with some experienced design engineers. A 'Masterclass' was set up for this purpose. Four senior design engineers from ICI were invited to join the PREMIUM project team in the application of the methodology to an example line diagram design exercise. More information on this trial is provided in section 6.2. The feedback generated from the 'Masterclass', together with the information gathered during the task analysis activities carried out at ICI (see section 3.3), was used to shape the 'final' version (#6) of the methodology.

4.7.1 Masterclass

The Masterclass trial generated a number of important pointers and suggestions for improving the methodology and its mode of application. The most significant of these are listed below:

- The method should be applied using a different approach to that used for HAZOP, i.e. one prompt should be applied to all equipment and lines in the diagram before the next prompt is considered. This should help to prevent any repetition of mistakes at the HAZOP stage.
- Formal methods for recording the issues / actions raised by each thought prompt need to be developed.
- The methodology prompts should spread back to the early PFD stage, i.e. they should also be used to help develop the PFD from the process flowsheet (see section 5.1 for

definitions). This is considered necessary due to the lack of consensus on the definition and content of each of these drawings.

- Ideally, the methodology should be applied by a design team consisting of:
 - lead process engineer
 - operations representative
 - project engineer.

The idea that the method would be most useful if applied by a team of design engineers rather than by individual designers represented a fundamental change of emphasis in terms of the application of the methodology. Since the method had evolved from Scott's undergraduate guide, it was, up until this time, intended for use by an individual designer.

This change of emphasis, together with the need to take the thought prompts back to the early PFD stage, led to a significant difference in the purpose and outcome of each level. Instead of being a working design support tool, the methodology became more of a planning tool. The levels in the method were renamed as level 1 - concerned with the development of the PFD from the process flowsheet, and levels 2a and 2b - concerned respectively with the development and checking of notional ELDs.

In taking the thought prompts back a step further, it was decided that for consistency and ease of application the same set of thought prompts should be repeated at each level.

The manner in which the method should be applied was easily amended by changing the introductory notes. The method is now intended to be used in a succession of meetings to generate actions for each level with the supporting design work being done on an individual basis between meetings. Chapter 6 explains more about the application of the methodology.

The formal methods adopted for recording the issues and actions raised by each thought prompt include record tables and annotation of the process diagrams. These are described in more detail in chapter 5. A specific approach to analysing and recording the operating states and transitions for the process was also devised. This is covered in section 5.5.3.

4.7.2 Task analysis

The task analysis work carried out at ICI and described in section 3.3 contributed to the shaping of the methodology in three ways:

- it emphasised the need to incorporate guidance on when process engineers should be interacting with engineers from other disciplines
- it highlighted the need to develop a formal approach to recording information, particularly on reasoning, assumptions and uncertainties arising during line diagram development
- it showed that the individual designers' approach to design is largely reactive and dependent on the overall project objectives and timescales.

Guidance on interactions with other disciplines was incorporated into the methodology by adding appropriate prompts to this effect in the 'interactions' column alongside each thought prompt (see section 4.6). This column was additionally used to include links to other activities which should be occurring in parallel with the ELD design. The problem of interactions between the different ELDs which make up the overall design was also considered. The concept of a 'global' PFD was introduced in order to help to ensure continuity across the different diagrams. This concept is explained in section 5.4.1.

The need for a formal approach to recording information generated during the design, identified here, reinforces the comment made to this effect at the Masterclass. The observation that the pattern of individual design is largely reactive supports the theory that the methodology is best applied as a planning tool by a design team. Both these issues are discussed above.

4.8 Summary

Methodology #1

- application of Scott's method
- new definition of methodology qualities required
- new concept of 'intermediate representation' introduced

- expansion of Scott's steps
- reorganisation into algorithm

Methodology #2

- further reorganisation of steps, including reduction in number by grouping to even out 'size'
- explanations added for why each step is necessary, tasks which need to be carried out, issues which might affect the decisions made and actions in terms of modification of the ELD
- introduction of the concept of 'Preliminary Considerations'

Methodology #3

- generation of a matrix of sets of design objectives and sets of solutions
- wording of steps changed to make each a design objective
- different sections for 'steady-state operations', 'changing-state operations' and 'emergency operations' introduced

Methodology #4

- generation of table of design hierarchies
- methodology structure changed from algorithmic to sequential
- steps regrouped and divided into three levels - entitled 'Design Strategy', 'Design Intent' and 'Design Resolution'
- levels 2 and 3 divided into sections with new section headings: 'routine operations', 'non-routine operations' and 'failures'

Methodology #5

- tabular format introduced, containing thought prompts and explanations for each design objective
- interactions between different thought prompts introduced at levels 2 and 3
- sections renamed once more as 'Process Plant and Materials', 'Process Plant Operation' and 'Process Plant Failures'

Methodology #6

- levels redefined as 1, 2a and 2b with different emphasis in purpose and outcome
- interactions modified to include those between different engineers and links to parallel activities
- interactions between drawings to be captured using ‘global PFD’
- thought prompts standardised so identical at each level
- formal methods for recording proposed, including a special approach to the handling of operating states and transitions
- change of emphasis in application from individual’s working design support tool to group planning tool.

4.7 Conclusions

Any methodology for the development of engineering line diagrams from process flowsheets should exhibit the following key features:

- it should encourage creative solutions
- it should integrate all the design activities including process engineering, control engineering, mechanical engineering, safety engineering
- it should permit a natural way of incorporating the use of computers in decision making and knowledge storage and retrieval
- it should be supportive without being prescriptive
- it should accommodate iteration / recycle between the different steps of activities and issues
- it should take account of the interdependence of issues raised in different steps where necessary
- it should accommodate the hierarchy of decisions which exists in the design process
- it should incorporate activities and issues associated with cost, SHE and operability.

‘Intermediate representation’ allows the design of line diagrams to be improved in the following ways:

- it enables the designer to produce an overall picture of the salient safety and operability features for the plant in a very short space of time
- it delays the need to provide specific (hardware) solutions until such time as all possible interactions with neighbouring equipment have been identified
- it precludes the need to make unnecessary assumptions early on in line diagram development
- it encourages the designer to identify where hardware can be used to achieve multiple objectives, and where it would be redundant
- it encourages the designer to consider alternative solutions for a particular problem rather than opting for the most common choice (e.g. always using pressure relief valves to handle pressure relief when other methods exist).

A matrix of design objectives and solutions can be used to provide a logical justification for the design requirements and a complete definition of the objectives of ELD development in terms of the equipment represented in the ELD. This makes it possible to adopt a closed approach to decision-making.

A table of design hierarchies can be used to illustrate the hierarchical nature of the design problem and to determine the best way of tackling this aspect of ELD design.

CHAPTER V - METHODOLOGY STRUCTURE

5.0 Introduction

The last chapter described how the PREMIUM methodology was developed and how various concepts in the representation of information contributed to its shape and structure. This chapter is concerned with explaining the final arrangement of ideas within the methodology[#]. The chapter also covers additional work which has been done to support the theory of the methodology on a more practical level.

Section 5.1 addresses the subject of engineering drawings, giving definitions of the process flowsheet, process flow diagram (PFD) and engineering line diagram (ELD) and showing how these relate to the different levels of the methodology.

Section 5.2 describes the component elements of the methodology and how these all fit together to give the core method.

Section 5.3 explains the logic behind the methodology structure and gives a final set of reasons why the design objectives are in the particular order given. This set of reasons is intended to complement rather than replace the other two sets given in chapter 4.

Section 5.4 discusses the facility for incorporating interactions into the methodology. In terms of diagrams, this involves the interactions occurring across the different ELDs which combine to form the overall design. In terms of the methodology steps, it involves the interactions between different engineering disciplines, between different objectives in the method and with other parallel design activities contributing to ELD development.

[#] The methodology is a confidential document between Loughborough University and ICI Engineering and as such is not publicly available. A copy of the methodology may be obtained (if permission is granted) from the the Head of Department for Chemical Engineering at Loughborough University.

Section 5.5 discusses how the methodology prompts may be used to record the information generated during its application in a clear, usable, complete and consistent manner and how a special form of record should be produced for defining operating states and transitions.

Section 5.6 introduces ‘detailed analysis’ - a section of research carried out in support of the methodology. This provides decision support at the most fundamental level, linking the theory of the methodology firmly to the practical execution of design.

Section 5.7 summarises the many ways in which safety, health and environmental (SHE) and operability issues are represented in the methodology.

Finally, section 5.8 draws together the conclusions for the chapter.

5.1 Engineering Drawing Definitions

The focus of this thesis is the development of engineering line diagrams (ELDs) from process flowsheets. Consequently, it is necessary to provide definitions of what is meant by the terms ‘process flowsheet’ and ‘engineering line diagram’ in the context of this work. The term ‘process flow diagram (PFD)’, which refers to a drawing somewhere in between the process flowsheet and ELD in terms of the amount of detail shown, also needs to be defined.

The definitions which are used have been derived from those found in the literature (see sections 2.3.2 and 2.3.3). They include definitions of the drawings themselves, the information they should contain and any additional information which should be provided in support of the drawings, such as datasheets, procedures and so on.

The complete set of definitions is given below.

5.1.1 Process Flowsheet

Definition

A 'process flowsheet' is a diagrammatic plant description which is sufficient to define all mass and energy flows in "steady-state" operation (for continuous plants) or sufficient to define all mass and energy flows in a "normal" operating cycle (for batch plants).

Features

- major items of equipment shown by generic equipment type
- equipment names and numbers
- line numbers
- design duties of major equipment
- a table showing process stream flowrates with temperatures, pressures and compositions.

Supporting information

- an account of the key process material properties
- an outline process description
- an equipment summary list
- mass and heat balances.

5.1.2 Process Flow Diagram (PFD)

Definition

A 'process flow diagram (PFD)' is a diagrammatic plant description which contains sufficient process engineering definition that one can be confident that the development of ELDs from it is feasible.

Features

- major and minor items of equipment (i.e. key processing units such as vessels and auxiliary equipment such as pumps, fans, etc.) by specific equipment type and at the proposed (provisional) relative elevations and orientations
- equipment names and numbers

- line numbers
- multiple streams
- utilities lines interacting with the process
- major duplicated equipment
- intermediate storage
- principal control loops
- design duties for major equipment
- flows, temperatures, pressures and compositions.

Supporting information

- a comprehensive account of process material properties
- a list of utilities and import and export requirements
- approximate sizes of major equipment
- a list of suitable materials of construction
- location specific requirements
- a more detailed process description outlining general solutions for control schemes, relief treatment, effluent treatment, etc.
- outline operating instructions
- outline of plant layout

plus

- outline safety and loss prevention philosophy
- outline pollution prevention philosophy
- inherent safety objectives
- waste minimisation objectives
- quality objectives
- outline quality control procedures
- outline control strategy
- outline start-up and shutdown strategy
- outline testing and maintenance strategy
- outline emergency procedures.

5.1.3 Engineering Line Diagram (ELD)

Definition

An 'engineering line diagram' is a diagrammatic plant description which is sufficient to define all the equipment necessary to support the intended process at and between its defined operating states.

Features

- all equipment required for each operating state and transition, by specific equipment type and at the correct relative elevation and orientation
- equipment names and numbers
- line numbers
- notes on special piping configurations where necessary
- multiple streams
- all utilities lines and connections required for every operating state and transition
- all duplicated or spared equipment
- intermediate storage
- all automatic control facilities with action on air (or other service) failure
- all manual control and remote control valves
- all sample points, indicators, trips, alarms and interlocks with display and operation locations as appropriate
- all isolation requirements including flanged connections
- all pressure and fire relief facilities.

Supporting information

- key dimensions / duties of all equipment
- all equipment datasheets, including information on operating and design temperatures and pressures and materials of construction of all equipment
- all instrument data sheets
- all line specs. (including materials of construction, diameter, insulation and / or heat tracing requirements, etc.)
- set pressures for relief devices

- a complete process description
- more detailed operating instructions
- final plant layout

plus

- completed safety and loss prevention philosophy
- completed pollution prevention philosophy
- an account of inherent safety achievements of the design
- an account of waste minimisation achievements of the design
- an account of measures taken to meet the quality objectives for the plant
- detailed account of quality control procedures
- detailed account of control strategy
- detailed account of start-up and shutdown strategy
- detailed account of testing and maintenance strategy
- detailed account of emergency procedures.

These drawing definitions are not intended to be ‘novel’, but have been generated in order to provide a consistent set, since consensus on the definitions of the different terms is lacking in both the literature and industry.

5.1.4 Position within the Methodology Structure

An overview of how the defined drawings fit within the methodology structure is given below in fig. 5.1. The details of the structure are explained more fully in the following section. The significance of the terms ‘local PFD’ and ‘global PFD’ is explained in section 5.4.1.

5.2 Structural Features of the Methodology

The PREMIUM methodology is incorporated in a document which captures the logic and the order in which decisions for developing a first engineering line diagram are made. The methodology is intended to assist designers in the development of engineering line diagrams from process flowsheets.

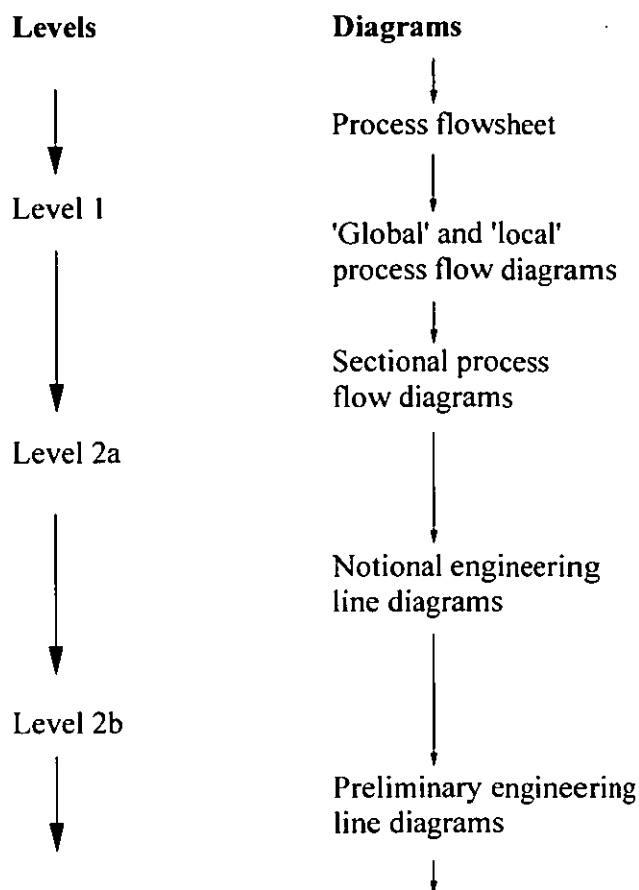


Fig. 5.1 - Diagram illustrating when each type of engineering drawing should be produced in relation to the levels in the methodology

Chapter 4 describes how the methodology came to be comprised of different levels which are divided into sections, each consisting of a series of objectives supported by thought prompts. This hierarchy is shown diagrammatically in fig. 5.2. The purpose of this section is to explain the significance and purpose of each of these structural elements of the methodology and to show how they are combined to provide a solid framework for the explanation and consideration of design issues. The application of the methodology is discussed in chapter 6.

5.2.1 Levels

An overview of the methodology at the highest level of abstraction is given in fig. 5.3. This diagram highlights the first structural element of the method - 'levels'. The methodology is split into two different levels - the second level being again divided into two parts. The presence of these different levels in the methodology reflects the hierarchical nature of the design problem which was examined in section 4.5.

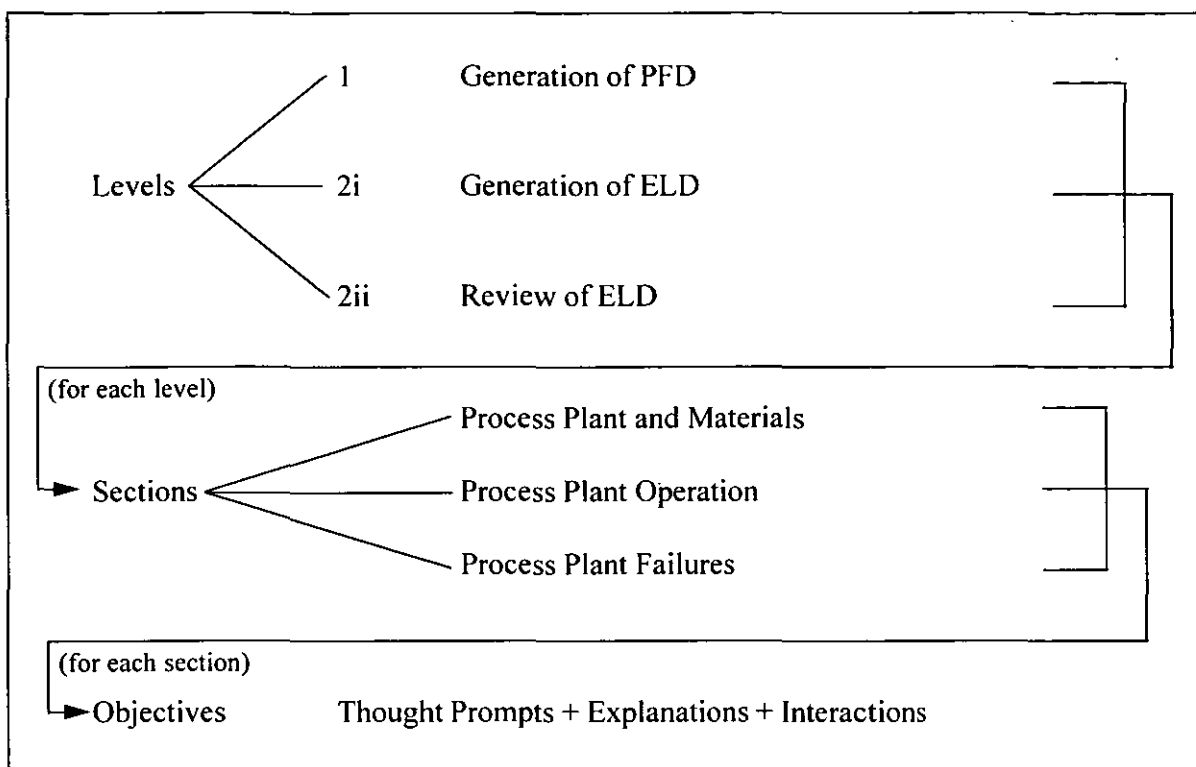


Fig. 5.2 - Hierarchy of the PREMIUM Methodology

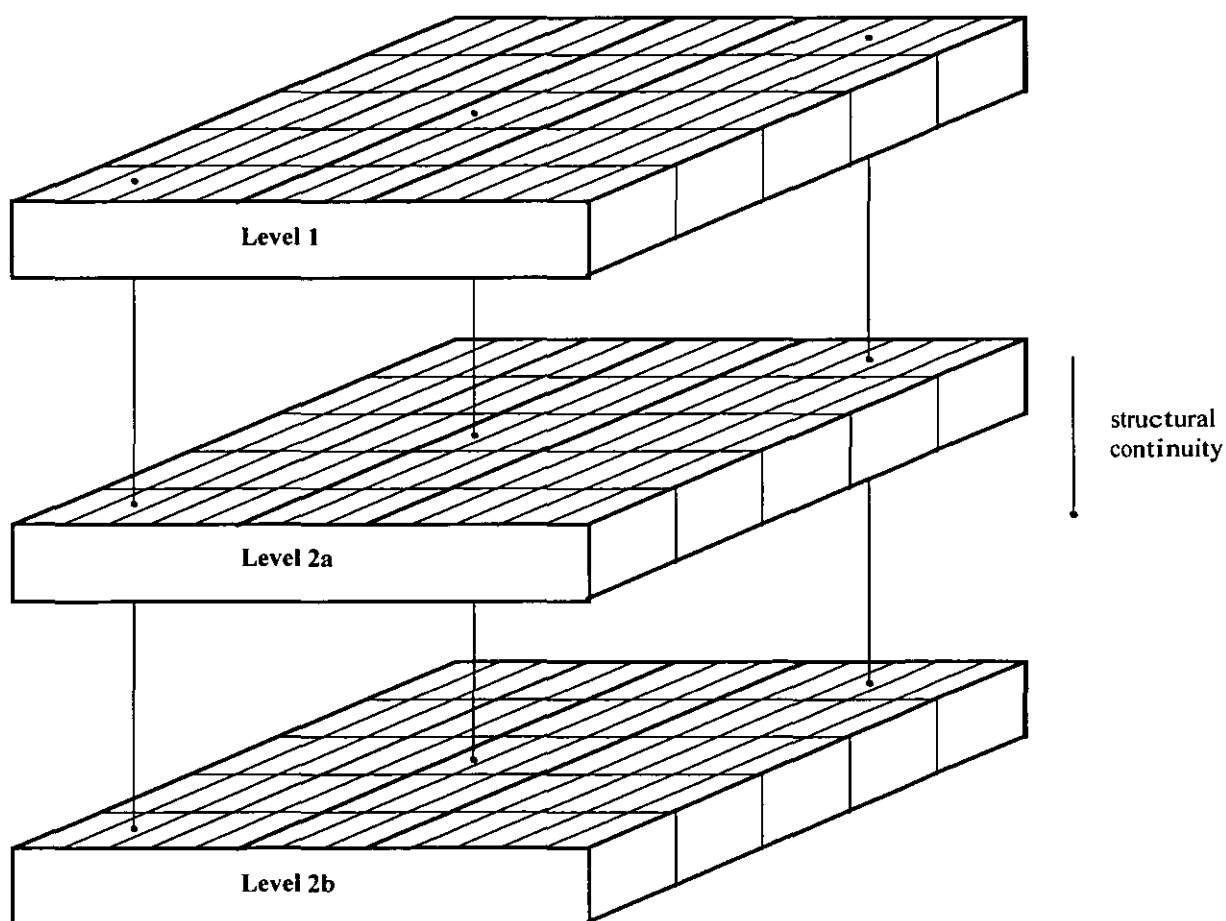


Fig. 5.3 - First structural element of the methodology: levels

Level 1

The purpose of the first level of the methodology is to guide the user through the issues and activities involved in generating, and/or reviewing the generation of, comprehensive process flow diagrams from process flowsheets. The method not only addresses the generation of the drawing but also the generation of supporting information such as process datasheets, operating and other procedures and so on.

This level is also intended to ensure that all the data which will be required for the next level is readily available and that the project team is aware of any 'bubbles' or uncertainties in the design. (A 'bubble' is often used to indicate an ill-defined part of a diagram.)

Level 2

The second level of the method is concerned with the generation of engineering line diagrams from the PFDs (see section 5.1 for definitions).

The first part of level 2 guides the user through the issues and activities involved in developing a first ELD from the PFD. When applied to a process design problem, it results in the generation of a full set of functional requirements for the plant under all identified operating states and transitions.

The second part of level 2 acts as a review to check that all the functional requirements have been met by the specification of the appropriate equipment and configurations. It largely repeats the issues raised under the first part of level 2 but was regarded by practitioners as essential for the purposes of application of the method.

As before, this level is not only directed at the development of the drawings themselves but also at the generation of the necessary supporting information.

5.2.2 Sections

An overview of the methodology at the next level of detail is provided in fig. 5.4. This shows the second structural element - 'sections'. Each level of the methodology is divided into three sections. These are 'Process Plant and Materials', 'Process Plant Operations' and 'Process Plant Failures'.

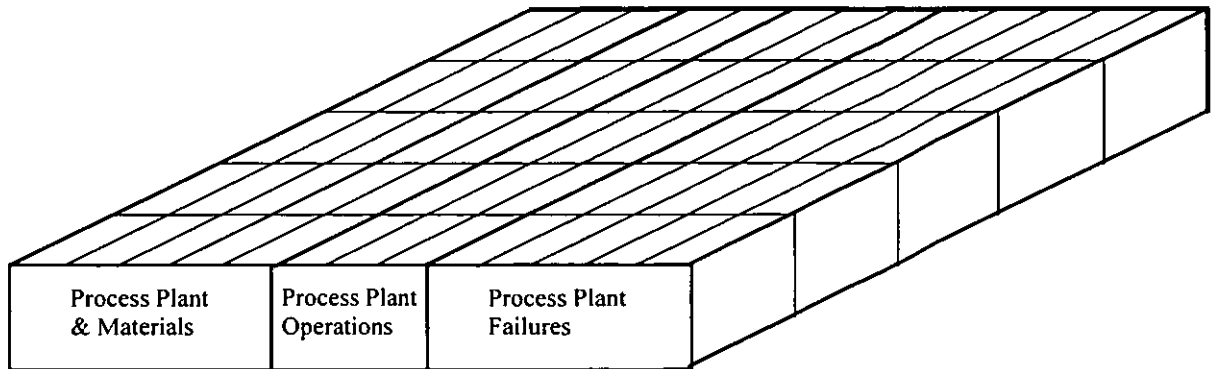


Fig. 5.4 - Second structural element of the methodology: sections (one level only)

Process Plant and Materials

The first section, 'Process Plant and Materials', is concerned with the expectations for the plant in terms of general equipment and material requirements and overall performance.

Process Plant Operations

The second section, 'Process Plant Operations', covers the operability of the plant and the provision of the necessary facilities to make the equipment decided upon in the first section operable.

Process Plant Failures

The final section, 'Process Plant Failures', addresses likely causes of failure in terms of both plant and materials, and operability.

5.2.3 Design Objectives

An overview of the methodology at the third level of detail is presented in fig. 5.5. This shows the third structural element - 'design objectives'. Each section of each level in the method is composed of a series of design objectives. These objectives group together issues and activities which are of a similar nature or which are highly interdependent. The objectives covered are given in table 5.1.

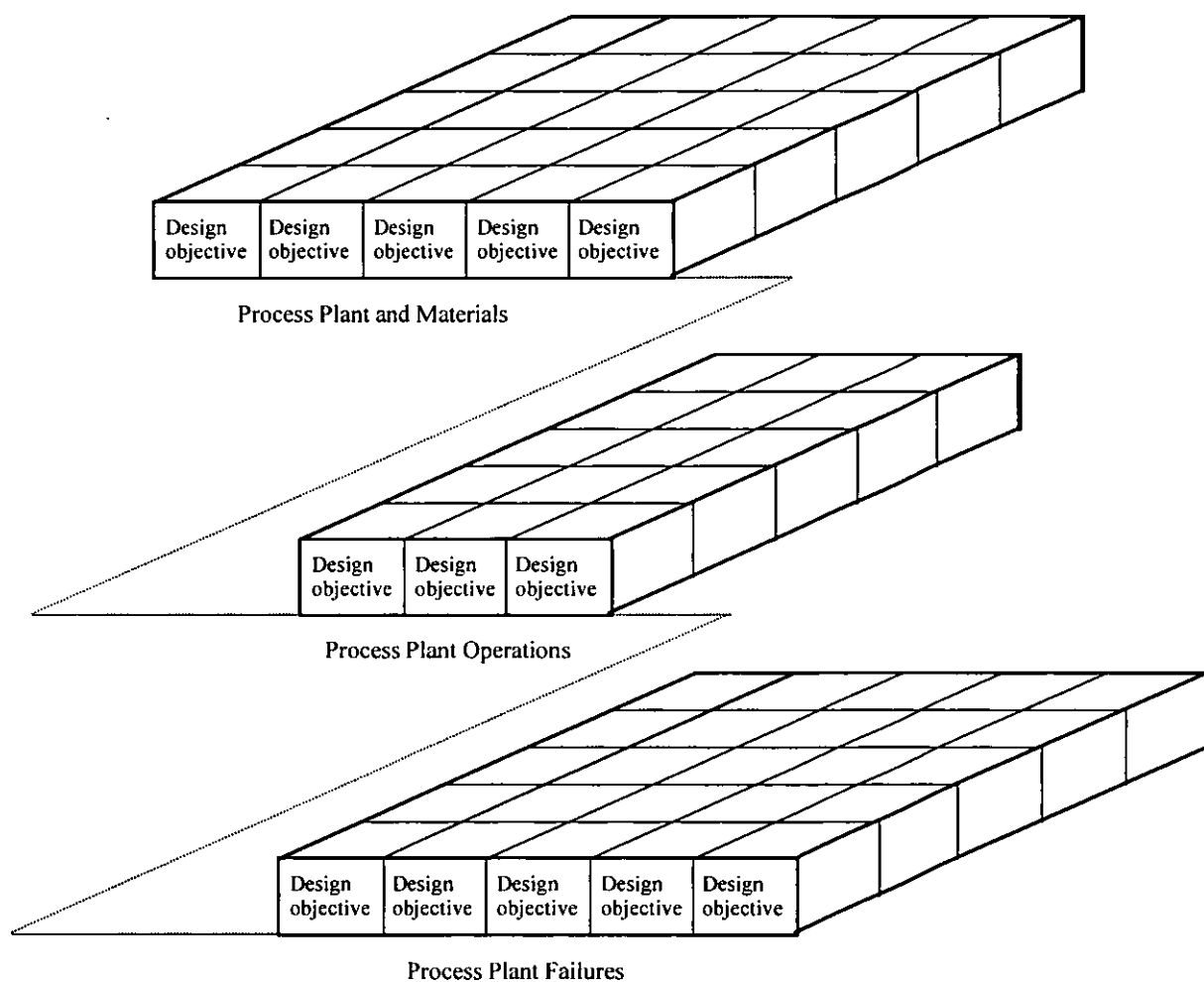


Fig. 5.5 - Third structural element of the methodology: design objectives (one level only)

Table 5.1 - List of design objectives covered by the methodology

<i>Section</i>	<i>Process Plant and Materials</i>	<i>Process Plant Operations</i>	<i>Process Plant Failures</i>
<i>Objectives</i>	Safety, health and environmental proficiency Quality Plant scale and integrity Process ancillaries Availability and reliability	Control Preparatory Operations Testing and maintenance	General protection Pressure protection Fire protection Explosion prevention Emergency procedures

5.2.4 Thought Prompts

An overview of the fourth level of detail in the methodology is given in fig. 5.6. This shows the final structural element - 'thought prompts'. Each design objective is supported by a series of thought prompts. These are accompanied by an explanation of the types of activities and design issues which could be relevant. In application terms, the thought prompts are intended to encourage the designer to think of as many design issues relating to each objective as possible.

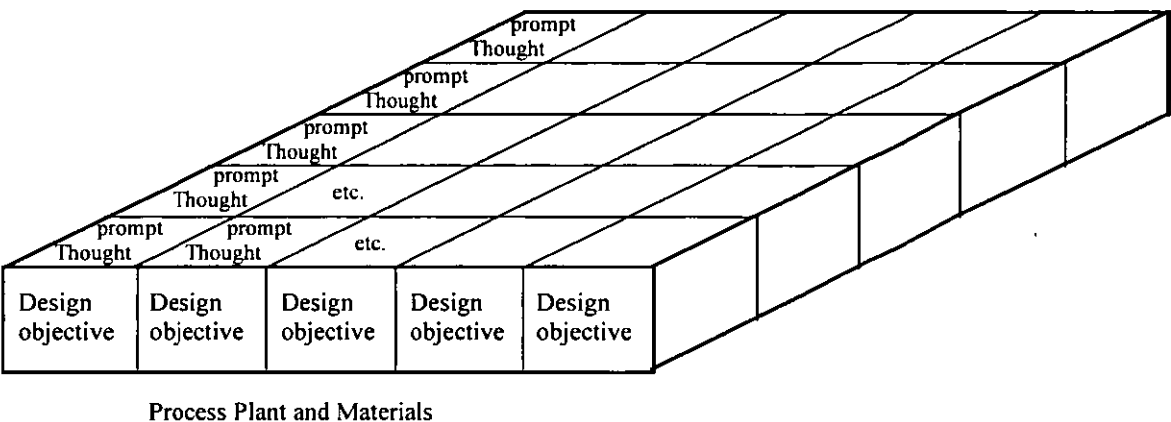


Fig. 5.6 - Fourth structural element of the methodology: thought prompts (one section of one level only)

For continuity, the thought prompts are repeated at each level but with a different emphasis. At the highest level, a general solution to the design problem under consideration is expected.

At the next level, a more specific functional solution should be proposed. At the lowest level, the functional solution should be confirmed to be represented by the appropriate equipment and configurations.

5.2.5 Overall Format

The component elements of the methodology are brought together using a series of tables which follow the format of table 5.2 below. The significance of the ‘interactions’ cell is explained in section 5.4.

Table 5.2 - Format for methodology elements

Section

Design objective

Thought Prompt	Explanation	Interactions

5.3 Logic of the Structure

The ‘final’ methodology reads as a series of steps (thought prompts) in much the same way as the basic Scott approach (ref. section 2.4.1). Particular attention has been paid to the order and content of the steps, their interrelationships and their ability to accommodate iteration. The logic behind the overall structure of levels, sections and design objectives has been explained in sections 5.2.1, 5.2.2 and 5.2.3 above. A brief reminder of this is given below, along with a more detailed summary of some of the logic to the order of the steps within the methodology.

5.3.1 Levels

The different levels in the methodology represent the hierarchical nature of the design task. This is explained in more detail in section 4.5.

5.3.2 Sections

The presence and order of the different sections of the methodology (Process Plant and Materials, Process Plant Operations, Process Plant Failures) provides a logical basis for the progression of the design problem. This takes the form of answering the questions:

- can we get the right sorts of equipment / materials / location to build the plant?
- can we operate the plant?
- can we minimise and / or control foreseeable plant failures?

5.3.3 Design Objectives

The design objectives are arranged in a manner which should minimise the number of iterations within a level. One of the primary objectives in attempting to systematize the process flowsheet to ELD development activity was to ensure that any steps which might lead to the specification of additional large items of equipment would be considered early in the decision process. The motivation behind this was to allow sufficient time for purchase requisitions to be made, to facilitate early approximate specification of layout arrangements and to minimise re-consideration of provision of necessary ancillary equipment.

A summary of the logic underlying the order of the design objectives within each section is provided below. This list complements (and where appropriate supersedes) those given in chapter 4.

Process Plant and Materials

1) *Safety, health and environmental proficiency*

- This first objective is concerned with overall drivers and constraints for the design in terms of safety, health and environmental performance and compliance. These should logically be established before any specific areas of design are tackled.
- Process materials' properties are an important element of this section as they relate directly to safety issues. They also need to be established early in the design process as they will influence most of the design issues and activities which follow. For example, if a process material is known to be toxic, then particular emphasis will need to be made in the design on minimum operator exposure and special facilities for handling loss of containment. These facts need to be established before the objectives for control and emergency procedures are considered.

2) *Quality*

- Having established the SHE drivers and constraints for the design, the next logical step is to define product quality requirements and the equipment expectations (such as throughputs, quality of outputs, etc.) which accompany these. This will generate further drivers for the design.
- The consideration of handling off-specification product is included here as it is important in the overall approach to quality.

3) *Plant scale and integrity (sizing and materials of construction)*

- Once all the drivers for the design have been established, we can begin to tackle specific areas of design. The principal development objective, and that which should be tackled first, is the specification of process equipment required for production. All the design decisions relating to other items of equipment, instrumentation or utilities will rely on this information being present.
- This step may also introduce additional major items of equipment as discussed above.
- The types of equipment chosen will depend to some extent on the plant location and external environment.

- The import and export facilities required form part of the process equipment specification and the types of facilities chosen may affect the overall plant layout (e.g. if vehicle access is required).
- Line sizes and materials of construction may affect decisions such as location of valves and specification of spares, so this step must come before any which may lead to the addition of such equipment.

NB In level 1, details regarding the sizing of vessels and allocation of headspace are not considered. These details may be determined by the control strategy chosen for the plant (e.g. crude control systems may introduce the need to accommodate flow fluctuations by increasing vessel sizes or level control may require the presence of headspace). They may also be affected by the availability and reliability requirements for the plant (e.g. if these dictate the need for extra capacity in vessels). They are therefore handled by specifying the general objectives for availability and control in level 1 and reserving the specification of sizes and headspace until level 2, when the designer will have an idea which factors are likely to impact on sizing.

4) *Process ancillaries*

- The next logical step, having addressed the topic of process equipment required for production, is to ensure that all the necessary utilities are in place.
- This step may also introduce major items of equipment, particularly if it is decided that some form of effluent treatment plant is required.
- The topic of utilities should be considered before availability and reliability as these terms do not only refer to process equipment items in isolation but also to their sources of power / actuation. Other utilities supplies also need to be reliable, such as nitrogen for purging or blanketing and air for protecting operators.
- In terms of effluent treatment, the presence of a third level in the method is important in ensuring that every outlet from the process has been allocated a suitable destination.

NB

In level 1, this step is concerned with general supply of utilities, not specific connections to plant, so does not rely on information concerning the detailed operation of the process. The

details of locations of connections are then addressed in level 2, when an outline operating strategy for the plant should be available.

5) *Availability and reliability (interstage storage capacity and spares)*

- Having established the basic production requirements in terms of equipment and materials, it is sensible to consider the availability and reliability of the facilities and the process streams.
- Availability and reliability should be considered in the event of equipment / utilities / import / export failure. It may also be appropriate to provide operating flexibility (running at different throughputs, processing different materials, etc.).
- A statement on the target availability of the plant is required at level 1, since factors such as number of hours on line, number of hours for maintenance, cost of loss of production will have an effect on the overall approach to the design and will directly affect decisions in a number of subsequent methodology steps.
- Spares and extra capacity are interrelated because there are instances where one will be used to eliminate the need for the other. Hence it is logical to consider them both together.
- If extra capacity is required in any of the major process vessels, this should be identified at an early stage (for reasons of early procurement).
- If extra capacity is provided by interstage storage vessels then the need for extra vessels to be specified for start-up etc. may be eliminated, so this step should come before the section on process plant operation.

NB

Though a maintenance strategy may be proposed in order to meet reliability targets, the detailed consideration of maintenance requirements is left until the end of section 2, when all the 'regular' (i.e. non-emergency) equipment and instrumentation which might need to be maintained should have been specified.

Process Plant Operations

6) *Control*

- The next logical step in the design process is to consider the control and operating strategy for the plant. This is handled by looking at each of the identifiable operating states and transitions in turn.
- By considering the different operating states and transitions in succession, the likelihood of identifying opportunities to utilise any lines or vessels to achieve multiple functions is increased.
- Operations such as purging may be affected by the presence of reverse flow prevention equipment. The provision of such equipment is therefore explicitly incorporated as part of the objective of control (which is considered in conjunction with purging and other 'preparatory operations') in level 2, under the thought prompt 'system integrity and sensitivity'.
- The need to specify spares for any control system equipment or instrumentation added under this objective in level 2i will be captured by the 'availability and reliability' objective at level 2ii, if the need for them is not realised earlier.

7) *Preparatory Operations*

- The term 'preparatory operations' covers operations such as purging, cleaning and drying which may be required during plant transitions. Though these are represented as a separate objective, they need to be considered in conjunction with control for each of the operating states and transitions identified.
- The need to size and specify materials of construction for any new equipment or lines added under this or the control objective in level 2i will be captured by the 'plant scale and integrity' objective at level 2ii, if the need for them is not realised earlier.

8) *Testing and maintenance*

- All 'regular' (i.e. non-emergency) equipment and instrumentation for the process should be in place once the control and operation of the plant (including preparatory operations) has been addressed. This means that the detailed maintenance requirements for this equipment and instrumentation can next be defined.

- The maintenance facilities required for emergency equipment such as trips and relief valves specified in response to level 2i will be captured by level 2ii, if the need for them is not realised earlier.

Process Plant Failures

9) *General protection*

- The plant failures section starts by considering the most likely causes of maloperation or failure of the plant. This is intended to focus the designer's attention on the specific areas which will need to be addressed in more detail later in the methodology.
- It is important that inventory control is addressed after all the 'regular' equipment and lines for the plant have been specified so that the need for isolation on any new lines is not overlooked.
- It is important that inventory control comes before consideration of pressure relief as the location of major isolation valves is needed to give some indication of the size and nature of the different plant sections which may require relief.
- The subject of over-temperature should also be addressed before consideration of pressure relief as the potential for over-temperature could significantly affect the size and type of relief system required.

10) *Pressure protection*

- Protection from over or under pressure is considered next as the need for some form of pressure protection is common to most plants.
- The need for any dedicated relief stream treatment unit is identified early on by considering this issue at level 1.
- The need for relief system spares and maintenance facilities is captured by repeating the thought prompts at level 2ii as explained above (under 'testing and maintenance').
- The need for any utilities supplies to prevent ingress of air in vacuum systems as specified in response to the thought prompt on 'under-pressure' in level 1 will be captured by the 'process ancillaries' objective at level 2i, if the need for them is not realised earlier.

11) *Fire protection*

- Fire protection is often linked to relief facilities, so this is the next subject to be considered in the logical progression of the design.
- The need for the appropriate utilities to be supplied as part of the fire protection systems specified under this objective in level 1 will be captured by the ‘process ancillaries’ objective at level 2i, if the need for them is not realised earlier.

12) *Explosion prevention*

- Some processes also require facilities for explosion prevention / mitigation. Explosion prevention is a large and distinct topic and as such warrants ‘design objective’ status.
- The need to design vessels to withstand explosion identified under this objective in level 1 will be captured by the ‘plant scale and integrity’ objective at level 2i, if the need for this is not realised earlier.
- The need for the appropriate utilities to be supplied as part of the explosion prevention / protection systems specified under this objective in level 1 will be captured by the ‘process ancillaries’ objective at level 2i, if the need for them is not realised earlier.

13) *Emergency procedures*

- The appropriate actions for personnel and public in the event of an emergency can be considered once all the equipment measures for prevention, control and response have been established.

5.3.4 Thought Prompts

The purpose of the thought prompts and their corresponding explanations is to provide a comprehensive reminder of the design issues or activities which might be pertinent to the design objective under consideration. Since many of the issues raised by the different thought prompts for one objective will interact, it is not always important that the specific order in which the thought prompts are presented is maintained. However it is important that all the structural elements of the method remain unchanged because it is these which ensure that the design is handled in a logical, consistent and comprehensive manner.

5.3.5 Iteration

The framework of levels, sections and design objectives is fundamental to the versatility of the method. Each of these structural components provides a natural boundary for iteration: the different levels incorporate iteration in themselves; the different sections provide convenient breaks for iteration as do the individual design objectives. The presence of the distinct 2i and 2ii levels is also used to capture those issues which fall through the ordered 'net' in an earlier level. An example of this is the capture in level 2ii of sizing and designation of materials of construction for lines or equipment added after section 1 of level 2i.

5.4 Interactions

There are two different classes of interaction which impact on the process flowsheet to line diagram design process. The first of these concerns the interaction between the different flowsheets and ELDs which come together to form the final design. It is important that continuity and consistency is maintained between these diagrams. The second class consists of interactions which should take place at various distinct points in the design process. These can only be articulated if a systematic approach to the design task exists. The manner in which both classes of interaction are incorporated into the methodology is described below.

5.4.1 Drawings

Fig. 5.7 illustrates how a typical design project can begin with a number of process flowsheets, each of which will be broken down into its own set of PFDs, which in turn spawn sets of ELDs. It is easy to see how, without adequate organisation and attention to detail, inconsistencies between the numerous drawings can develop.

The 'tool' devised within the PREMIUM project to overcome this problem with inconsistencies between drawings is the 'global PFD'. This drawing is based on an adaptation of the 'intermediate representation' concept introduced in section 4.2.2. The global PFD is intended to show how all the process facilities for pressure relief, utilities, sampling and so on

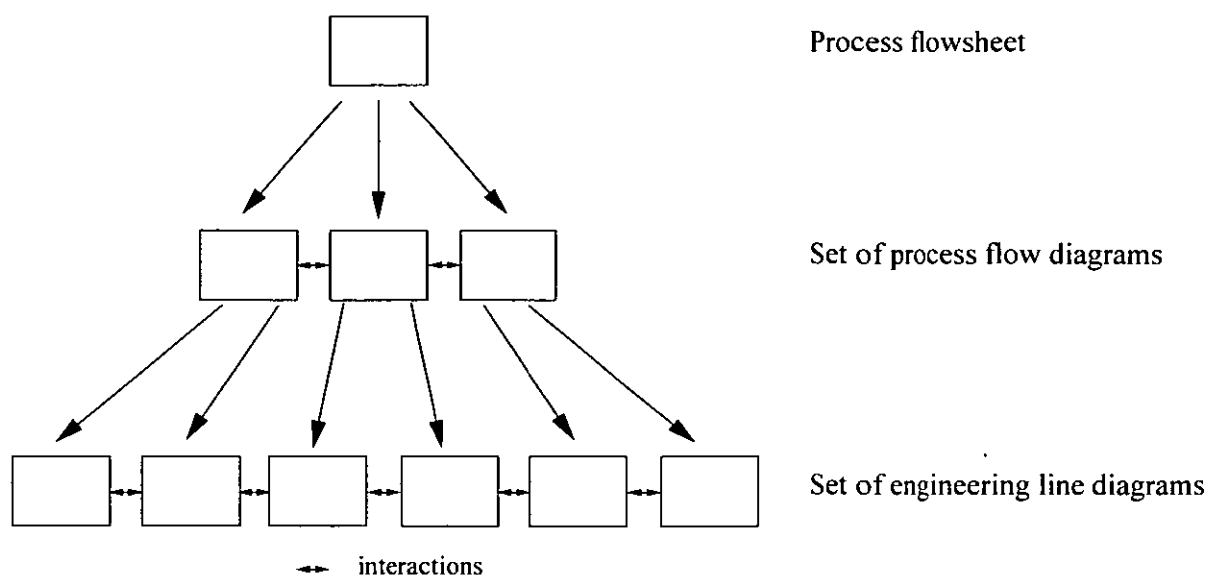


Fig. 5.7 - Diagram illustrating the progressive increase in the number of engineering drawings generated during process flowsheet to ELD development

interact between the different ELDs. It should be developed alongside the ‘normal’ PFDs produced after the application of level 1 of the method. By referencing the global PFD during the development of the individual ELDs, it is possible to see how the design fits and works together, and to be sure that no details such as sample points are lost by assuming that they will be handled on another drawing when they will not.

The types of features which should be shown on a global PFD are listed below. In keeping with the intermediate representation philosophy, these features should not be given standard symbols, but should be indicated by some other notation (e.g. simple labelling), in order to avoid pre-empting the solution.

The ‘global’ PFD should include only top level control showing how the overall plant is operated. Otherwise, it should show all of the information required in a ‘normal’ PFD (ref. section 5.1.2), plus:

- sample points
- major isolation valves
- pressure and fire relief requirements (locations only)
- venting and drainage systems
- effluent treatment systems.

The global PFD is not intended to form part of the final project documentation but simply to act as a working document to assist in the optimal development of ELDs.

5.4.2 Methodology Interactions

Once a framework for a systematic approach to the design task exists, it can be used to incorporate many different types of design-related information in a formal manner. This feature was first used in the methodology to cover possible interdependency of issues and activities arising under a given thought prompt with those arising under different thought prompts. A new column in the methodology table was introduced so that an ‘interactions cell’ could be provided alongside each thought prompt. This is shown in table 5.2. The interactions cells were then used to list the possible prompts with which each prompt itself might interact.

This concept of interactions within the methodology, initially devised for the purpose described above, has been extended in two ways. First, it was modified to incorporate guidance on when interactions should be taking place between the different engineering disciplines. Second, it was amended to include links to other design activities which should be occurring in parallel with the ELD design.

A significant consequence of the current ‘haphazard’ approach to line diagram development is the lack of awareness amongst the engineers from different disciplines about when they should be exchanging information on or meeting to discuss particular design issues. This problem of communication was highlighted in section 3.3. The methodology aims to improve communication between the different engineering disciplines during ELD development. It does this by using the interactions cells to prompt the user to consider consulting other people with regard to the particular design issues and activities to be addressed.

The second modification mentioned above is concerned with ensuring that the ELD development is fully integrated with the other activities contributing to the design project and that all design activities progress at an even rate. Suggestions for where other design activities such as documentation of operating instructions or preparation of layout drawings should be occurring in parallel with the ELD design are incorporated into the interactions cells.

5.5 Recording the Information Generated

Part of the benefit of having a logical and consistent approach to the design task, as represented by the PREMIUM method, is that it provides a basis for improving the traceability of the design activities. Realisation of this benefit relies on the complete and concise recording of information generated during the application of the method. Two general methods for recording the information generated by the methodology are proposed here. The first uses tables and the second uses the engineering drawings. In addition, a specific method for recording information on operating states and transitions is presented.

5.5.1 Tables

As each thought prompt in the methodology is applied, it is proposed that any pertinent comments and actions are noted in a table as shown in table 5.3. Pertinent comments might include design options which were considered, reasons for choosing a particular solution, reasons for avoiding the use of particular equipment and so on.

Table 5.3 - Table for recording information generated by the methodology with example entries

Thought Prompt	Comments	Actions
Safety and loss prevention and pollution prevention philosophies	Inherent SHE study, Environmental State, Occupational Health, Hazard Study 1,2 should have been completed.	Read, become familiar with Hazard Study 1 etc. Be aware of dominant hazard issues.
etc.		

The tables should be produced with each level of application of the methodology, using tables from the previous levels where appropriate to check how the design is progressing and whether the philosophy has changed. In this way, design development can be recorded in a clear, usable, complete and consistent manner.

5.5.2 Drawings

In the past, designers were in the habit of writing on drawings in quite an unconstrained manner (see section 2.3.1). This practice can contribute significantly to the ease of understanding of the diagram. In order to capture this type of understanding through the application of the methodology, it is proposed that the process flowsheets and process flow diagrams should be used for noting key design features. Fig. 4.2 illustrates this technique.

The annotated drawings can be used to enhance understanding of the tabular notes taken, and give a much better overview of the progress that has been made with the design, highlighting areas which require further work.

5.5.3 Operating States and Transitions

One of the fundamental strengths of the PREMIUM methodology is its continuous and rigorous attention to control and operability in design. It is therefore appropriate to include a recommended method for recording the key information generated under this particular objective. The method proposed uses the combination of a diagram and tables. The diagram shows the anticipated operating states and transitions. The tables show, separately, the 'control states' at each operating state and the transitions required between each operating state. These are illustrated, respectively, in fig. 5.8 and tables 5.4 and 5.5 below.

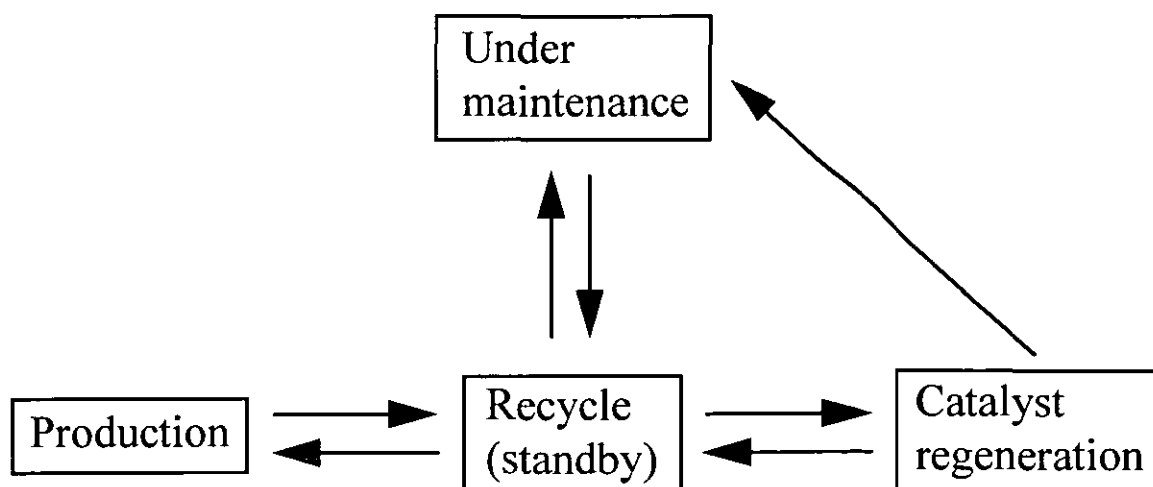


Fig. 5.8 - Operating states and transitions

Table 5.4 - Control states

Control states	Production	Recycle	Regeneration	Maintenance
Air	off	off	on	off
Nitrogen	off	off	on	off
Toluene	on	off	off	off
Hydrogen	on	on	off	off
Natural gas	on	on	on	off
Compressor	on	on	off	off
Furnace	on	on	on	off

Table 5.5 - Transitions

Transition	Actions
Maintenance to recycle	<ol style="list-style-type: none"> 1. Switch on nitrogen and purge system 2. Check oxygen levels - switch of nitrogen when safe 3. Switch on hydrogen and start compressor to bring in recycle loop 4. Switch on gas, light furnace and check temperature control
Recycle to production

5.6 Detailed analysis

The methodology described in the preceding sections of this chapter is a tool which alerts designers to the pertinent issues in ELD development and which encourages them to progress the design in a logical manner. The method does not provide any decision support. In practice, it is assumed that the designer would rely on personal expertise and on personally selected reference sources to resolve the various issues raised in the course of the design work. However, in order to demonstrate that PREMIUM has resolved the issues of detailed process design to an appropriate level of detail and that decision-making is practical at this level, decision support documents for a selection of individual design issues have been produced. This set of documents could, in principle, be extended to cover the whole spectrum of issues raised during detailed process design. The section of work which addresses this topic is entitled 'detailed analysis'.

The issues selected for ‘detailed analysis’ include heat tracing, insulation and reverse flow prevention. Information from the literature on each subject was collated and is presented in a single document to facilitate qualitative comparisons of the solution options. One of two techniques for presenting the information is used, depending on the nature of the issue to be resolved.

Equipment type

If the issue is concerned with equipment types, then PMI (Plus, Minus, Interesting) lists are used. These were introduced in section 2.4.2. They allow information on the advantages, disadvantages and ‘quirks’ of a particular option to be presented in a way which can assist in decision-making. PMI lists are preferred over decision trees as the design problems are not sufficiently clear cut to enable yes / no answers to be made. They are also preferred over semantic networks as PMI lists are more easily interpreted and more straight-forward to develop.

Equipment configuration

If the issue to be resolved is concerned with equipment configuration, then illustrations of the alternative configurations with their associated problems and merits are given. An example of each type of document is included in appendix C1. The general format for each type of document is shown in figs 5.9 and 5.10 below.

Modification chains

One issue of particular importance in detailed process design is that of ‘modification chains’. The meaning of this term was described in chapter 1. Modification chains can be represented as a configuration problem but are anomalous in that the decision to be made is not which configuration to use but whether to pursue a design proposal given the additional changes which might ensue. An example analysis of modification chains is also provided in appendix C1.

Further examples of issues which would come into each of these categories are given in tables 5.6 and 5.7. Those which have been worked on in the PREMIUM project but which are not given in the appendix are marked with an asterisk.

Title of issue
Brief description explaining what the issue is
Information on why it is an issue: why the equipment/feature in question might be needed / why it should be avoided
Information on problems which may arise / problems which may be avoided
Solution options with advantages, disadvantages and 'quirks' in PMI list form
References for further reading

Fig. 5.9 - Format of decision support document for equipment type selections

Title of issue
Title of a possible equipment configuration
Illustration
Advantages, disadvantages and 'quirks' in PMI list form
Title of another possible equipment configuration etc.

Fig. 5.10 - Format of decision support document for equipment configuration selections

Table 5.6 - Design issues categorised by equipment type

Topic	Characteristic
Reverse flow prevention*	Options depending on integrity req'd
Isolation*	Options depending on integrity and nature of materials
Insulation*	Options depending on application
Heat tracing	Options depending on application
Thermal expansion*	Options for accommodation and relief
etc.	

Table 5.7 - Design issues categorised by equipment configuration

Topic	Characteristic
Control archetypes	Options depending on action required
Monitoring / diagnostics	Relative positioning of instruments and other equipment
Sample points	Options depending on integrity req'd
Interlocks	Options depending on action required
Trips	Options depending on reliability req'd
etc.	

5.7 Incorporating SHE into the methodology

The primary objective in generating the methodology described above was to capture the logic and the order in which decisions for developing a first ELD are made. In meeting this objective, the method has provided the opportunity to incorporate SHE and operability into the design process in many ways.

The most direct incorporation of SHE and operability is represented by the specific thought prompts on ‘basis of safety’, ‘basis of environmental protection’ and ‘operating strategy’. But safety and operability, in particular, are also represented indirectly in a number of different ways. The features of the methodology which improve attention to these objectives are listed below:

- rigorous and timely handling of operating states and transitions
- early and ongoing consideration of likely failures and of requirements for operator protection and response
- development of operating and other procedures in parallel with the design (not as an afterthought)
- a consistent approach to interactions, including those between the different diagrams produced during design, those between the different people contributing to the design and those between the different activities and issues arising during the design.

All of these improvements are made possible by introducing structure to the process flowsheet to ELD development task.

Better consideration of inherent SHE and operability is also encouraged by two further means. First, by the provision of option charts on inherent safety and waste minimisation which suggest changes which could be made to the design in order to attain these objectives. These charts are included in the appendix to the methodology provided. Second, by the use of intermediate representation in the ‘global’ PFD (section 5.4.1), which defers specification of equipment until all pertinent design data has been evaluated. This should encourage the designer to identify opportunities for assigning multiple functions to equipment and to choose the most suitable equipment to achieve all the functions intended. Copies of the option charts

are included in appendix C2 and an illustration of a global PFD is provided in the appendix to the methodology.

5.8 Conclusions

An explanation for the logic and the order in which decisions for developing a first engineering line diagram should be made has been generated. This is embodied in a methodology which details the issues and activities involved in line diagram design in a systematic manner. There are four main structural components to the method: levels, sections, design objectives and thought prompts. These create a framework within which the details of the design task may be presented (and subsequently recorded).

While the methodology represents a logical approach to ELD development, the reasoning behind the logic is not self-evident. An account of the reasoning which led to the particular structure described has therefore been given.

The methodology framework provides for the improvement of many different aspects of the design task. It allows systematic incorporation of information on interactions between different engineering disciplines and design activities. It acts as an interface to the decision support tools of the kind developed in the 'detailed analysis' section of research (the purpose of which was to link the theory of the methodology to the practice of design decision-making). It also allows SHE and operability issues to be addressed in a rigorous and consistent manner.

Methods for recording the information generated by application of the method are also described. These include tabulation of design issues and actions discussed under each thought prompt and annotation of drawings with detailed design development notes. A new form of drawing - the 'global PFD' - is introduced. These records should help to ensure compatibility between the different ELDs which make up the complete design. They should also improve traceability of the design, contributing to Corporate Memory.

CHAPTER VI - APPLICATION OF THE METHODOLOGY

6.0 Introduction

The last two chapters of the thesis described, respectively, the evolution of a methodology for ELD development from process flowsheets and the final structure of this methodology. The purpose of this chapter is to demonstrate the application of the methodology using extracts from worked examples.

Section 6.1 summarises the manner in which the methodology is intended to be applied. This subject was touched upon in chapter 5.

Section 6.2 contains extracts from the documentation produced through application of the methodology to the PREMIUM Masterclass worked example. These extracts include tables and a sample drawing illustrating the methods for recording development notes.

Section 6.3 discusses the application of the methodology to the design of a batch process, showing how careful identification of the operating states and transitions can simplify the design process.

Section 6.4 summarises the feedback obtained from application of the methodology to a 'live' design case at ICI.

Section 6.5 draws together conclusions for the chapter.

6.1 Mode of application

In chapter 5 it was concluded that in order to achieve maximum benefit from the methodology in a design project, the method should be applied by a group of design engineers and used to plan the development of the design. The optimum number of group

members was agreed to be three or four. This is sufficient number to generate good discussion and ideas without being so many as to hinder progress by pulling the design in too many different directions and generating inappropriate compromises.

The team should ideally comprise:

- lead process engineer for the project
- an operations representative
- a project engineer
- (a chemist in the flowsheet stages)
- (a control / electrical engineer in the detailed design stages).

These people are considered to be key in giving a balanced view of what is still quite an innovative stage in design.

Three separate meetings should be held, each addressing a successive level of the method in association with the appropriate engineering drawing. In these meetings, each thought prompt in the method is considered in turn and applied to either the whole diagram or successive sections of the diagram. The line-by-line approach is avoided in order to minimise the chances of early mistakes / omissions being overlooked again at the HAZOP. Any key discussion points, design proposals and actions are recorded alongside each thought prompt in the standard record table (see section 5.5). Key comments may also be noted on the diagram to aid understanding / recollection of any design changes implied and any knock-on effects these might have.

Once all the thought prompts for one level have been addressed, the group is disbanded while the design is formally developed and new drawings (with corresponding process description and operating philosophy) are worked up in preparation for the next level. The group then reconvenes to begin work on planning for the next level. The tabular and diagrammatic records of the proposals made at the previous meeting are used for reference to ensure continuity of the design. These records may also be used to recapture any proposals which have been overlooked. This process is presented diagrammatically in fig. 6.1.

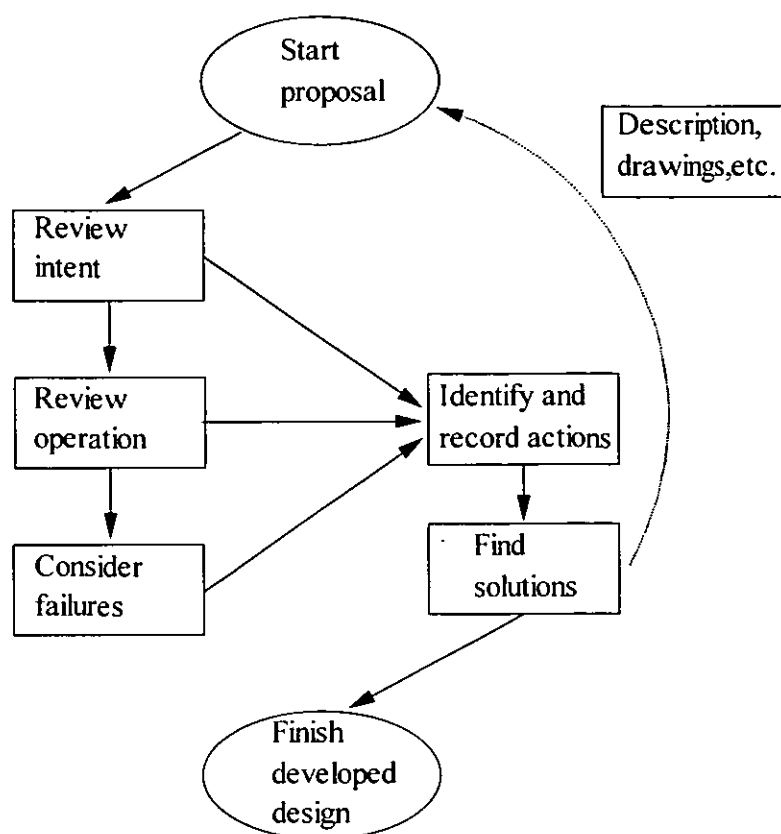


Fig. 6.1 - Diagrammatic representation of methodology application

6.2 'Masterclass' example

The staging of a 'Masterclass' with senior engineers from ICI in order to trial the method was discussed in section 4.7.1. The worked example used for this Masterclass was based on the toluene hydrodealkylation process described by Douglas (1988). The initial design was worked up by PREMIUM project team members within ICI so that a good flowsheet and outline process description were available as a starting point for the Masterclass. Copies of these are given in fig. 6.2 and appendix D1 respectively.

The methodology used at the Masterclass was not the final version, so the specific order and names of the thought prompts given below will not tie in with the definitive PREMIUM methodology. However, the structure and content of the method is largely unchanged, so that the details of the output are not significantly different from those which would have been generated by the final method.

It was not possible to work through the entire methodology during the Masterclass due to time constraints. In addition, a complete run-through of all the levels in one session would have been inappropriate, considering the ultimate mode of application of the method. Instead, a fixed amount of time was spent on systematically working through the level 1 thought prompts, and the remainder on the beginning of level 2. Level 2 was subsequently completed, followed by level 3, in later meetings with ICI members of the PREMIUM project team. In this way, one complete example of the application of the methodology was generated.

6.2.1 Application

Summary process description

The plant is designed to manufacture 66000 tpa of benzene by the catalytic hydroalkylation of toluene. The fresh toluene and hydrogen streams are respectively combined with recycled toluene and hydrogen streams before being sent to a vaporiser. From here, the mixed gas stream passes through a preheater, then a furnace and on into the reactor. The reacted material passes back through the preheater and vaporiser, and through a cooler and phase separator. The gas from the phase separator is sent along the hydrogen recycle line (with purge if necessary) while the liquid continues into a benzene column. Benzene is taken from the top of the column and toluene is taken off as a sidestream for recycle. Heavies are expelled at the bottom of the column.

The remainder of this section is dedicated to presenting an extract of the documentation produced through application of the methodology to the Masterclass exercise. This extract focuses on the safety and quality aspects of the design. For each level in the method, the thought prompts with their corresponding explanations are quoted individually, followed by the tabular records made in response. Fig. 6.2 shows the overall flowsheet for the process and Fig. 6.3 the 'sectional PFD'. Fig. 6.4 provides an example of the diagrammatic records made while Fig. 6.5 shows a draft of the notional ELD. No global PFD is shown here as the concept was not formalised until after the trials had been carried out.

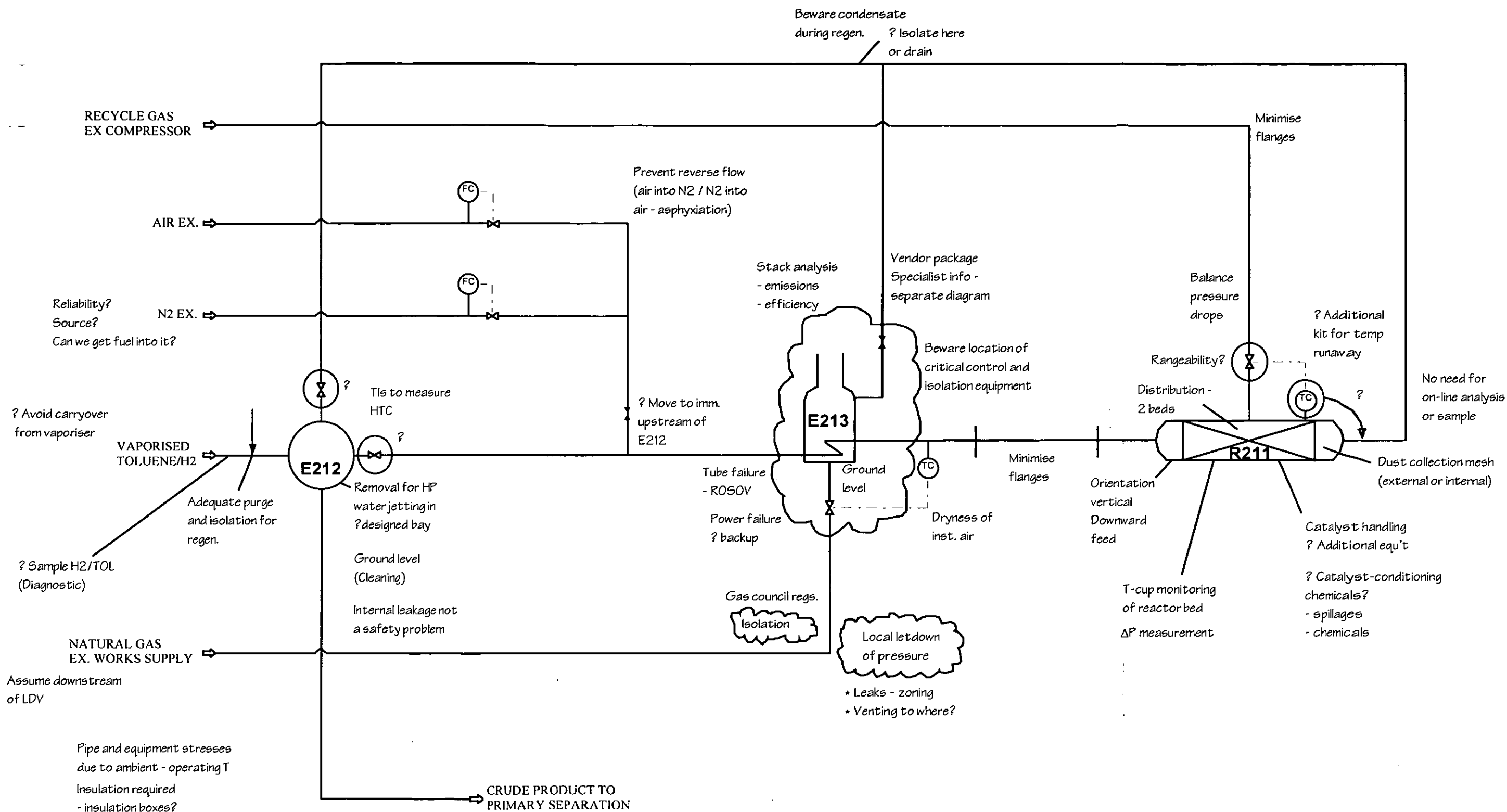


Fig. 6.4 - Sectional PFD showing diagrammatic records made in response to application of the thought prompts at level 2i

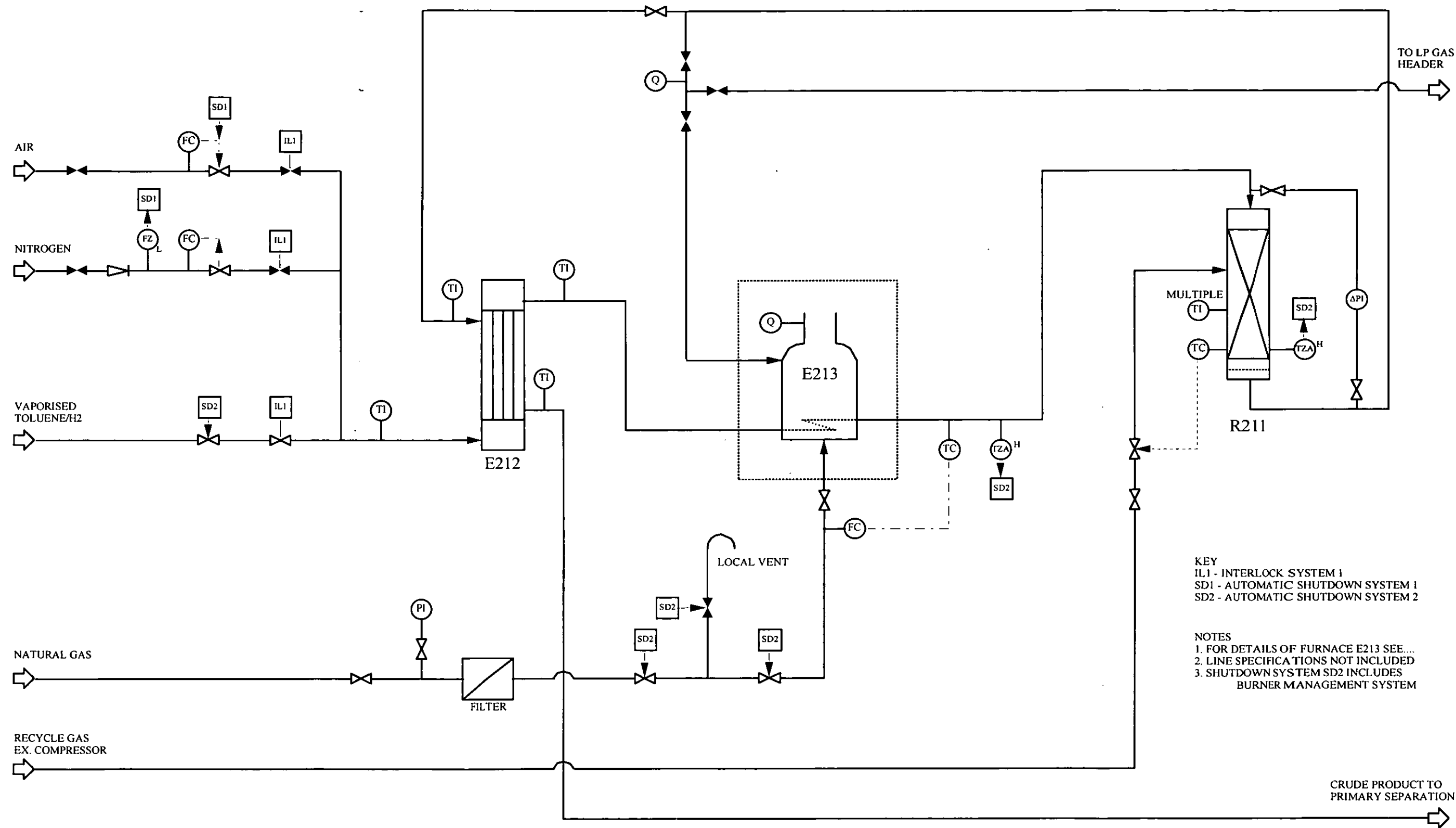


Fig. 6.5 - ELD generated following application of level 2ii of the methodology to the Masterclass example

For the application of level 1 of the method to the Masterclass exercise, two sets of responses were documented - the first made by the 'Masterclass' delegates and the second by myself.

LEVEL: 1

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation
Safety and loss prevention philosophy	<p>Has a statement been drawn up which takes into account the particular hazards and processes involved?</p> <p>(Often a modification of the general company loss and safety prevention philosophy will suffice. There are four identified activities which must be satisfied in order to comply with safety regulations:</p> <ul style="list-style-type: none"> • assessment • control of problems identified • maintenance of controls • monitoring of their effectiveness.)

* * * * *

Responses

Masterclass delegates' record

Thought prompt	Comments	Actions
Safety and loss prevention philosophy	<p>Is statement comprehensive?</p> <p>Next level down required.</p>	

My record

Thought prompt	Comments	Actions
Safety and loss prevention philosophy	<p>Has one been drawn up? Is it comprehensive?</p> <p>Often the assumptions made are not valid and this is not realised until later.</p> <p>Refined as the design becomes more detailed.</p>	

LEVEL: 1

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation
Physical properties	Is there an adequate understanding of the physical properties (of feedstocks, products, by-products, intermediate products, catalysts and additives such as anti-corrosion chemicals or water treatment chemicals)? What are the implications of: <ul style="list-style-type: none">• density• viscosity• particle size on plant operability? What additional provisions should be made for this?

* * * * *

Responses

Masterclass delegates' record

Thought prompt	Comments	Actions
Physical properties	Readily available. Reboiler HTC Reboiler fouling leading to shutdown	

My record

Thought prompt	Comments	Actions
Physical properties	Should be understood. Fouling / heat transfer / operability problems due to heavies in the reboiler not well understood.	

LEVEL: 1

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation
Chemical properties	<p>Is there an adequate understanding of the chemical properties (of feedstocks, products, by-products, intermediate products, catalysts and additives such as anti-corrosion chemicals or water treatment chemicals)?</p> <p>What are the possible consequences of:</p> <ul style="list-style-type: none">• side-reactions• reactions between products, by-products and intermediate products• reactions at different temperatures, pressures, residence times or concentrations• reactions with common contaminants• autocatalytic reactions• exothermic reactions• formation of unstable polymers? <p>What implications do these have on plant operability? What additional provisions should be made for this?</p>

* * * * *

Responses

Masterclass delegates' record

Thought prompt	Comments	Actions
Chemical properties	Side reactions understood. 'What ifs' - poorer understanding, hard to anticipate all.	

My record

Thought prompt	Comments	Actions
Chemical properties	Good understanding of side reactions. Poor understanding of 'what ifs' e.g. runaways. It is difficult to anticipate these 'what ifs'.	

LEVEL: 1

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation
Toxicological properties	Is there an adequate understanding of the toxicological properties (of feedstocks, products, by-products, intermediate products, catalysts and additives such as anti-corrosion chemicals or water treatment chemicals)? What implications do these have on plant operability? What additional provisions should be made for this?

* * * * *

Responses

Masterclass delegates' record

Thought prompt	Comments	Actions
Toxicological properties	Hazard Study I.	

My record

Thought prompt	Comments	Actions
Toxicological properties	Should be addressed because these represent an occupational hazard.	

LEVEL: 1

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation
Flammability	Is there an adequate understanding of the flammability limits and autoignition temperatures (of feedstocks, products, by-products, intermediate products, catalysts and additives such as anti-corrosion chemicals or water treatment chemicals)? What implications do these have on plant operability? What additional provisions should be made for this?

* * * * *

Responses

Masterclass delegates' record

Thought prompt	Comments	Actions
Flammability	None	

My record

Thought prompt	Comments	Actions
Flammability	This is considered early on, upstream of Hazard Study I.	

LEVEL: 1

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation
Mixing	What are the implications of mixing of incompatible fluids in drains or effluent systems?

* * * * *

Responses

Masterclass delegates' record

Thought prompt	Comments	Actions
Mixing	Revisit Hazard Study I matrix. Paving and draining review picked up at Hazard Study III. Mixing of effluent lines is Layout / Drainage issue.	Process Separate

My record

Thought prompt	Comments	Actions
Mixing	Revisit with PFD. One of the standard reviews carried out is a paving and drainage review at the Hazard Study III stage. It is too late by this stage to make any major changes to the design. This review is part of developing layout. This prompt is useful to trigger thinking on bunding and effluent mixing. It is important to have these parameters defined and agreed.	

LEVEL: 1

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation
Inherent safety	What inherent safety features can be built into the plant? Can any changes be made to the proposed process or materials to improve inherent safety?

* * * * *

Responses

Masterclass delegates' record

Thought prompt	Comments	Actions
Inherent safety	Too late? Challenge "extra vessels for control", cf modern control.	

My record

Thought prompt	Comments	Actions
Inherent safety	Mindset - consideration of SHE issues is a way of thinking at the higher level leading up to the production of the PFD. The point was made (by participants in the Masterclass) that maybe it is too late to consider inherent SHE at this more detailed level. Perhaps there is a feeling that inherent SHE is only about higher level considerations but it can influence very detailed decisions for instance to permit inherently safer maintenance. The prompt can be used to check the PFD. In addition, the concept can continue to be applied, perhaps just not with the same impact. Is the mix-up pot for the toluene an inherent SHE issue? We should not underestimate the degree of controllability which can be achieved using current technology. However, operators do not like fancy control systems which they do not understand.	

LEVEL: 1

Classification: Process Plant and Materials

Objective: Quality

Methodology

Thought Prompt	Explanation
Specifications	What are the target and acceptable qualities for process feedstocks, products and by-products? Are there any unacceptable impurities? What quality control procedures will be required?

* * * * *

Responses

Masterclass delegates' record

Thought prompt	Comments	Actions
Specifications	Look into 5 '9's (99.999%) purity. Cost implications of high specification.	

My record

Thought prompt	Comments	Actions
Specifications	Quite well defined normally. Sometimes defined by quality of first few tonnes coming out. Depends on what you are making and if it is a new product. We do not explore it or understand it enough.	

LEVEL: 1

Classification: Process Plant and Materials

Objective: Quality

Methodology

Thought Prompt	Explanation
Loss minimisation	How will resources be distributed to minimise the losses associated with sub-quality product? (For instance, in batch processes the required output may be achieved by making one large batch or several small batches per day. The choice will be influenced by the risk and magnitude of possible accidents and this may have an effect on the economics of the plant. If contamination occurs, the cost of lost saleable product will obviously increase in line with batch size.)

* * * * *

Responses

Masterclass delegates' record

Thought prompt	Comments	Actions
Loss minimisation	None	

My record

Thought prompt	Comments	Actions
Loss minimisation	Use two or three rundown drums on distillation column to allow for removal of off-spec. product from the process. This proposal would be looked at stochastically but is likely to go out because it is too costly.	

LEVEL: 1

Classification: Process Plant and Materials

Objective: Quality

Methodology

Thought Prompt	Explanation
Off-spec. product	What can be done with off-spec. product? (For example can it be reworked or sold as a lower grade product or will it have to be dumped?) Where will off-spec. product be identified? (Dumping or reworking may be facilitated or limited by diverting off-spec. material at an intermediate stage.)

* * * * *

Responses

Masterclass delegates' record

Thought prompt	Comments	Actions
Off-spec. product	Small rundown or straight into product. Why off-spec.?	Dump / bypass / refeed

My record

Thought prompt	Comments	Actions
Off-spec. product	Why is it off-spec.? Has the reactor 'gone wrong'? Has the distillation column been operated wrongly? In the latter case the product can be re-fed into the column but then it is likely to generate a SHE issue with complicated pipework.	

During the application of level 2 of the method to the Masterclass example, the delegates were not provided with tables to record their response to the thought prompts but were encouraged to write on the PFD as shown in fig. 6.4. (The concept of using the table for recording at each level was generated in response to this first trial.) Meanwhile, I continued to record the delegates' verbal response in tabular format. From this point onwards, the designation of actions was omitted as the situation is hypothetical. Consequently, the 'actions' column does not appear in the tables shown below.

LEVEL: 2

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation	Interactions
Flammability	What measures will be taken to keep process materials away from their autoignition temperatures and outside of their flammability limits? What measures will be taken to ensure that operations involving materials within the flammable range are carried out safely?	Utilities, purging

* * * * *

Response

My record

Thought prompt	Comments
Flammability	<p>Fuel supply and process and regeneration.</p> <p>Assume gas is available at a higher pressure than required. Gas supply regulations apply. If the letdown device has a vent then care must be taken to specify the location / direction of vent release.</p> <p>The furnace is a specialist subject - decided to 'bubble' it and show it on a separate diagram.</p> <p>Are there any trace fuels in the raw materials, e.g. in the nitrogen supply?</p> <p>What is the source and reliability of raw materials? (Should have been established at Level 1.)</p> <p>Decided to take all valves other than control valves off the PFD and add them later.</p> <p>Need to prevent backflow into the air system.</p> <p>Internal heat exchanger failure is not a safety problem.</p> <p>Avoid carryover of droplets from presaturator into preheater.</p> <p>Minimise flanges on inerted lines.</p> <p>Temperature control should be drawn more towards the back end of the reactor.</p> <p>Need to balance pressure differential on the recycle gas control valve.</p> <p>Simulation of pressure differentials is required to determine rangeability.</p> <p>Simulation of cold gas distribution in the reactor is also required.</p>

LEVEL: 2

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation	Interactions
Mixing	What measures will be taken to ensure that there is no mixing of incompatible fluids in drains or effluent systems? What measures will be taken to ensure that there is no mixing of incompatible fluids within the process?	Additional flow control

* * * * *

Response

My record

Thought prompt	Comments
Mixing	Look at every node systematically. Move regeneration line upstream of preheater to improve effectiveness of purging? Prevent reverse flow of air into nitrogen. Furnace tube failure - need remote shut-off valve. Catalyst conditioning? Connections / spillages.

LEVEL: 2

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation	Interactions
Inherent safety	What inherent safety features can be built into the plant? Can any changes be made to the proposed process or materials to improve inherent safety?	

* * * * *

Responses

My record

Thought prompt	Comments
Inherent safety	Not a level 2 issue(?).

LEVEL: 2

Classification: Process Plant and Materials

Objective: Quality

Methodology

Thought Prompt	Explanation	Interactions
Quality control procedures	Where will samples need to be taken for quality control? What sampling methods will be required?	Control

* * * * *

Responses

My record

Thought prompt	Comments
Quality control procedures	No sample system around reactor as it would be dangerous and the necessary information can be inferred from downstream samples. Sample downstream of presaturator for diagnostic purposes? Should diagnostic instrumentation as well as sampling be incorporated at this point in the method?

LEVEL: 2

Classification: Process Plant and Materials

Objective: Quality

Methodology

Thought Prompt	Explanation	Interactions
Off-spec. product	What measures will be taken to handle off-spec. product?	Handling transitions between operating states

* * * * *

Responses

My record

Thought prompt	Comments
Off-spec. product	Not relevant. Prevent generation of off-spec. product.

The following output from the application of the third level of the methodology was generated by the PREMIUM project team.

LEVEL: 3

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation	Interactions
Flammability	Have adequate measures been taken to keep process materials away from their autoignition temperatures and outside of their flammability limits? Have adequate measures been taken to ensure that operations involving materials within the flammable range are carried out safely?	Utilities, purging

* * * * *

Responses

My record

Thought prompt	Comments
Flammability	Yes, it is a relevant issue. The hazards are: - getting air into the system - escapes of material. The risks of the former can be minimised by procedural methods - purging before start-up and using interlocks to prevent air entering the operating system. The latter could generate problems around the furnace but these would be described elsewhere. This type of information should already have been documented either in the process description or in the outline operating procedures (or both).

LEVEL: 3

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation	Interactions
Mixing	Have adequate measures been taken to ensure that there is no mixing of incompatible fluids in drains or effluent systems? Have adequate measures been taken to ensure that there is no mixing of incompatible fluids within the process?	Additional flow control

* * * * *

Responses

My record

Thought prompt	Comments
Mixing	The interlock system prevents air from entering the process during production. Automatic shutdown system 2 (SD2 in fig. 6.5)will alleviate any problems associated with incompatible mixing in the furnace. (HS 1 would have produced information on incompatible fluids.) The level 2 response provided answers to these questions - have they been followed up?

LEVEL: 3

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation	Interactions
Inherent safety	What inherent safety features have been built into the plant? Have any changes been made to the proposed process or materials to improve inherent safety?	

* * * * *

Responses

My record

Thought prompt	Comments
Inherent safety	Could have imported mixed gas rather than mixing the air and nitrogen <i>in situ</i> for regeneration (when minimum nitrogen flow should be 2-3 times maximum air flow to avoid risk of fire / explosion).

LEVEL: 3

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation	Interactions
Quality control procedures	Have adequate sampling facilities been provided?	Control

* * * * *

Responses

My record

Thought prompt	Comments
Quality control procedures	Yes - have sampling to check the composition of the gas to the furnace, plus other sample points as detailed in level 2.

LEVEL: 3

Classification: Process Plant and Materials

Objective: Safety

Methodology

Thought Prompt	Explanation	Interactions
Off-spec. product	Have adequate provisions been made for handling off-spec. product?	Handling transitions between operating states

* * * * *

Responses

My record

Thought prompt	Comments
Off-spec. product	A new sample point has been added at the three way junction with the LP gas header so that when the system is purged after maintenance it can be checked for oxygen. The sample point is also used to check on the hydrocarbon content during the purge for regeneration. The process description should include a list of sample points and their purposes.

6.2.2 Points of Interest

- Looking at the records made in response to the level 1 prompts there is quite a contrast between those made by the Masterclass delegates and those made by myself. The experienced designers' records provide much less information on the reasoning behind the decisions made but are more concise and user-friendly. My records are more verbose, but capture some important reasoning in support of the design decisions.
- The practice of recording some of the design decisions made in response to the thought prompts on the diagrams makes it easier to identify where these might have knock-on effects. For example, in fig. 6.3 a note has been made to change the orientation of the reactor from horizontal to vertical, with the new requirement for a downward feed. In response to a later prompt, the need for a dust collection mesh was then identified. If the first design proposal had only been recorded in tabular form, then it is quite likely that the second design proposal would have been overlooked.
- The Masterclass delegates' responses to the prompts on inherent safety indicate that there is a mindset which says that it is too late to influence the inherent safety of the design by the ELD development stage.

6.3 Batch example

Since the methodology is intended to capture the generic logic and order in which decisions for developing a first ELD should be made, it is important that it is applicable to both batch and continuous processes. Consequently, the methodology was also trialled on an example batch exercise provided by ICI. An extract from the documentation of the exercise, showing the proposed method for handling the consideration of operating states and transitions, is provided below. Fig. 6.6 shows the flowsheet for the process.

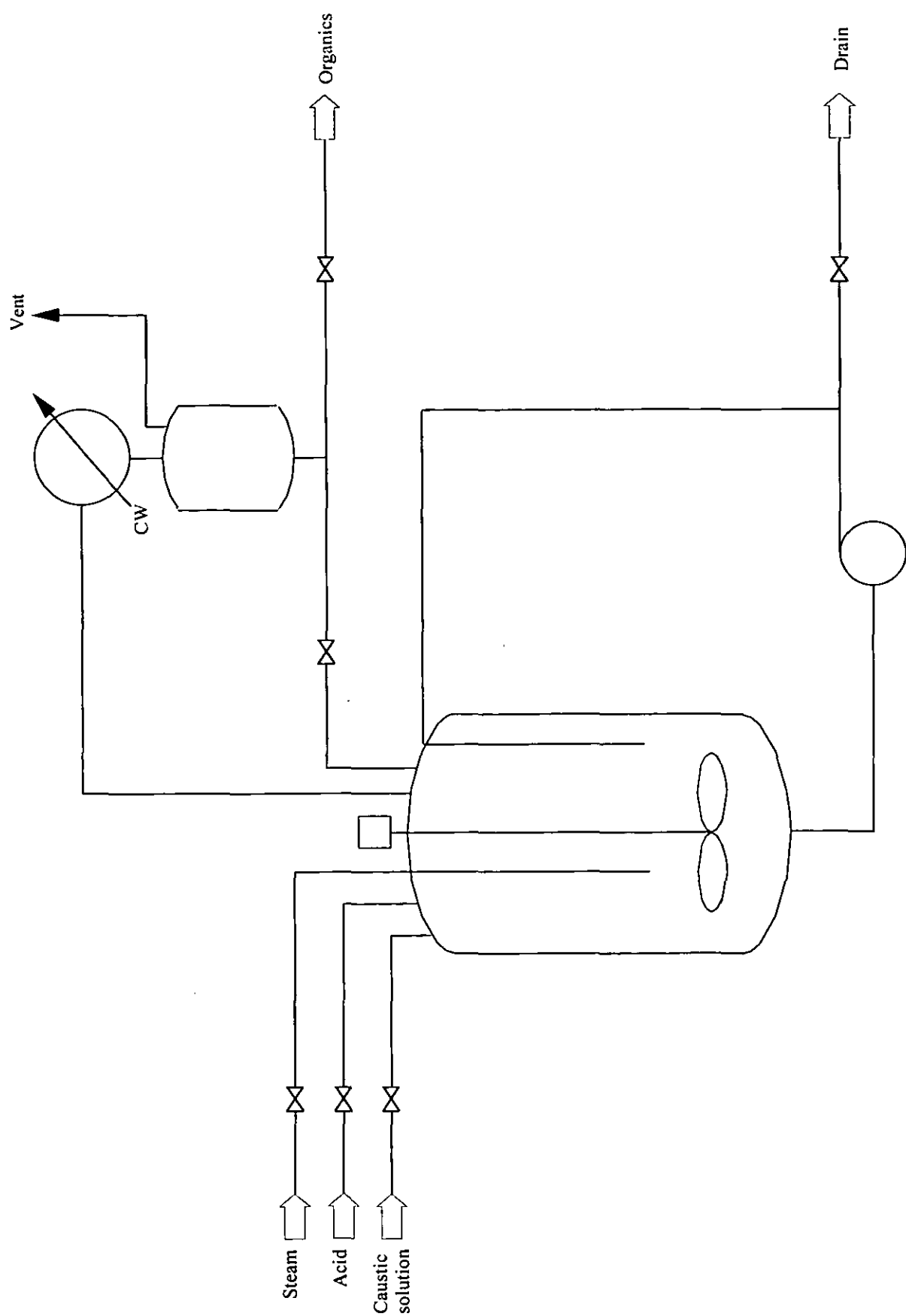


Fig. 6.6 - Flowsheet for batch example

6.3.1 Application

Summary process description

The process consists of a batch neutralisation and stripping operation on a byproduct effluent stream. The effluent is an aqueous acid stream containing dissolved acid-soluble and free-phase organics. The organics concentration is too high to allow the effluent to be sent to drain - hence the requirement for stripping.

Batches of effluent are to be neutralised by the addition of caustic. The neutralised liquid will then be steam purged to remove the organics which have come out of solution. Following this, the organics are condensed and collected in water to form a two-phase liquid (because the organics are not water soluble). The water is returned to the batch pot. The organics are recycled or collected for disposal. The neutralised acids are sent to further effluent treatment.

Since a key part of batch process design revolves around the sequencing and scheduling of the various operations which must be performed, the emphasis in applying the methodology to a batch process example was on control and operability. The extract of the output from this exercise shown below therefore focuses on the control strategy for the batch process. As before, the thought prompt with its corresponding explanation is quoted directly from the methodology and followed by the response, which is presented in the format described in section 5.5.3.

Methodology

Thought Prompt	Explanation	Interactions
1.18 Control strategy	What are the main identifiable operating states (e.g. production, standby, shutdown, cleaning) at which the plant must be controlled and what transitions are required between these operating states? (See appendix E*) What is the primary controlled variable for each major item of equipment?	People: Control engineer Steps: 22-24 Parallel Studies: Scheduling

* Not included here

The first and most important step in the consideration of control in the methodology is to define the identifiable operating states and transitions for the process. This is best done using a diagram such as the one shown in fig. 6.7. Tables showing the distinct control states and outline operating transitions (Tables 6.1 and 6.2 respectively) can then be produced.

Operating states / transitions

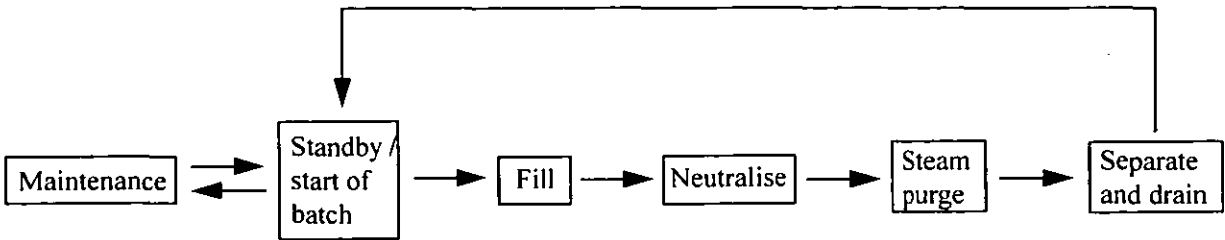


Fig. 6.7 - Operating states / transitions for batch exercise

Table 6.1 - *Control states*

Control states	maintenance	standby	fill	
			add caustic	add acid
steam	off	off	off	off
effluent	off	off	off	on
caustic	off	off	on	off
agitator	off	off	off	on
cooling water	off	on	on	on
pump	off	off	off	on

Control states	neutralise	steam purge	separate and drain
steam	off	on	off
effluent	off	off	off
caustic	off	off	off
agitator	on	on	off
cooling water	on	on	on
pump	off	off	on

Table 6.2 - *Transitions*

Transition	Actions
standby to fill	<ol style="list-style-type: none"> 1. Analyse acid concentration upstream 2. Add caustic 3. Switch on recirculation pump 4. Switch on agitator 5. Add effluent
fill to neutralise	<ol style="list-style-type: none"> 6. Check pH 7. Adjust pH as necessary
neutralise to steam purge	<ol style="list-style-type: none"> 8. Add steam for time t 9. Sample for organics 10. Repeat purge if necessary
steam purge to separate and drain	<ol style="list-style-type: none"> 11. Turn steam off 12. Drain organics from separator 13. Turn agitator off 14. Drain batch vessel: <ul style="list-style-type: none"> - open drain valve - shut off pump recirculation valve
separate and drain to fill	<ol style="list-style-type: none"> 15. Shut drain valve 16. Drain water from separator into reactor 17. Repeat as for standby to fill

6.3.2 Points of interest

- By analysing the control and operability problem in this way, the difference in the nature of the problem for batch plants and for continuous plants is highlighted. Batch plants are effectively always in transition - there are no clearly definable 'steady' operating states. Meanwhile continuous plants tend to be viewed as a series of steady states, with transitions considered separately as a means of moving from one steady state to another. A conclusion which can be drawn from this is that control for batch process is actually less complex to handle using the methodology than control for continuous process. Since there is no distinction between operating states and transitions, the operating requirements are easier to define and understand.

6.4 'Real-life' example

A final trial of the finished methodology was carried out on a 'live' project at ICI. Though the details of this application cannot be given, some of the feedback generated from this trial is summarised below.

Key observations

- Application of the process plant and materials section at level 1 did not raise very many new issues. This is because the team's work had largely focused on the steady-state operation of the process. In addition, this level of the method was probably applied too late to be of much use - it would have been appropriate a few months previously. However it was found to be a useful way of getting people new to the project up-to-date with the technology and the outstanding problem areas.
- Application of the process plant operation section resulted in a completely different response. The team had not given much thought to control or to any state other than production. In particular, they had not considered how the plant would interact with the upstream plant supplying feedstock. There was no consensus in the group on these issues.
- The section on failures also raised several important issues.
- Application of level 2i of the methodology could not be carried out as effectively as it relies on the issues raised at level 1 having been resolved. This was not possible in the limited time available. Consequently, it was only possible to apply the first two sections of level 2i. However, the team did end up with a reasonably marked up flowsheet ready for conversion to a notional ELD.
- As the meeting progressed from an area in which the project team were confident in their work to one in which they lacked consensus, the methodology prompts were generating debates rather than just 'yes / no' answers.

Comments made by the team

- The form of the methodology supplied is too wordy for application in the design project environment - it is difficult to find the key points and hence is particularly difficult to use as an introductory document.

- It was difficult to look at the interactions throughout the exercise.

It is not easy to discern whether it was the method which helped the project team or whether the outcome was just the result of bringing experienced people together to debate and discuss the design at length. However, it can be said that somewhere in the region of fifty actions were generated as a result of working through the first half of the methodology and that the team, particularly those on the operations side, were persuaded by the general principles of PREMIUM.

6.5 Conclusions

Methodology

- The methodology works well when applied to both batch and continuous process design.
- The methodology is useful in the context of the company design project.
- Some changes to the length and format of the methodology would be required to adapt it for routine commercial use.

Records

- Tables are an effective way of recording the actions and key comments generated by the thought prompts in the methodology but there is still a difficulty in persuading people to record sufficient explanations in support of their decisions.
- Diagrams provide a complementary vehicle for recording information because they make it more obvious to the designer how each change made can affect the surrounding process. If a change is made early in the application of the methodology and is recorded on the appropriate diagram then it is easy to see where it affects decisions which come under other prompts. The designer is less likely to make the connection if the change is only recorded in a table.

Points of interest

- There is a mindset that it is too late to influence the inherent safety of the design at the ELD development stage.
- The rigorous treatment of the subject of control is a key feature of the methodology and can significantly contribute to improved operability and more optimal design.
- Using the methods for handling operating states and transitions proposed in the methodology, it appears that defining the control requirements for batch processes should be far more straightforward than defining those for a continuous process. The general improvement in understanding should help to facilitate better development of operating instructions.

CHAPTER VII - DISCUSSION

7.0 Introduction

In the preceding three chapters, the generation, composition and application of a methodology which provides a systematic approach to the development of ELDs from process flowsheets have been presented. This chapter aims to discuss how this overall methodology and its constituent parts reflect the concepts which have been acquired or created through the course of this research.

Section 7.1 begins with a re-iteration of the reasons for the generation of a methodology for process flowsheet to ELD development.

Section 7.2 describes how important concepts taken from the literature have been used to shape the methodology.

Section 7.3 discusses the new concepts which have arisen in the course of the research and the manner in which these have also been incorporated into the methodology.

Section 7.4 compares the new methodology which has been developed with existing methodologies in the fields of conceptual process design and inherent SHE.

Section 7.5 summarises the key strengths of the new methodology.

7.1 Reason for Generating Methodology

The introduction to this thesis outlines the concepts of the hazard and operability study and of other hazard studies. It highlights their particular strengths and weaknesses and explains why they should not be relied upon as the only formal and systematic method for handling SHE issues in detailed process design. As Skelton writes, safety in design must be addressed both

proactively and reactively (Skelton, 1997). This means that as well as being considered at specific decision points such as reviews, safety must also be used as a continuous driver in design. This point is stressed by Koivisto (1996 - see section 2.2.1). The same is also true for health and environmental issues.

If SHE issues are to be taken into account continuously throughout the design process, then a fuller understanding of the various activities contributing to design and of the connection between these activities is required. As Chandrasekaran (1990) writes, “the key to understanding design is to understand the structure of the task, and how the tasks, methods, subtasks and domain knowledge are related”.

The Douglas (1985) methodology articulates the decisions and activities involved in conceptual process design, providing a systematic approach to the evaluation of the process. Such an approach is considered by Wells (1980) to be a key requirement for the proper consideration of safety in a chemical plant throughout the different stages of design. However, when it comes to the detailed process design stage, there is no such methodology which captures the logic and the order in which decisions for developing a first ELD should be made. Reasons for this might include:

- a fear of destroying creativity by systematising design
- the difficulty in producing a model which is compatible with the nature of this part of the design process
- a general lack of interest or motivation for developing the subject further.

This lack of methodology meant that it was first necessary to create a methodology for the systematic generation of ELDs in order to be able to develop a proactive approach to the consideration of SHE issues in detailed process design. The objectives in creating this method are described below.

7.1.1 Methodology Objectives

Combining the key characteristics taken from the literature (see section 2.4.1) with those deemed important as a consequence of the preliminary research, the following list of objectives for a sound methodology for detailed process design was devised:

- encourage creative solutions
- integrate all the design activities including process engineering, control engineering, mechanical engineering, safety engineering
- permit a 'natural' way of incorporating the use of computers in decision-making and knowledge storage and retrieval
- be appropriate for any scale of project and any type of project
- fit in with conventional project procedures
- be supportive without being prescriptive
- complement existing hazard study systems and other reviews
- be sufficiently rigorous to merit widespread use.

7.2 Existing Concepts Incorporated

Referring back to the literature review, there are many important concepts highlighted by the various authors which can contribute to the realisation of the objectives outlined above. The manner in which each of these concepts has been incorporated into the methodology is described in the paragraphs which follow.

7.2.1 Knowledge Use

Recalling the research of Silverman & Mezher (1992) on different forms of knowledge and the problems of misconceptions and missing concepts, we have learnt that one of the most significant misconceptions in detailed process design is that of the steady-state mindset. This is a problem highlighted by Roodman (1982 - ref. section 2.1.3) who believes that an outline preliminary operating guide and start-up and shutdown sequencing plans should be prepared to enable a complete flow diagram to be drawn. Not only does the steady-state mindset have a

detrimental effect on design for operability of continuous plant, but it is also completely inappropriate for the design of batch plant.

The new methodology which has been generated endeavours to overcome this steady-state mindset in many ways. The most powerful of these is the manner in which plant operation is defined: as a series of equally important control states and transitions. For a continuous plant, the control states are clearly distinguishable from the transitions and a significant proportion of time is spent in one control state (i.e. production at steady state). In order to discourage the designer from placing too much emphasis on this one control state, the methodology is structured so that equal attention is given to all control states and transitions. Since batch processes are constantly in a state of transition, there is no equivalent mindset to be overcome. The concept of handling control and operability in this way is revisited in section 7.3.

Other measures which contribute to improved design for operability are the recommendations on parallel studies and on interactions with other disciplines, and the use of the global PFD to ensure continuity between the separate ELDs which constitute the complete design. The emphasis on parallel development of procedures with the engineering drawings is particularly important in the design of batch plants and the methodology ensures that these are dealt with systematically.

Another concept which can contribute to better use of the designer's knowledge is the recording of the design history. By recording the key issues and decisions made during the application of the methodology in a table such as that given in table 5.2, continuity of the design at each successive level of detail can be achieved and mistakes due to memory lapse avoided. The notes taken will also be useful for bringing newcomers to the project up-to-date on the issues which have already been explored. Other benefits include the following:

- saving time in future designs
- helping to avoid past mistakes
- helping to prevent disasters caused by modifications to existing plants
- improving management of uncertainties, assumptions and constraints.

A recurring problem famously highlighted by Kletz (1991) is that engineers “do not know what they do not know”. This is an example of a ‘missing concept’ as defined by Silverman & Mezher (1992). Such designer errors could be minimised through:

- better training to make people aware of when they should consult experts
- use of formal procedures to prevent rash decisions
- a culture of better communication - encouraging people to ask questions and to volunteer information beyond the obvious immediate response.

The methodology should contribute to the reduction of this type of error by providing comprehensive guidance on the concepts relevant to each step and by indicating where it might be necessary to consult engineers from other disciplines in order to make use of their expertise. At a more detailed level, the work done on specific topics such as heat tracing and insulation can also help the designer to focus on the correct forms of knowledge.

In summary then, the methodology and its associated application tools enable us to proactively influence knowledge use. They focus the designer on the correct knowledge, they support him by the provision of overlooked and missing knowledge and they help him to eliminate the irrelevant knowledge.

7.2.2 SHE Issues

As indicated in section 7.1 above, the hazard study system for assessing process safety needs to be complemented by a proactive safety system in order to form a complete approach to the consideration of safety issues in design. The methodology described in this thesis is an example of such a proactive safety system. It provides ongoing support in the consideration of safety issues through the use of both direct and indirect measures as described below. Alongside the safety issues, health and environmental aspects are also addressed.

Direct measures for improving consideration of SHE and loss prevention issues are focused on the use of thought prompts to highlight the objectives underlying ‘basis of safety’ and ‘basis of environmental protection’. These objectives are used as drivers in the methodology

(ref. thought prompts for first objective - safety, health and environmental proficiency). They are supported by option charts for pollution prevention / waste minimisation and inherent safety / user friendly plants. References to the probability of conflicts between inherent safety and environmental objectives, the possibility of using equipment such as valves and vents to achieve multiple functions and so on are also incorporated.

Aspects of the methodology which contribute indirectly to the improved consideration of SHE issues include:

- tools for recording the issues raised and the decisions made during application of the methodology
- the measures taken to address interactions:
 - across different drawings
 - between different disciplines
 - between different steps in the method
 - between parallel design activities
- comprehensive treatment of operability through designation of operating states and transitions and again through linking the methodology steps to parallel design activities.

All these measures help to support the designer by encouraging an ongoing awareness of the consequences of the decisions made - a concept which Koivisto (1996) believes to be key to the improved consideration of safety in design.

7.3 New Concepts

During the course of the research into the activities contributing to process flowsheet to ELD development, a number of new concepts arose. Probably the most significant of these was the concept of intermediate representation: the development of the design in terms of functions before equipment solutions are ascribed. Other important new concepts include:

- the approach to handling process plant operations
- the use of a combination of diagrams and tables for recording the information generated with each thought prompt

- the incorporation into the methodology of links to parallel design activities and to key disciplines who should be involved
- the provision of ‘detailed analysis’ documents to support the methodology at a practical level.

7.3.1 Intermediate Representation

The idea of intermediate representation can be considered to be an extension of the concept raised by Hill (1968), as discussed in section 4.2.2. It also reflects the approach taken by Takeda et al (1990) who consider the general design task to be a mapping from the function space to the attribute space (ref. section 2.1.2). A similar point on the dangers of fixing the design too early is made by Douglas (1985) with reference to the exploration of alternatives during conceptual design (ref. section 2.1.1).

Initially, the research on intermediate representation focused on the generation of new generic symbols to facilitate the expression of design intent and on the grouping of potential candidates for intermediate representation (pressure relief, reverse flow prevention equipment, isolations, etc.) into certain categories depending on their characteristics. A paper which was written on this topic is included in appendix E1. It soon became apparent, however, that the introduction of more symbols and formalities into a system which is already swamped by different standards and different procedures would be completely inappropriate.

Intermediate representation is intended to be a transitional measure to help the design team to understand the intent of the design. It is therefore not necessary for the methods used to convey the intent to be universally understood. Since there is so much confusion over symbols, with many companies using in-house standards (ref. section 3.1) and even these varying between different parts of the same company, it was decided that it would be better to allow each design team to develop their own approach to representing design intent. This might simply mean writing notes on the drawing, or might take on a more structured form, for instance if the team members speak different languages.

Intermediate representation is reflected in the application of the methodology through the 'global' PFD. This is used to generate an overall picture of the salient safety and operability features of the design in a very short space of time. This drawing should not be annotated with general comments. It should include only names or some other chosen symbols to show how the design is intended to be progressed in terms of the features specified in the definition (given in the methodology) and how these features of the process interact. By eliminating the need to stop to consider the detail of the hardware required to achieve these intentions, the development process is accelerated. The designer is not forced to provide specific (hardware) solutions to problems without knowing all the possible interactions with neighbouring items of equipment. The global PFD becomes a reference document to allow the design team to check for continuity across the component ELDs through successive levels of application of the methodology.

7.3.2 Operating States and Transitions

As mentioned previously, the process flowsheet or flow diagram is usually identified with the presentation of heat and mass balances or of the steady-state process objectives. Such descriptions are only really appropriate for continuous plants which operate at a dynamic equilibrium. Batch plants have no identifiable steady-state, so their process flowsheets must be defined in terms of some other parameter. The new concept developed to encourage the designer to see beyond this steady-state mindset is that of a set of equally important operating states and transitions. The logic behind this concept was described in section 7.2.1 and a demonstration of the proposed tools for handling the consideration of operating states and transition was given in section 6.3.1.

7.3.3 Information Handling

Good information handling must be a fundamental part of good design. Because the design process involves so many different people, and so many different types of information are generated, it is not possible to carry out the design without some sort of formal system for information handling. Such a system should ensure consistency and completeness in design.

Unfortunately, as the survey results (ref. section 3.1) indicated, the current approach to information handling lacks system and structure.

One type of information that is particularly poorly managed in current process design systems is that encompassing assumptions, uncertainties and constraints. Design engineers are very good at recording what they do know (i.e. certainties) and very poor at recording what they do not know (i.e. assumptions and uncertainties). Consequently, designs may often progress to quite a detailed level based on assumptions which have not been properly thought out, or on uncertainties which should have been resolved much earlier. It is this tendency for ‘putting off’ addressing the difficult issues (and not recording the fact) that can lead to late, and costly, changes in design.

The new concept related to this issue was to use the methodology framework as a basis for a structured and methodical recording system. By noting key design issues and decisions alongside the appropriate thought prompt under which they were discussed, a complete, consistent and traceable record of the design progression can be created. Used in conjunction with the written records on drawings, this system can make a powerful contribution to the improvement of continuity and awareness of consequences in design.

7.3.4 Interactions

As well as contributing to the improved recording of design history, the methodology framework provides a means of incorporating information on the various interactions between people and activities which should take place in the course of the design. The types of interactions covered are:

- links to parallel studies
- suggestions for involvement of other engineering disciplines in the decisions to be made
- indications of where the issues and decisions considered under one thought prompt might affect some of those which will be considered under another thought prompt.

The representation of the first two sets of interactions in the methodology is relatively satisfactory in terms of application. The manner in which the third set, interactions between

the different thought prompts, is presented makes them a little difficult to follow in practice. The idea of presenting the interactions in terms of words rather than numbers was considered, however it was felt that this would detract too much from the main focus of the thought prompts. A decrease in the number of interactions presented was also considered in order to improve usability, but it was decided that from the point of view of the research all possible interactions should be represented in the methodology for completeness.

7.3.5 Detailed Analysis

The concept of ‘detailed analysis’ was introduced in order to link the theory of the methodology to the practice of making specific design decisions. While the methodology details the theory of the order in which decisions for developing a first ELD should be made, it makes no attempt to explain how these decisions would be reached in practice. At the more conceptual end of ELD development this lack of decision support is not too important as it is often the case that one factor will noticeably outweigh all others, or that the choice is governed by company preference or policy. Under these conditions, a decision can be made quite easily by an experienced engineer without any support. A less experienced engineer could probably cope equally well given a limited amount of information on the advantages and disadvantages of the proposal under consideration.

At the more detailed levels of line diagram development, however, there will often be a number of factors having less clearly distinguishable weightings. In this case a more structured form of decision support would be useful in helping to choose the most appropriate solution. The detailed analysis documents compiled in the course of the research (ref. section 5.6) seek to provide such structured decision support. The nature of the support provided was described above in section 7.2.1.

7.4 Comparison with Other Methods

The methodology which has been produced is both hierarchical and iterative in nature. The use of a hierarchical approach follows the example of both Douglas (1985) and Pohjola et al

(1994). Meanwhile the incorporation of iteration reflects Silverman & Mezher's (1992) observations that process design is an iterative sequence of 'generate / test / refine / remember' steps.

The methodology combines both procedural (i.e. 'what to do') and declarative (i.e. 'what to achieve') knowledge as does that of Pohjola et al (1994). Each decision level is not supported by heuristics but by a series of objectives broken down into thought prompts with suggested issues and activities for consideration. This framework helps to ensure that the methodology is supportive without being prescriptive or restrictive. The methodology is intended to be applied in a breadth first manner in order to avoid errors which can occur through fixing the design too early, as alluded to by Douglas (1985) in the context of the process flowsheet. The use of intermediate representation in the form of the global PFD also contributes to maintaining a focus on the overall problem at all times.

Good handling of assumptions, the importance of which is emphasised by Douglas (1985), is encouraged through the structured recording tools proposed. Meanwhile, attention to the consequences of each decision is encouraged through:

- the consideration of interactions across each of the constituent ELDs
- the consideration of interactions associated with each of the thought prompts in the method.

Maintaining an awareness of the consequences of each decision made is of particular importance in developing safe designs (according to Koivisto, 1996) as mentioned earlier (see section 7.2.2).

While Tanskanen et al (1995) use control, profit and safety as drivers in their extension of Pohjola's methodology, the PREMIUM methodology focuses on safety, health, environment and quality as drivers, complemented by a considerable amount of emphasis on consistency / continuity and interactions, which also contribute significantly to the operability of the design. Since economics tend to be at the forefront of the designer's mind and there are a number of methods already available for analysing this aspect of design, profit is not explicitly included as a driver in the new methodology.

The approach to the handling of SHE issues bears some resemblance to the tool proposed by Mansfield et al (1995). The PREMIUM methodology is similar in that it is intended to help the design team to:

- identify potential hazards / problems
- provide options (in the form of charts) for solutions to these problems
- contribute to decision support through the detailed analysis documents.

7.5 Strengths of the New Methodology

The PREMIUM methodology articulates the order in which decisions for developing a first ELD should be made. In doing so, it provides a distinct framework which can be used to enhance many different aspects of the process flowsheet to ELD design process. The following are perceived to be the main strengths of the PREMIUM methodology:

- it helps the designer to establish what he does / does not know about the design
- it makes the designer aware of the assumptions and uncertainties upon which the design is based
- it allows the designer to trace back through each level of detail of the design to see what issues were raised under a particular thought prompt and what actions should have been completed
- it encourages parallel development of the process description and operating instructions which is key to effective design, particularly for batch processes where the ELD is generally not very informative
- it encourages better communication between the different engineering disciplines
- it offers a proactive, team-based approach to the consideration of SHE and operability issues
- it provides a consistent, efficient and effective approach to ELD development.

Overall method

The new methodology, in providing an explication of the order in which decisions for developing a first ELD should be made, with supporting information on pertinent design issues and activities, represents a useful tool for teaching the design process to new graduates.

Thus the methodology can be used to help meet the desire, expressed by PREMIUM survey respondents (see section 3.1), for formal training in process flowsheet to line diagram development.

Uncertainties, assumptions and constraints

Given a 'free reign', the tendency of the designer would most likely be to work on design problems he is comfortable with and can easily solve first. The methodology deliberately steers the design team towards uncertainties in the design since, in general, it is these that are most likely to cause problems as the design progresses.

Recording

Management of uncertainties, assumptions and constraints and recording of design reasoning are areas in design which raised considerable concern amongst respondents to the PREMIUM survey (ref. section 3.1). The recording methods proposed as a part of the new methodology should improve this information management. These recording methods are likely to be particularly useful to contractors as they provide a means of justifying the design to the customer. The records should also enable project team members to quickly learn or recall previous work done on a project in the event of team changes or project time delays, or if modifications are required to an existing plant.

Interactions

The methodology addresses both software and hardware solutions to the design problem, in parallel, by use of the interactions prompts. This is important because the software and hardware elements of a design should work together, not in isolation. For instance, in some cases, software solutions such as operating procedures might be safer if they were complicated less by engineered solutions such as interlocks and alarms. In other cases, such as in the use of trips, a co-ordinated approach may be required to ensure that there are adequate management procedures to prevent their actions being compromised, for instance by disarming or failure to reset. The current approach to design is not sufficiently structured to ensure that this issue is handled effectively.

The methodology ‘interactions’ prompts are also used to remind designers that there may be specialists in other disciplines who can help to provide a more optimal solution to a particular problem. In this way, the methodology endeavours to improve communication between different engineers, thus addressing a significant problem highlighted during the task analysis work (see section 3.3.1).

SHE

Kletz (1996) believes that companies have been slow to adopt inherent SHE principles because a fundamental change in the design process would be required to accommodate the systematic study of alternatives during the early stages of design. The research carried out for this thesis shows that most designers think that it is too late to influence the inherent safety of design at the process flowsheet to ELD stage (see section 6.5). The new methodology framework allows the consideration of alternatives to be continued throughout the detailed process design stage when it is still not too late to incorporate inherent SHE features. This is done in a team-based development environment which encourages the designers to produce solutions which are optimal from the point of view of all contributing disciplines, not just their own.

Koivisto (1996) cites the lack of tools and methods for handling safety proactively as a further contributing factor to industry’s reluctance to adopt inherent SHE principles. The act of systematising the design process and co-ordinating the drawing development with other contributory design activities in itself provides a method for improving consideration of inherent SHE principles as well as process operability. The key components of the methodology which make this possible are:

- the first two objectives of each level: ‘Safety, health and environmental proficiency’ and ‘Quality’
- the charts for inherent SHE / user-friendly plants and pollution prevention / waste minimisation
- the memory prompts alongside each thought prompt
- the interactions prompts alongside each thought prompt
- the proposed working and recording tools.

CHAPTER VIII - CONCLUSIONS

Safety in Design

The existing approach to handling safety, health, environmental (SHE) and operability issues in process plant design is incomplete. Reactive methods, such as the HAZOP and other hazard studies, are relied upon to check the design for acceptance with regard to these issues. However, there are no methods in place which proactively influence the SHE and operability features of the design as it is generated. Past experience is relied on heavily to achieve good standards of design with regard to these features.

The need for such proactive methods to influence the manner in which the design is developed in terms of SHE and operability is particularly acute in the realm of detailed process design, when engineering line diagrams (ELDs) are created from process flowsheets. A full understanding of the activities and issues contributing to this part of the design process is required before any attempt can be made to generate such a method. The method will not only drive the development of the design in terms of SHE and operability, but it will also provide a means of increasing the rate at which experience can be acquired.

Line Diagram Design

Though methodologies exist in the literature on the subject of conceptual process design, the number of authors attempting to document the task of detailed process design is minimal. In fact, there is only one text which addresses this task, and it does so in quite a superficial manner.

The key to generating a design method which proactively influences the SHE and operability features of the design lies in understanding knowledge use. Identifying how the different types of knowledge - 'irrelevant', 'correct', 'overlooked' and 'missing' are reflected in the

detailed process design task and how the problems of misconceptions and missing concepts can be overcome, has led to the foundation of a new methodology.

Current Practice

A survey of current practice in line diagram development confirmed that the existing approach seems to be rather haphazard. Task analysis showed that in particular, there is a problem in achieving good communication between the different disciplines forming the design team and in recording the design development information adequately.

Development of a Method

The objectives to be met in generating a new methodology for line diagram development were the following:

- encourage creative solutions
- integrate all the design activities including process engineering, control engineering, mechanical engineering, safety engineering
- permit a 'natural' way of incorporating the use of computers in decision-making and knowledge storage and retrieval
- be appropriate for any scale of project and any type of project
- fit in with conventional project procedures
- be supportive without being prescriptive
- complement existing hazard study systems and other reviews
- be sufficiently rigorous to merit widespread use.

Using these objectives and the information collected on knowledge use and SHE and operability issues in design, the PREMIUM methodology was generated.

Structure of the Method

The PREMIUM methodology is both hierarchical and iterative in nature. It combines procedural ('what to do') and declarative ('what to achieve') knowledge, using thought prompts supported by explanations to convey the necessary information. The thought prompts are grouped to form a series of design objectives.

The PREMIUM method captures the logic for and articulates the order in which decisions for developing a first ELD should be made. In doing so, it provides a framework which can be used to incorporate SHE and operability issues. These issues are addressed both directly and indirectly. Direct measures include:

- the use of thought prompts to highlight the objectives underlying 'basis of safety' and 'basis of environmental protection'
- the provision of option charts for solutions to the problems of pollution prevention / waste minimisation and inherent safety / user friendly plants
- references to the probability of conflicts between inherent safety and environmental objectives
- references to the possibility of using equipment such as valves and vents to achieve multiple functions and so on.

Meanwhile indirect measures comprise:

- tools for recording the issues raised and the decisions made during application of the methodology
- facilities for addressing interactions:
 - across different drawings
 - between different disciplines
 - between different steps in the method
 - between parallel design activities
- comprehensive treatment of operability through designation of operating states and transitions and through linking the methodology steps to parallel design activities.

All these measures help to support the designer by encouraging an ongoing awareness of the consequences of the decisions made.

Trials

Three trials of the methodology have been carried out. The first of these took the form of a ‘Masterclass’, applying the methodology to a continuous process with senior engineers from ICI. The second was a trial on a batch example, performed by members of the PREMIUM project team. The third entailed applying the method to a ‘live’ project at ICI.

Feedback from all three trials was positive. Participants in the live trial were particularly impressed with the improvements in handling operability brought about by application of the methodology.

Concluding Remarks

The PREMIUM methodology serves two purposes:

1. It fills the gap in the literature associated with the capture of the logic and the order in which decisions for developing a first ELD should be made
2. It provides a systematic and practical tool for the proactive consideration of SHE and operability issues in detailed process design.

The strengths of the PREMIUM methodology are as follows:

- it helps the designer to establish what he does / does not know about the design
- it makes the designer aware of the assumptions and uncertainties upon which the design is based
- it allows the designer to trace back through each level of detail of the design to see what issues were raised under a particular thought prompt and what actions should have been completed

- it encourages parallel development of the process description and operating instructions which is key to effective design, particularly for batch processes where the ELD is generally not very informative
- it encourages better communication between the different engineering disciplines
- it offers a proactive, team-based approach to the consideration of SHE and operability issues
- it provides a consistent, efficient and effective approach to ELD development.

CHAPTER IX - FURTHER WORK

There are three significant areas in which the research could be taken further. The first of these is concerned with improving the interface which is used to present the methodology. The second is the continued development of the detailed analysis documents. The third is to incorporate cost issues into the methodology.

Improving the interface

When the methodology was trialled on the live design project at ICI (see section 6.4), a 'condensed' version of the objectives and thought prompts was used. This was because the 'full' methodology contains too much information to be assimilated and used in a short space of time. If the methodology is to be applied within industry as a team-based development tool, then a suitable reduced format needs to be developed. This could eventually be presented on a computer, perhaps with links to a project database which can be called up in support of the discussions which take place. The ICI members of the project team are intending to work on the generation of a suitable interface for repeated, team-based application.

Detailed Analysis

As indicated by tables 5.6 and 5.7 shown in section 5.6, the number of subjects touched upon as part of the research on 'detailed analysis' is small. There are many more design problem areas which could benefit from being handled in this way. Examples are listed in the aforementioned tables. The information produced could then be used to compile a database for decision support. This, in turn, could be linked into the management system supporting the methodology to ensure that designers do consult the database when appropriate.

Cost issues

In the discussion (section 7.4) the reasons for not including cost issues explicitly in the PREMIUM method were quoted as the tendency for economics to be at the forefront of the designer's mind and the existence of a number of established methods relating to this issue. Although costs were not the priority for this research, there is no reason why they should not also eventually be represented within the methodology framework. Further work should therefore be done to ensure that the methodology fits with existing approaches to costing and to incorporate cost issues where appropriate. An analysis of the short-term benefits of 'add-on' safety, health and environmental equipment versus the long-term benefits of inherent SHE features should be included.

Miscellaneous

Other recommendations for smaller projects include the following:

- develop a new definition of the ELD in terms of user objectives
- consider the incorporation of the annotation used by the ICI engineer in the Lawley design exercise (see appendix B2 part 2) into the recommended methods for recording design
- consider incorporating descriptions of 'function', 'problems solved' and 'problems caused' for each equipment addition proposed
- improve the representation of design interactions.

On a general note, it can be said that now a framework for understanding and structuring the detailed process design task exists, there are numerous possibilities for using it as an interface to other design systems. An example would be using the framework as a means of accessing expert systems.

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APPENDIX A1 - PREMIUM SURVEY AS PUBLISHED IN 'THE CHEMICAL ENGINEER'

This survey has been developed as a part of the PREMIUM (Process Risk Evaluation Methodology) project, which is a collaborative research project between Loughborough University and ICI focusing on the development of engineering line diagrams (ELDs) from process flow diagrams (PFDs).

The survey is designed to confirm or refute perceived problems in post-flowsheet design procedures, and to assess interest in this subject as a whole. Individual responses will be treated confidentially, but an analysis of the results will be published in *TCE* at a later date.

The aim of the PREMIUM project is to develop a formal methodology to aid in this part of the design process, which will improve the safety and consistency in designs and lead to a more comprehensive record of important reasoning and decisions

leading to the final design. This, in turn, should lead to fewer modifications at the Hazop stage and should contribute significantly to corporate memory.

For the purposes of this questionnaire:

- a PFD is defined as a diagram sufficient for establishment of "normal" heat and mass flows (as a minimum requirement);
- an ELD is defined as a diagram sufficient to provide for all process requirements (including, for example, pressure relief, sample points and drains).

This questionnaire needs only a few minutes to complete. Partially completed responses are welcome. Please continue any written answers on a separate sheet, if necessary, quoting the question number.

Name of respondent: _____

Title and organisation: _____

Contact address: _____

Tel: _____

Fax: _____

Email: _____

Please tick the appropriate box

1. Within my organisation, the source of process flow diagrams (PFDs) for development to engineering line diagrams (ELDs) is:

	All	Most	Few	None
Internal	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
External	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
No formal PFDs produced	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

2. Within my organisation, a formal, up-to-date PFD is maintained in parallel with the ELD: .

☐ Yes ☐ No ☐ Sometimes

3. Within my organisation, the following information is already shown on the PFD, rather than being added at the ELD stage:

	Yes	No	Sometimes
Immediate storage	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Principal control loops/control philosophy	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Duplicated equipment (major: reactors, HEX)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Duplicated equipment (minor: pumps, valves)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Multiple streams	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Utilities lines	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Isolation valves	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Pressure relief	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Hardware associated with start-up, shutdown, decontamination and maintenance	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

4. Within my organisation, expertise in the development of line diagrams (see note 1 at end of survey) is provided by:

	Yes	No
Formal training	<input type="checkbox"/>	<input type="checkbox"/>
Company methods, procedures	<input type="checkbox"/>	<input type="checkbox"/>
Public methods, procedures	<input type="checkbox"/>	<input type="checkbox"/>
Employment of experienced personnel	<input type="checkbox"/>	<input type="checkbox"/>
On the job training	<input type="checkbox"/>	<input type="checkbox"/>
Other (specify)	<input type="checkbox"/>	<input type="checkbox"/>

5. Are you satisfied with current provision of expertise for the development of line diagrams in the following areas (regardless of whether or not they are provided by your organisation)?

	Satisfied	Not satisfied	Don't care
Formal training	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Company methods, procedures	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Public methods, procedures	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Employment of experienced personnel	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
On the job training	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other (specify)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

6. Within my organisation, the job titles or roles of the persons responsible for ELD development are:

7. Within my organisation, the job titles or roles of the people who contribute to ELD development are (please list, for example, functional and commissioning/operating staff involved):

8. Within my organisation, there is a distinction between the methods used for ELD development of batch processes and those used for continuous processes:

Agree ☐ Disagree ☐

If you agree, please specify the differences:

9. Within my organisation, the ELD is developed:

	All	Most	Few	None
By computer, using CAD tools	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Manually	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

10. Within my organisation, the following standards for ELD presentation are adopted:

BS 1553 ☐ BS 1646 ☐ BS 5070 ☐ ANSI ☐ Other (specify)

11. Within my organisation, costs and benefits are taken into account during ELD development:

Yes ☐ No ☐

If yes, please specify or give examples:

12. Are you satisfied that the completed design (including, of course, the ELD) provides sufficient record of:

	Yes	No
The base function of equipment	<input type="checkbox"/>	<input type="checkbox"/>
Multiple or ancillary functions of equipment (see note 2)	<input type="checkbox"/>	<input type="checkbox"/>
Constraints on equipment relationships (see note 3)	<input type="checkbox"/>	<input type="checkbox"/>
Design prohibitions (see note 4)	<input type="checkbox"/>	<input type="checkbox"/>
SHE /environmental requirements	<input type="checkbox"/>	<input type="checkbox"/>

	Yes	No
Reasoning leading to the design decisions	<input type="checkbox"/>	<input type="checkbox"/>
Provision for start-up, shutdown, decontamination, maintenance operations	<input type="checkbox"/>	<input type="checkbox"/>
Batch and non-steady state operations	<input type="checkbox"/>	<input type="checkbox"/>
All other aspects of the design necessary for subsequent decision-making (please specify briefly any aspects which you consider are not sufficiently recorded in your present practice)	<input type="checkbox"/>	<input type="checkbox"/>

13. Does your organisation have specific methods of making records concerning:

	Yes	No
Multiple or ancillary functions of equipment	<input type="checkbox"/>	<input type="checkbox"/>
Constraints on equipment relationships	<input type="checkbox"/>	<input type="checkbox"/>
Design prohibitions	<input type="checkbox"/>	<input type="checkbox"/>
Reasoning leading to design decisions	<input type="checkbox"/>	<input type="checkbox"/>

Please specify any similar aspects of recording for which your organisation has specific methods

14. Do you personally have specific methods of making records concerning any of the above:

Yes ☐ No ☐

If yes, please specify:

15. Supposing a written aid for line diagram development were available, which of the following formats would you prefer:

Decision trees	<input type="checkbox"/>
Matrix structures	<input type="checkbox"/>
Interactive computer programs	<input type="checkbox"/>
Index-linked reference notes	<input type="checkbox"/>
Other (ideally provide an example)	<input type="checkbox"/>
No strong preferences	<input type="checkbox"/>

16. "Capturing corporate knowledge relevant to line diagram development is not a problem in my organisation":

Agree ☐ Disagree ☐

17. "Effective use of corporate knowledge relevant to line diagram development is not a problem in my organisation":

Agree ☐ Disagree ☐

18. Are you prepared to consider undertaking a small line diagram development exercise in order to provide comparative data in support of this work?

Yes ☐ No ☐

Please send the completed form, together with any supplementary sheets, to Suella Long, Department of Chemical Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, tel 44 1509 222532, fax 44 1509 223923 by 26 July 1996.

Notes

1. The focus of this work is on aiding decision-making in engineering line diagram (ELD) development, not support for the drawing process as such. Thus, for example, company methods/procedures which exist for deciding such things as which equipment to duplicate or where to position indicators and alarms for diagnostic control would be relevant.

2. An example of a multiple function would be where an isolation valve is required for maintenance purposes, but also for

start-up. An example of a main and an ancillary function would be that a positive displacement pump is required for transfer of material, but is also incidentally relied upon for prevention of reverse flow.

3. An example of a constraint on equipment relationships would be where a pipe must enter another specifically at the top for process reasons.

4. An example of a design prohibition might be "no dead ends permitted", to prevent water collection, perhaps.

APPENDIX A2 (PART 1) - SURVEY RESPONDENT'S LINE DIAGRAM DEVELOPMENT EXERCISE

The flowsheet for the line diagram development exercise is attached.

Please complete the exercise as follows:

- Develop a Piping and Instrumentation Diagram (P&ID) or an Engineering Line Diagram (ELD)[#] from the flowsheet
- Explain your decisions on choices of equipment, location etc.
- Note down when you would negotiate with other disciplines (piping, instrumentation, operators etc.).

The exercise concerns the feed line from storage of a mixture of styrene and ethyl benzene (EBZ) to a separation unit and the styrene product line returning from the separation unit to storage.

The storage is 200m away from the separation unit. Both storage and separation have the same ground level. The feed to the vacuum distillation unit must be delivered 25m above ground level.

The control strategy for the flowsheet is as follows:

- Achieve a set flow of styrene / EBZ feed to the separation
- Achieve a set temperature of styrene / EBZ feed to the separation
- Maintain a level in the separation section by controlling the styrene product stream.

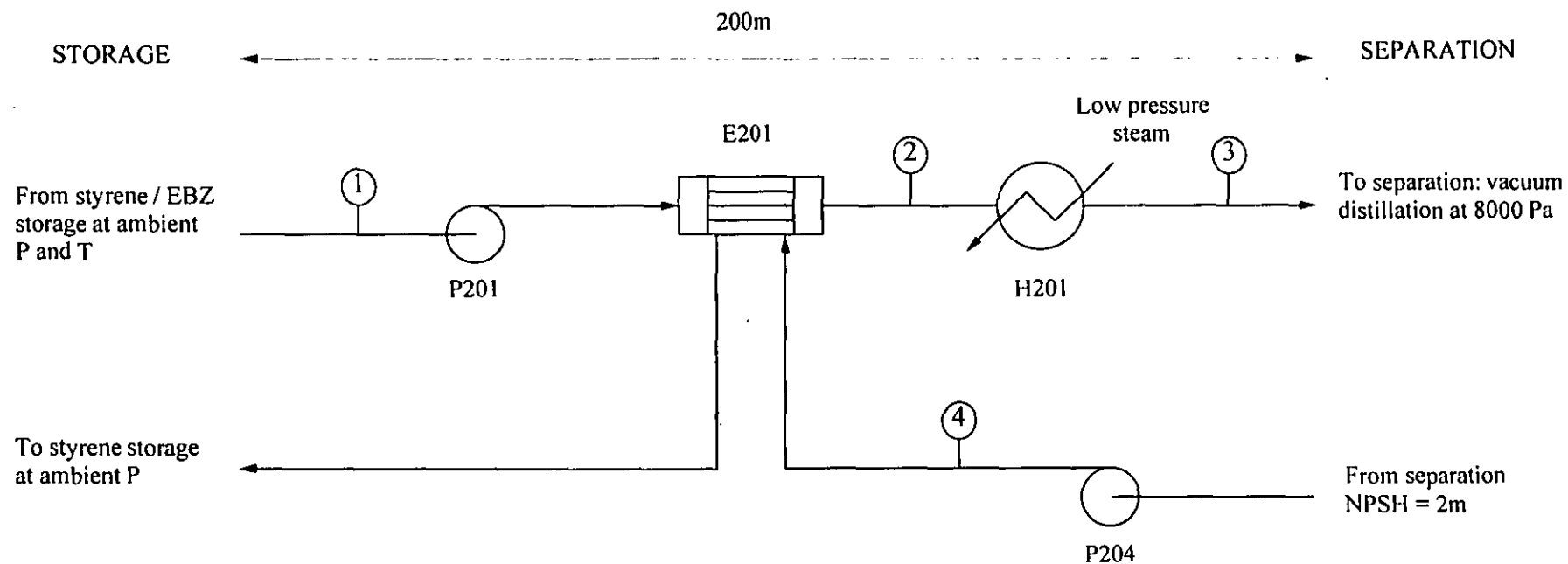
Information on the properties of styrene and EBZ is attached. [Not included in thesis]

The plant is to operate continuously and automatic control (DCS) is available.

Steam is available at 4 barg.

If something is not specified in this description (e.g. equipment details, legend sheet, main control functions) it is because we would like you to make the relevant decisions (giving reasons, sources of information and so on). If you consider that any decision would require substantial work *not* connected with development of the flowsheet into a P&ID or an ELD, please make any reasonable assumption and continue (preferably noting that the assumption has been made).

[#] Due to inconsistent definitions across the process industries we would like you to develop either a piping and instrumentation diagram (P&ID) or an engineering line diagram (ELD) depending on your understanding of the terms. Ideally you will also include in your response a specification for the type of diagram which you have produced. Where you are unable to include features which you would consider necessary for a complete diagram it will be helpful if you could list these.



Stream	1	2	3	4
Mass fraction styrene	0.577	0.577	0.577	0.999
Mass fraction EBZ	0.423	0.423	0.423	0.001
Mass flowrate (t/hr)	1.5	1.5	1.5	2.5
Temperature (C)	20	35	~60	15

EBZ = Ethyl Benzene

APPENDIX A2 (PART 2) - SUMMARY REPORT ON RESPONSES TO SURVEY EXERCISE

After the apparent initial enthusiasm towards participation in the line diagram development exercise, it was disappointing to receive only three responses. These ranged from a one page account of who is involved with each part of the design process to a 24 page detailed attempt at the problem.

Though no real conclusions can be drawn from such a limited response, a number of interesting points have arisen. The first of these is concerned with the overall approach to the design problem. One of the responses clearly takes a breadth first approach to the design with quite a staged structure for ELD development. In contrast, the second longer response seems to take a depth first approach with significant amounts of detail being given in relation to one problem before the next is addressed. The latter provides no obvious structure for the stages of line diagram development.

A second point which is immediately striking is the timing of the *HAZOP* Study. All three responses state that a *HAZOP* would be carried out on the preliminary ELD, and one specifies a further Hazard Study on the updated ELD. This contrasts with my existing understanding, based on ICI practice, that the *HAZOP* is carried out on the firm ELD, with no Hazard Study on the preliminary drawing.

Whilst all three responses demonstrate good practice in terms of early identification of hazards and their effects on safety, little attention seems to have been paid to environmental considerations such as waste minimisation and effluent treatment. In addition, none of the responses mentions quality control or consideration of transitional operations such as start-up, shutdown (except emergency shutdown) or decontamination. Although interactions with other disciplines concerning specifications, control systems and so on seem to be well established, there is no indication of where operating and other procedures should begin to be developed.

Looking at the specific problem in more detail, significant contrasts in the proposed design are immediately obvious. Firstly, the perceived risk of autopolymerisation varies tremendously from 'assumed negligible' to sufficiently hazardous to warrant changing the PFD. This demonstrates clearly that although current practice is good at raising the safety issue, there is an inherent subjectivity in its handling and resolution. This is true of most design issues.

The other contrasts in the responses are concerned with the choice and location of control equipment. One response locates the level control from the still upstream of pump P204 and exchanger E201. This is probably due to a slip while drafting the drawing rather than a conscious decision to specify this position. The other locates the level control downstream of both E201 and P204 (which have been swapped over to minimise the risk of autopolymerisation). The reason given for choosing this configuration is to prevent starving the pump of liquor.

Meanwhile, one response uses the level of the styrene / EBZ mixture in the preheater (H201) to control the amount of steam fed to the preheater. Pressure and hence temperature control can then be achieved by regulation of the vacuum on the separation process. The other response uses temperature of the mixture in the preheater to control the steam feed.

The responses do agree on the location of flow control upstream of exchanger E201 on the feed line where the flow is more stable.

A comparison of the additional proposals for control is given in table 1 below:

Response 1	Response 2
High flow and low flow alarms on feed line 1	High flow and low flow alarms on feed line 1
High temperature and low temperature alarms on feed line 3	Temperature indication on E201
High level and low level alarms on still	High temperature and low temperature alarms on H201
Pressure indication on pumps P201 and P204	Pressure indication on pumps P201 and P204
High temperature alarms on product pumps P204	Blowdown control for H201

Table 1 - Additional control proposals

In conclusion then, though only three responses (two with diagrams) to the survey exercise were received , these have raised some interesting issues concerning both the approach to ELD development and the resulting line diagram designs.

APPENDIX A3 - TASK ANALYSIS DIARY INSTRUCTION SHEET

Introduction

The PREMIUM (Process Risk Evaluation Methodology) project is a collaborative research project between Loughborough University and ICI Engineering Technology. The purpose of the project is to produce a methodology for process flow diagram (PFD) to engineering line diagram (ELD) development, incorporating the key issues of safety, health and environmental protection.

As a part of this research we need to understand how designers actually engage in the task of PFD to ELD development given their current design guidelines. In order to do this we require records of daily design activity. We would therefore like to ask you to participate in this Task Analysis Study.

We are looking to obtain the following information from this study:

- the main sorts of design activity which you undertake
- the amount of time you spend on the different activities
- your reasons for moving between the different activities
- the way you communicate in order to progress the design.

We have produced a form to help you record this information. Instructions on how to use this form are given below. The input required of you is not onerous and will not take much of your time. We ask you to try to keep this record book to hand and to keep it up to date. It will be much easier if you add the required information concurrently with your work.

When you have completed your project or used all the record sheets provided, please return this booklet in the envelope included at the back.

Instructions

The record you make must relate to one drawing, so please only make entries in the record sheets when you work on one particular drawing.

The record sheet provided is set out as follows:

Activities engaged in during design	Record	List of reasons for switching to a new activity
		List of communication actions between you and colleagues, suppliers and clients

- 1) As you start an activity, insert a bar on the record sheet in the position corresponding to that activity and time.
- 2) To the right of this bar, insert a letter from the key provided (top right) representing your reason for moving from the previous activity to this activity.
- 3) As you proceed with the activity and you need to give information to others or acquire information from others, insert a digit code from the key provided (bottom right) at the correct time to signify this.
- 4) When you finish the design activity, insert a second bar to complete the box representing the time spent on that activity.
- 5) Move on to the next activity and follow the procedure again from step one.

Example

It is 9:00am and since you arrived at 8:00am you have been working on vessel sizing, carrying on from where you left off yesterday. At 9:00am you receive a phone call from the mechanical engineer on the project who needs to know your proposed materials of construction for a particular section of the plant represented on your diagram by the end of the day. You switch from line sizing to designation of materials of construction. At 10:30am you go and speak to your in-house materials specialist about a specific design requirement that is posing some problems....

Design activities	Record				Reason(s) for starting design activities
	8 - 9	9 - 10	10 - 11	
.....					a - Continuing from yesterday
Vessel size	a				b - Need to meet a target for somebody
Venting arrangements				
Equipment design					Obtaining information
Materials of construction		b	2	
Thermal expansion of equipment					2 - Obtaining info from other disciplines
.....				

	Record								
	8 - 9	9 - 10	10 - 11	11 - 12	12 - 13	13 - 14	14 - 15	15 - 16	16 - 17
Design activities									
Elevations									
Services									
Control scheme									
Control ancillaries									
Flow fluctuations									
Reverse / excess flow prev'n									
Instrumentation									
Sample points									
Lines									
Vessels									
Venting									
Equipment									
Materials									
Thermal expansion									
Vibration									
Inventory									
Duplication / spares									
Production rate / raw materials									
Subdivision									
Bypass lines									
Start-up / shutdown									
Solid wastes									
Isolation									
Waste streams									
Inventory failures									
Pressure failures									
Temperature failures									
Other failures									
Interlocks									
Trips / alarms / emergency isol'n									
Safety equipment									
Organisational activities									
Formal meetings									
Informal meetings									
Reports									
Forms, datasheets etc.									
Reading									

Key**Reason(s) for starting design activities**

- a - Continuing from yesterday
- b - Need to meet a target for somebody
- c - Attention drawn to a problem in the design
- d - Need a change from yesterday
- e - Thought of a modification / improvement
- f - Obvious thing to do next
- g - Prompted by previous activity
- o - Other

Obtaining information

- 1 - Obtaining info from clients
- 2 - Obtaining info from other disciplines
- 3 - Obtaining info from suppliers
- 4 - Other

Date

APPENDIX B1 - LAWLEY DESIGN PROBLEM

This study was carried out in the first year of research with the purpose of determining the effectiveness of the method described by Scott (1992). The documentation generated by this study is presented in its original format for completeness. It is not intended to represent a model solution to the problem.

Alkene dimerisation: Feed preparation

(Taken from 'Process Design Case Studies' by Scott & Macleod, 1992)

The objective of alkene dimerisation is to produce high octane hydrocarbons which enhance the value of gasoline. Anhydrous aluminium chloride, a Friedel-Crafts catalyst, may be used in a fixed bed reactor under carefully controlled conditions, which exclude traces of water. General process information is disclosed in Hatch & Matar (1977).

The following is a brief process description of fig. B1, an abbreviated process flowsheet for the feed section of such a plant.

An alkene/alkane fraction, which may occasionally contain small amounts of suspended water, is pumped continuously by the P9101 (transfer pump) from bulk storage through a pipeline half a mile long into tank T9201 (buffer tank). This acts as a buffer and settling tank where any traces of water are settled out and run off at intervals. P9202 (feed pump) then pumps dry hydrocarbon to a feed/product heat interchanger H9203, a preheater H9204 and thence to the reactor R9205, where residence time is held within close limits to secure adequate conversion while avoiding polymer formation and consequent fouling of heat transfer surfaces.

Feed composition is variable and includes pent-1-ene, pent-2-ene with pentane and some C₄ and C₆ components. Physical properties of these are found in standard handbooks. Table B1 gives stream data for fig. B1.

Table B1 - Stream data for alkene dimer flowsheet

	Stream	°C	bar
11	P9101 transfer pump outlet	20	2.4
	T9201 buffer/settling tank contents	20	1.05
12	Feed stream at H9203 inlet	20	20.7
13	Feed stream at H9203 outlet	160	20.0
14	Product leaving reactor R9205	205	17.9
15	Product leaving H9203	60	16.6

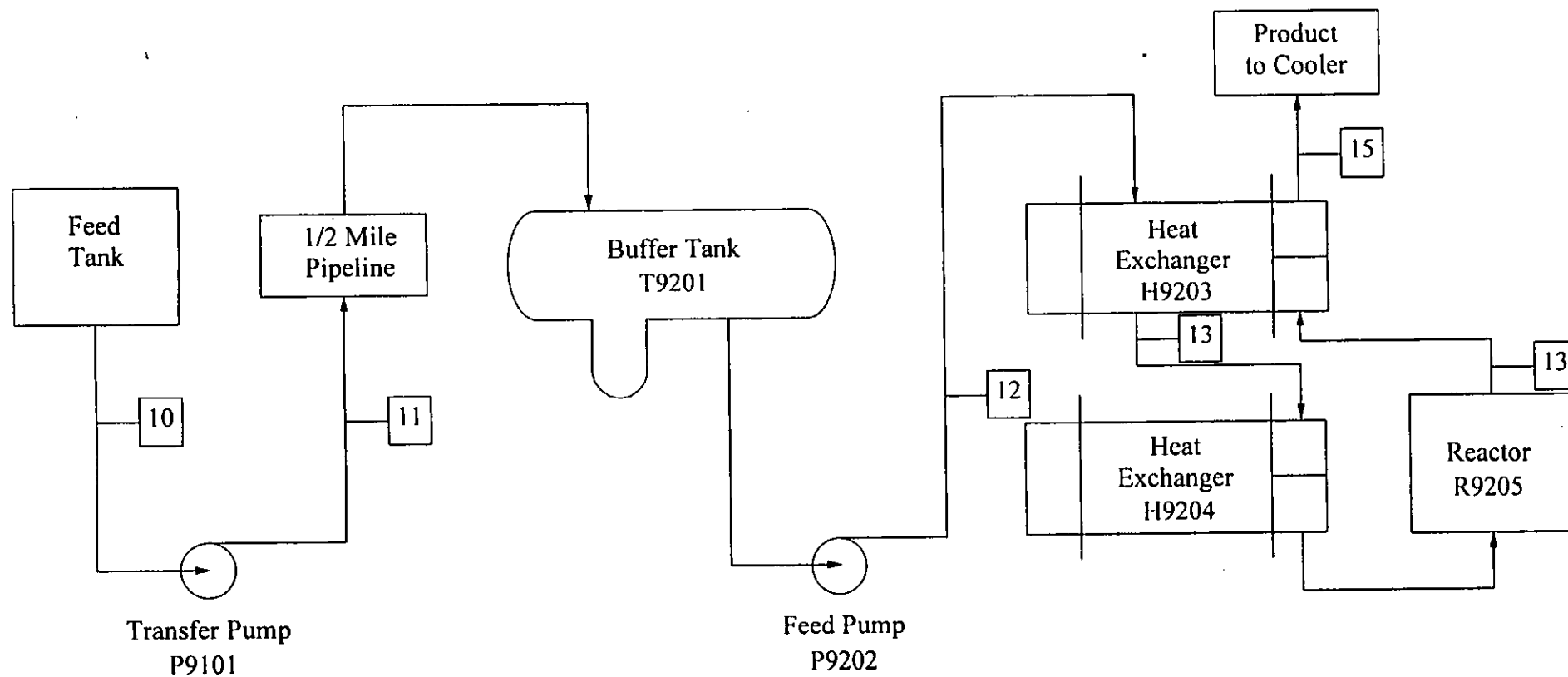


Fig. B1 - Abbreviated flowsheet for feed section of alkene dimerisation plant (Scott & Macleod, 1992)

Exercise

Draw an engineering line diagram to show the process pipelines and ancillaries required for the feed section of an alkene dimer plant starting at the inlet to the transfer pump P9101 and ending where feed leaves the interchanger H9203. No line diagram additions are required for the feed preheater item H9204 or the reactor R9205.

References

Scott R & Macleod N, Process Design Case Studies, IChemE, Rugby, 1992

Hatch LF & Matar S, From Hydrocarbons to Petrochemicals, Part 4, Hyd Proc 56, 155 (Aug 1977)

APPENDIX B2 (PART 1) - MY REASONING BASED ON APPLICATION OF THE SCOTT METHOD TO THE LAWLEY DESIGN PROBLEM

1) Design objective, physical and chemical changes taking place and operating constraints -

Item	Objective(s)	Physical changes	Chemical changes	Operating constraints
Feed Tank	Stores feed Provides NPSH for transfer pump	none	none	
Transfer Pump	Transfers feed to buffer / settling tank	none	none	
Buffer Tank	Buffer to ensure adaptable flow to reactor Allows water droplets to settle and run off Provides NPSH for feed pump	feed mixture is dried	none	
Feed Pump	Supplies feed to HEX 1 Increases pressure to 20.7 bar from ambient	none	none	
HEX 1	Heats feed from 20°C to 160°C Cools product from 200°C to 60°C	none	none	
HEX 2	Heats feed from 160°C to 205°C	none	none	
Reactor	Alkenes / alkanes converted to high octane hydrocarbons	possible polymer formation	alkene dimerization	avoid formation of polymers ensure adequate conversion

2) Check that main process variables, including composition, are adequately controlled and that manipulated variables are known.

Temperature changes occur across the following:

HEX 1
HEX 2
reactor

Pressure changes occur across:

- pump 1
- pump 2 (significant)
- HEX 1
- HEX 2
- reactor

Composition changes occur across:

- buffer tank
- reactor

Hence, options for control include the following:

Change	Equipment	Depend on...	Control
Temperature	HEX 1	Flowrates of both streams Heat of reaction	Feed flow to HEX 1 Heat supplied by HEX 2 / feed flow through HEX 2 Residence time (i.e. reactor outlet temperature) Product flow to HEX 1
	HEX 2	Feed flowrate Feed temperature Heat transferred	Heat supplied (Feed flow fixed by flow to HEX 1) (Feed temperature fixed by heat exchange in HEX 1)
	Reactor	Feed temperature Heat released by reaction Extent of reaction (degree of conversion)	Residence time Feed temperature fixed by HEX 2 Heat of reaction fixed
Pressure	Pump 1	NPSH Flowrate to buffer tank Back pressure	Flow to pump Pump speed Outlet flow (back pressure)
	Pump 2	NPSH Flowrate to HEX 1 Back pressure	Flow to pump Pump speed Outlet flow (fixed by HEX 1 requirements) - or feed to reactor requirements?

Change	Equipment	Depend on...	Control
Pressure (cont'd)	HEX 1 HEX 2		Do not require control - pressure losses
	Reactor		Pressure loss
Composition	Buffer tank	Settling time	Inlet flowrate Outlet flowrate - fixed by pump 2 requirements Tank level
	Reactor	Correct temperature and pressure Residence time Active catalyst	Inlet temperature (fixed by HEX 2 outlet) Inlet pressure (fixed by pump 2 outlet) Inlet flowrate Outlet flowrate Level in reactor (or volume) Product spec (re catalyst life and effectiveness)

Manipulated variables:

- flowrate
- heat transfer
- pump speed (?)
- tank levels (residence time)

3) Susceptibility of each item to fouling, corrosion or failure and the effect on the system of its possible unreliability. What installed spares are necessary and what can be covered by workshop spares and maintenance policy?

Equipment		Susceptibility	Possible unreliability	Associated problems	Spares
Feed tank	Fouling Corrosion Failure	Low Low Low	Leak Overflow Low level	Fire hazard Disrupted feed to pump / low NPSH	None (benefit does not outweigh cost)
Transfer pump	Fouling Corrosion Failure	Low Low Medium	Leak Failure to transfer feed to buffer tank Reverse flow	Fire hazard Lost production	None because a) not exceptional duty, b) buffer tank provides some leeway - <i>but how much?</i> OR Yes, because pump cost small in comparison to lost production
Buffer Tank	Fouling Corrosion Failure	Low Low Low	Leak Overflow Low level Failure to separate water from HCs	Fire hazard Disrupted feed to reaction (flow / composition) Low NPSH to pump	None
Feed pump	Fouling Corrosion Failure	Low Low Medium	Leak Failure to deliver feed to HEX 1 Failure to increase pressure sufficiently Reverse flow	Fire hazard Lost production Off-spec. product	Yes, because a) exceptional duty b) major importance in main processing stream c) lost production costs would outweigh pump cost (?)

Equipment		Susceptibility	Possible unreliability	Associated problems	Spares
HEX 1	Fouling Corrosion Failure	Medium Low Low	Leak (external / internal) Blockage	Fire hazard Loss of product spec. Over-pressure	Yes, because a) main stream b) likelihood of fouling c) loss of spec. OR is it too expensive because of pressure rating?
HEX 2	Fouling Corrosion Failure	Low/medium (if steam heated) Low Low (qualify / quantify??)	Leak Blockage Failure to reach required temperature Temperature too high	Fire hazard Loss of spec. Incomplete reaction Runaway reaction(?) Over pressure	None, because failure is unlikely and equipment cost does not outweigh benefit (high pressure drop across shell and tube) but if this fails, whole process goes down, whereas if HEX 1 fails, HEX 2 might be able to compensate...

Is water presence in reactor dangerous or just undesirable?

Reactor	Fouling Corrosion Failure	Medium (polymers may foul catalyst bed) Low (movement of bed / disintegration ?) Low	Leak Incomplete reaction Polymer formation Inactive catalyst Runaway reaction Effects of water present	Fire hazard Off-spec. product Over-pressure Over-temperature	None, because too expensive OR yes, because of need to renew catalyst - how often? - how long does it take? ... plus water effects, polymer causing fouling
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4) What provision should be made for interstage storage capacity, to ensure smooth, continuing operation in the face of minor malfunctions?

Feed tank and buffer tank are already shown.

Storage between HEX 1 and HEX 2, and HEX 2 and the reactor is undesirable as it defeats the object of the equipment (i.e. would have to maintain heat somehow).

Ditto for the line from the reactor to HEX 1 - defeats preheating function.

5) Consider all operations which have to be performed and draw the necessary pipelines. Draw spaciouly using approximately scaled and positioned items.

Operations to be performed: start-up
shutdown
maintenance
cleaning

- inerting / purging

Lines added (refer to '2nd layer'):

- a) Steam to and from HEX 2 (assuming no electrical or other heating)
- b) Bypass around reactor - for start-up, to enable feed to reach correct temperature before entering reactor. Alternatively, need massive heating capacity in HEX 2 - ***if HEX 2 had a larger heating capacity it could also act as a stand-by in the event of HEX 1 failure...***
- c) Recycle loop to HEX 1 feed inlet, also to allow for heating at start-up. Could alternatively insert loop at HEX 2 inlet to give faster initial warm-up in HEX 2 but no initial heating in HEX 1 - does this matter? Could heat HEX 1 with steam initially, but would this compromise product spec.? Or, could loop HEX 1 and HEX 2 separately - getting rather complicated now...***If this is done, some form of pressure generator is required in order to force the recycle stream to join the high pressure inlet stream!! (see '6th layer')***
- d) Vents on all vessels to allow for filling at start-up - also allows for draining out. Vent to where...?
- e) Duplicate pump lines inserted - ***are these necessary?***
- f) Pump bypass lines inserted - **do you need one for each line, or will one do for both? Are they always necessary anyway? Do pumps generally have variable speed drive? If yes, no bypass - ??**

Kickback lines are used rather than bypass lines - these can often introduce complications, but are useful on pumps which are normally operating but often not in demand, such as the feed pump (pump 1) in this example.

- g) Duplicated HEX 1 includes piping facility for feed to be recirculated between the two HEX 1 exchangers e.g. to warm up one before the other is taken off-line - ***is this technically feasible? If so, are further pumps required and hence, is it really worthwhile??***
- h) Drain on HEX 2 shell-side - where to?
- i) Drain on HEX 1 shell-side - don't rely on drain in pipework as likely to want to isolate without breaking flow - ??
- j) Drain on all large vessels which are likely to be entered for cleaning / maintenance. **When can drains on pumps etc. be relied upon to drain the system? Drain at lowest point in vessel (if possible)?** - important for buffer tank.

Need to define an isolation strategy - which vessels need to be isolated singularly, which equipment can be isolated as a group, and hence where are drain points and isolation valves required??

- k) **Drain on all pumps (?)**, particularly those at ground level because they are at the lowest point.
- l) Vents added on pumps which are duplicated because there is no other way the extra line can be vented. **Vents on all pumps anyway?**
- m) **How do you drain the tube-side of the heat exchangers?**
- n) Maintenance - for a flammable gas, the following options are available:
 - vent to a low pressure section of the plant
 - vent to a flare stack / scrubbing system
 - vent to a safe place in the open air.

Does the vent need to be separate from the pressure relief valve? - Yes!!

How much gas is likely to be present? Vapour pressure (or partial pressure)?

- o) HEXs and reactor will require cooling and depressurizing for maintenance. When cooling, inert gas / air should be used to maintain atmospheric pressure and prevent the formation of a vacuum. Inert gas is preferred, especially with flammable liquids - **does the benefit outweigh the cost?**

Therefore, consider cooling water supply to HEX and reactor - but don't want water in the reactor...

How to cool the tube side? HEX 2 tube side cooled by water from HEX 1 - or will this cool sufficiently when shell side is cool? ***don't want water in HEX 1 as this contains organic liquids...***

BUT - need to cool vessels before depressurizing because they contain liquids at elevated pressure at temperatures above their atmospheric boiling points...hence cooling jacket on the reactor?? This may be necessary anyway if the reaction is very exothermic / liable to 'run away'. Or just allow to cool naturally...?

HEX 1 - cool naturally

HEX 2 - can pass water through shell side.

p) Any lines for detergent etc.??

6) Insert all valves, meters, controllers etc. required for mass flow and control (see '3rd layer').

a) Valves on all vents and drains.

b) Isolation valve on feed tank outlet.

c) Isolation valves on pump suction and discharge lines. - *why??*

d) Back pressure valve on pump outlets to control pressure.

e) Control valve on pump bypass (if used!) to prevent back pressure valve from sending all the flow back to the inlet.

f) Buffer tank isolation valves on inlet and outlet.

g) Pump set-up as before.

h) HEX 1 isolation valves on inlet and outlet (shell side).

See earlier note on isolation strategy...

i) Reactor inlet / outlet isolation valves.

ditto

j) Bypass valve for reactor.

k) HEX 1 tube side inlet / outlet isolation.

ditto

l) Valves to control HEX recycle loops.

m) Isolation can be achieved using other valves, therefore no need to isolate HEX 2 separately.

Too many valves!!

Eliminate reactor isolation valves because HEX 1 shell side isolation valves can be used for the same purpose. These cannot themselves be eliminated because you need to be able to switch between the two HEX - ***unless they are not duplicated...***

Replace one of the valves just removed because it is needed to enable operation of the bypass around the reactor!

Valves in lines from tanks to pumps are not needed because pumps have separate isolation valves anyway - *or do they...?*

n) **Valve on steam inlet line to HEX 2 or on outlet line?**

(Leave valve in before buffer tank because of distance between it and pump).

o) Mass flow indicator and controller on feed tank to buffer tank transfer line.

See later comments / decisions...

p) Mass flow indicator and controller on buffer tank to HEX line.

ditto

q) FIC on reactor outlet - reinstate reactor outlet valve!

How do you decide whether to use level as a controller or flow / flow differences? e.g. knowing flow in and out of buffer tank, you can also calculate level, so which is more important to measure?

7) Temperature measurement and control (see '4th layer').

a) TIC on HEX 2 outlet, controlling steam feed to HEX 2 - feedback control not feed forward!

b) TI on HEX 2 tube-side outlet to control operation of reactor bypass line back to HEX?

c) TI on product line from HEX 1. TI on reactor outlet. **Do you need TI on HEX 1 inlet as well (in case something goes wrong)?**

8) What determines the pressure in each plant item and how might this vary in normal plant operation? How might valve closures isolate plant sections containing fluids which could cause over pressure? Make additions for pressure measurement, control and relief from possible over pressure (see '4th layer').

Feed tank: Pressure is determined by constraints upstream. If the pump isolation valve was left closed then over-pressure could occur - hence, fit relief valve. Also, the process fluid is flammable such that heat may cause significant amounts of vapour to form. Or, relief valve not necessary because not under significant pressure?? - *Relief valves should be fitted on all closed vessels (unless there is a neighbouring vessel with a relief facility that is not isolatable from the vessel under consideration) as there is always the potential for pressure*

build-up. In the event of reliance upon another vessel's relief system, care must be taken to size this appropriately to be able to cope with the combined demands of the two vessels.

Pumps: Pressure is determined by a combination of the NPSH and the downstream valve settings. Use a pressure indicator on the pump outlet to ensure that the pump is operating properly, i.e. generating the desired pressure. The indicator should be positioned before the valve on the outlet line (which should be a non-return valve).

Buffer tank: Pressure depends on that generated by the feed pump (pump 1). Again, a relief valve should be fitted (especially as liquid is flammable / volatile) - ***see above***. Fit a pressure indicator on the tank to ensure that there is sufficient NPSH for the next pump to operate effectively.

HEX 1: Pressure depends on that generated by the transfer pump (pump 2) on the shell-side. This vessel is under high pressure, therefore a relief valve should be fitted. - ***see earlier comment on relief valves***.

HEX 2: Shell-side pressure depends on the steam pressure. No need for a relief valve because steam is not flammable / volatile?? - ***fit a relief valve!!***

Reactor: Pressure depends on that generated by the pump minus losses across upstream equipment plus any pressure change caused by the reaction. Fit a pressure indicator to show whether the reaction is occurring at the correct pressure. Fit a relief valve.

N.B. Does the back pressure valve to generate 20 bar need to be the last item of equipment before the pressure is allowed to drop back to atmospheric??

A pressure indicator should be fitted on the tube-side of HEX 1 to show whether the tubes are blocking due to the presence of polymers. **(should there always be a PI on the tube-side of an exchanger to check for fouling / blockages?)**

9) The properties of the materials handled at each stage may indicate the need for additions e.g. hydrocarbon / air mixtures can be flammable and explosive so need safe pressure relief and venting. Nitrogen purging and blanketing may be required e.g. in storage tanks.

No storage tanks (as yet...)

a) Relief valves need to be vented somewhere safe / contained, i.e. either to a vessel or to some sort of scrubbing system - ***or flare stack...*** If venting to a vessel, it may be possible to recover / recycle the material.

b) **Is any inert purging / blanketing required?**

10) Are special provisions required to allow for lower flowrates / different feed stocks? - ??

11) Are additions required for controlled shutdown, cleaning and maintenance, or for start-up? - ??

- a) Is there any alternative to allowing the vessels to cool naturally?
- b) Is air admission o.k. or should inert gas be used?
- c) What are the requirements for cleaning - detergent solution? cold water rinse?
- d) If a detergent solution is used, would a permanent installation be appropriate?
- e) The cleaning fluid must be disposed of properly - what waste treatment is required?

Comments:

FIC does not tell you much if positioned after the first pump (see '3rd' & '4th' layers), therefore use the level in the feed tank as the controlling variable (but level measurements generally are not very reliable). The same argument is valid for the second pump. If a control valve is used to moderate the flow from the second pump according to the level in the buffer tank, how is the correct pressure for the reaction maintained....?.....control of flow has an inherent effect on pressure. Use a PIC on the outlet with a variable speed drive on the pump to correct for pressure when the flow changes?

If the reactor is tubular, the level control system option is eliminated - hence choose flow or pressure control? Flow is more important - we need the pressure to be correct for the reaction to occur under suitable conditions but is there some leeway? Flow must be controlled to enable monitoring of residence time as this is critical to obtaining the desired product.

Why do some control valves have bypass set-ups and others not?

But now we have 2 controlling elements in the same line.....the FIC is more important than the level controller as the level is not fundamental to the process, therefore eliminate the level control on the buffer tank. Where to position the FIC - before or after the reactor?? Put it in before reactor for now...(see '4th' & '5th' layers) - *this is a good position because if it is put here, the reactor pressure can be controlled independently using a back-pressure valve downstream (see '6th layer' and later comments). This flexibility would be eliminated by putting the FIC downstream of the reactor.* Now that FIC has been chosen, variable speed drive control of the pump is not necessary as for a fixed flowrate, a given speed will give a fixed pressure.

Now, what's missing??

Sample points
Filters
Alarms
Inerting lines
Washing lines
Flushing lines
Flame traps
Steam traps

Restriction orifices
Non-return valves
Filters
Bellows etc.
Comments e.g. 'gravity flow'

So.....(see '5th layer')

- 1) Add level alarms (high and low) and indicators on both tanks.
- 2) Add non-return valves on pump outlet lines.
- 3) Add filters before the pumps - *why?? Is this a standard procedure? How important is it?*
- 4) Sample points:
 - The drain valve can be used on the feed tank.
 - Add a sample point at the buffer tank to check for water - **after or on the tank?**
 - Add a sample point at the reactor outlet to enable checking of the product spec.

Revisions.....1
(see '5th layer')

Change the TI to one on each HEX as both may then be used at once - **but then do this with all indicators on all HEXs? e.g. PI either side to show leaks, etc.?**

Add a PI on steam supply line.

Add high / low flow alarms on the line supplying the reactor, immediately before the reactor. (If you put it by the controller, it won't be activated if there is a leak in the heat exchanger. When in front of the reactor, the FIC will show whether the problem is at or before the pump, which will in turn indicate whether or not it is the HEX that is faulty.)

Add a pressure alarm on the reactor.

Add a flow indicator on the immediate supply line to the reactor.

Would the TI be better positioned on the reactor or on the exit line?

Are pressure indicators and alarms standard for all major vessels?

Add a pressure alarm before the first control valve because if it jams shut, we need to know. Could alternatively have a flow indicator and flow alarm downstream of the valve...? A flow indicator is probably a good idea anyway.

The same argument is valid for the second line. Change the FIC to feedback!!! **Would it be possible to use a restriction orifice instead of the FIC?**

In the first section, the pressure alarm will tell you whether any of the following has occurred:

- pump has failed
- control valve is stuck shut
- (bypass is open)

In the second section, the pressure alarm tells you if the....

- pump has failed
- control valve is stuck shut
- (bypass is open)

.....and the flow alarm tells you if the...

- pump has failed (i.e. it is achieving the correct pressure but not the desired flow)
- control valve is stuck open.

The flow alarm before the reactor should not be relied upon to demonstrate these things as there would be too much of a time delay between the occurrence of change in conditions and it's detection. - ??

Revisions.....2

(see '6th layer')

Change the level control to feedback from the buffer tank (!).

Eliminate both pump bypasses as shown originally. Change the first to a kickback line to the feed tank, because if something goes wrong, attention is more likely to be initially focused on the latter section of the process shown and by the time the fault is traced back / discovered irreparable damage could have been done (?).

A pump will be necessary on the reactor bypass to enable flow to proceed in the direction indicated, i.e. to enable the pressure to be increased sufficiently for the recycle streams to join the main streams.

A relief valve should be fitted on HEX 2 - *see earlier observations on relief valves.*

A cascade temperature to pressure control set-up will be required to control the steam flow to the heater. *(the easiest way to control the heat transfer coefficient is by changing the pressure)*

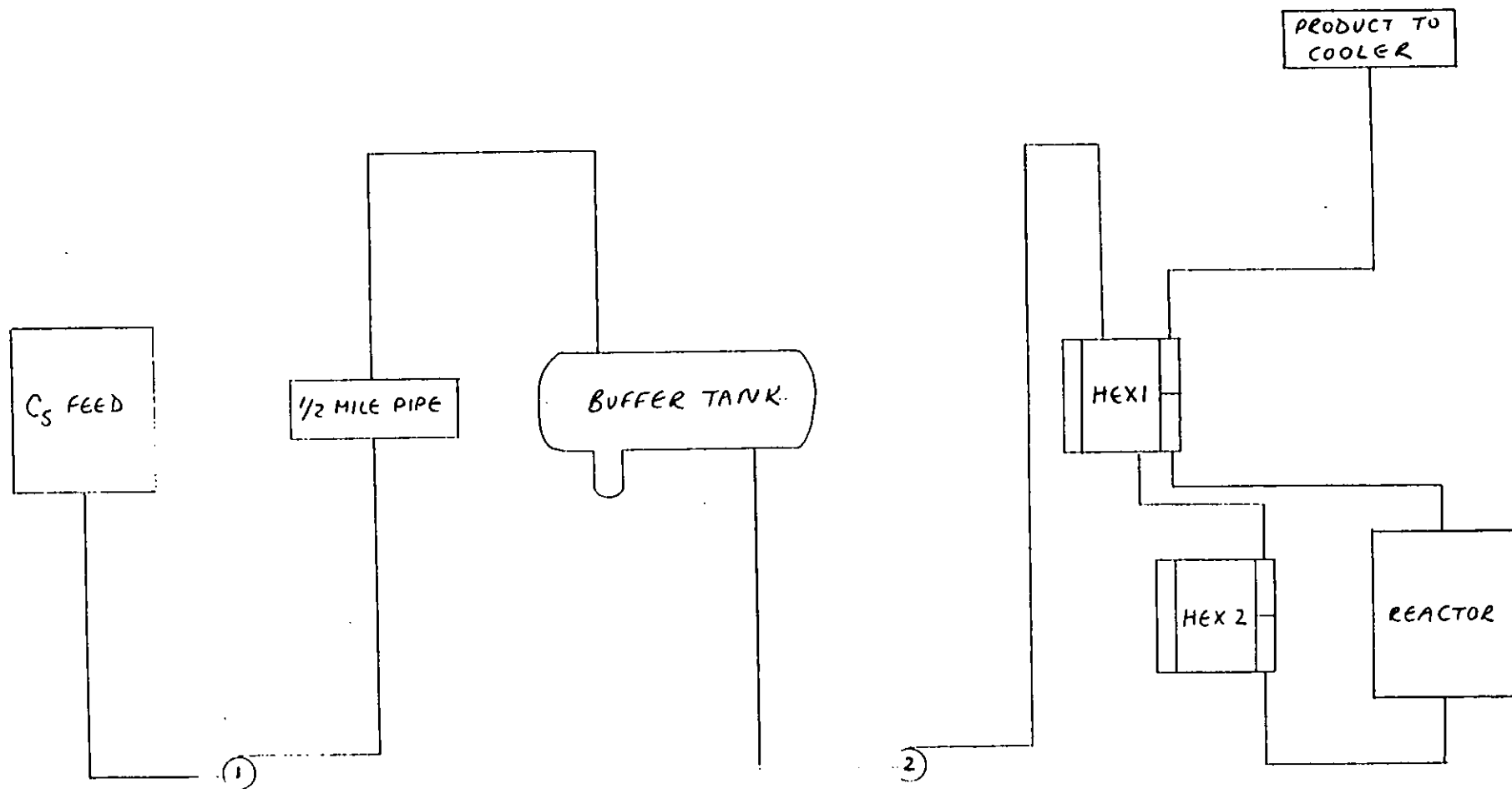
With the FIC in the position shown, the pressure of the system can also be controlled independently, hence add a back-pressure valve downstream of the reactor. This valve should

be positioned after the cooler in order to prevent vaporisation of the process fluid if the valve opens suddenly. *Alternatively, the FIC could have been placed on the product line based on the argument that this is a better position for maintaining product flow, this being the most important consideration.*

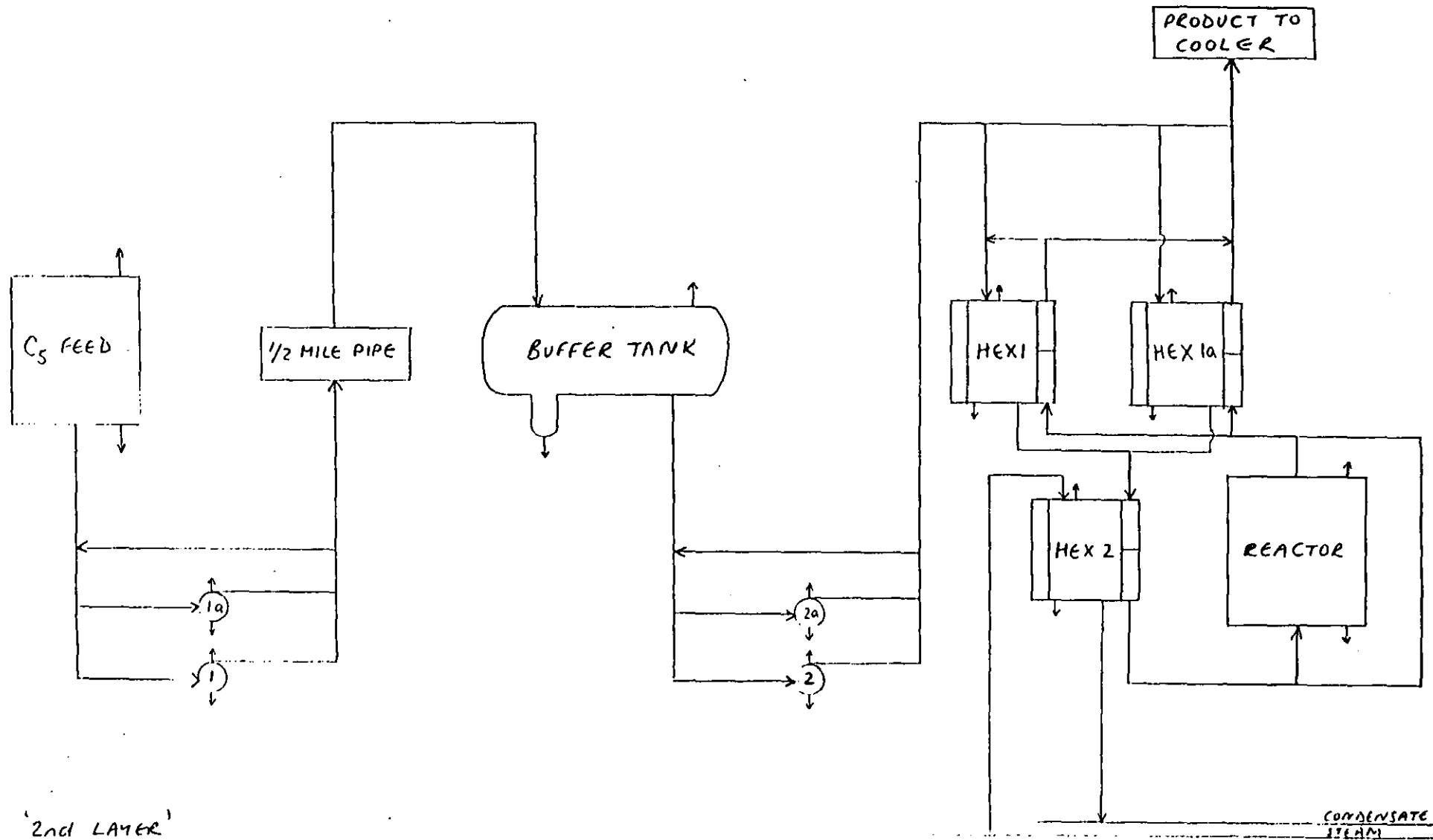
If the TI and TA are positioned on the reactor outlet line rather than on the reactor, then they can also be used to measure the temperature on start-up / during bypass operation. But, there is already a TIC after HEX 2 so is this necessary??

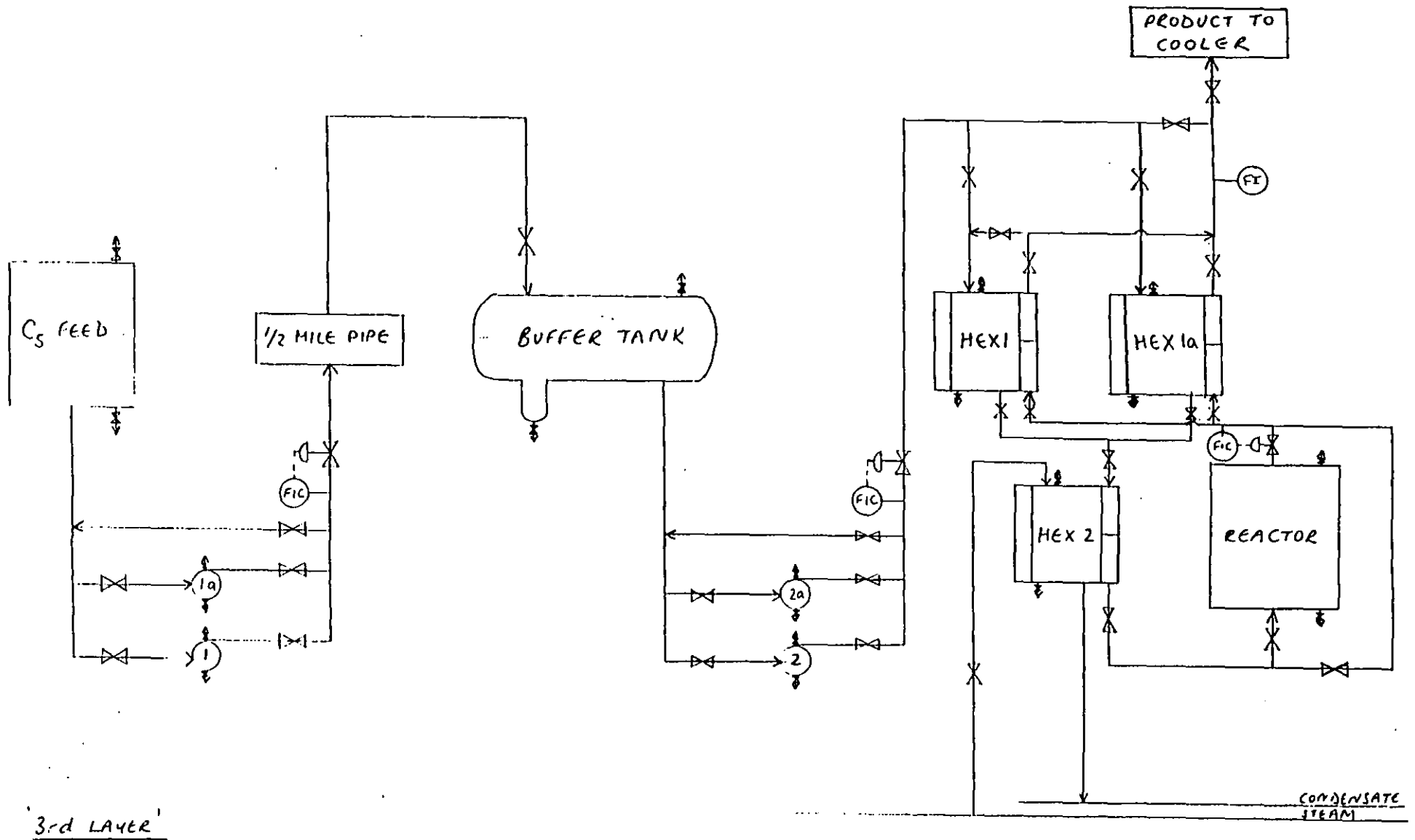
Do you always isolate both sides when bypassing?

Should a TA be installed on the HEX 1 tube-side outlet to indicate the effectiveness of cooling? (due to leaks etc. - the FA would indicate no flow but not a shell-side leak).

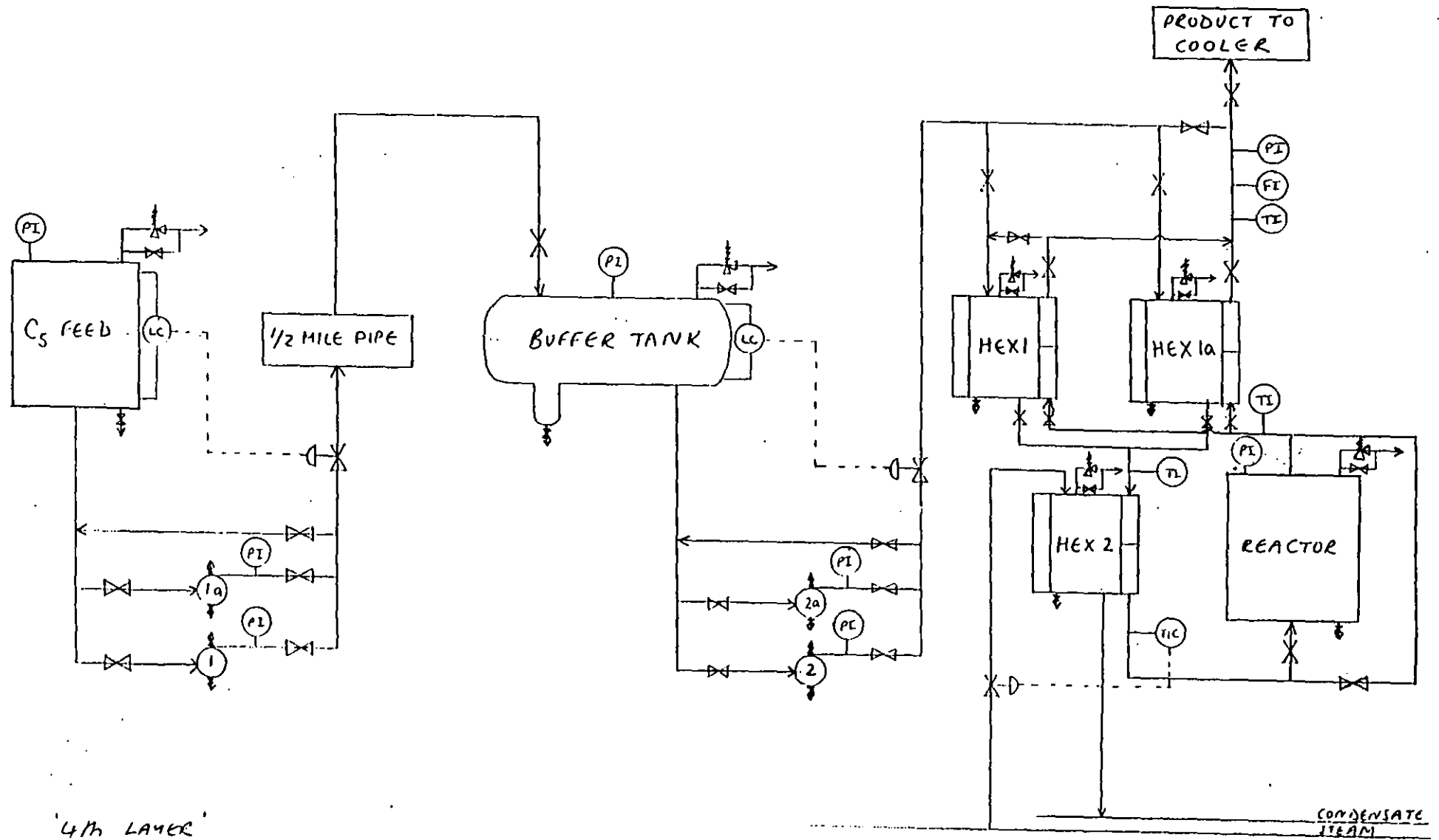


1ST LAYER (ORIGINAL PFD)

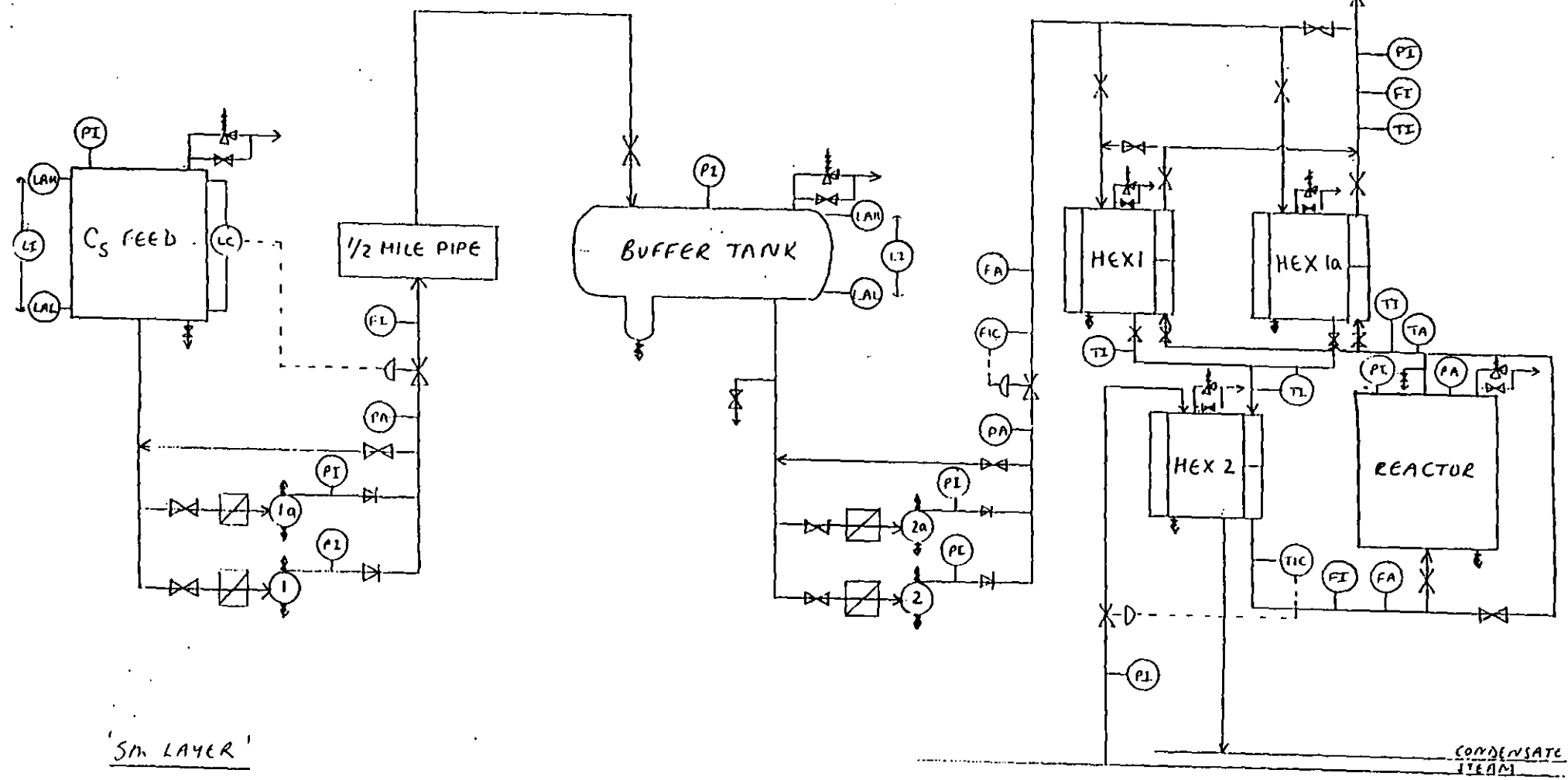




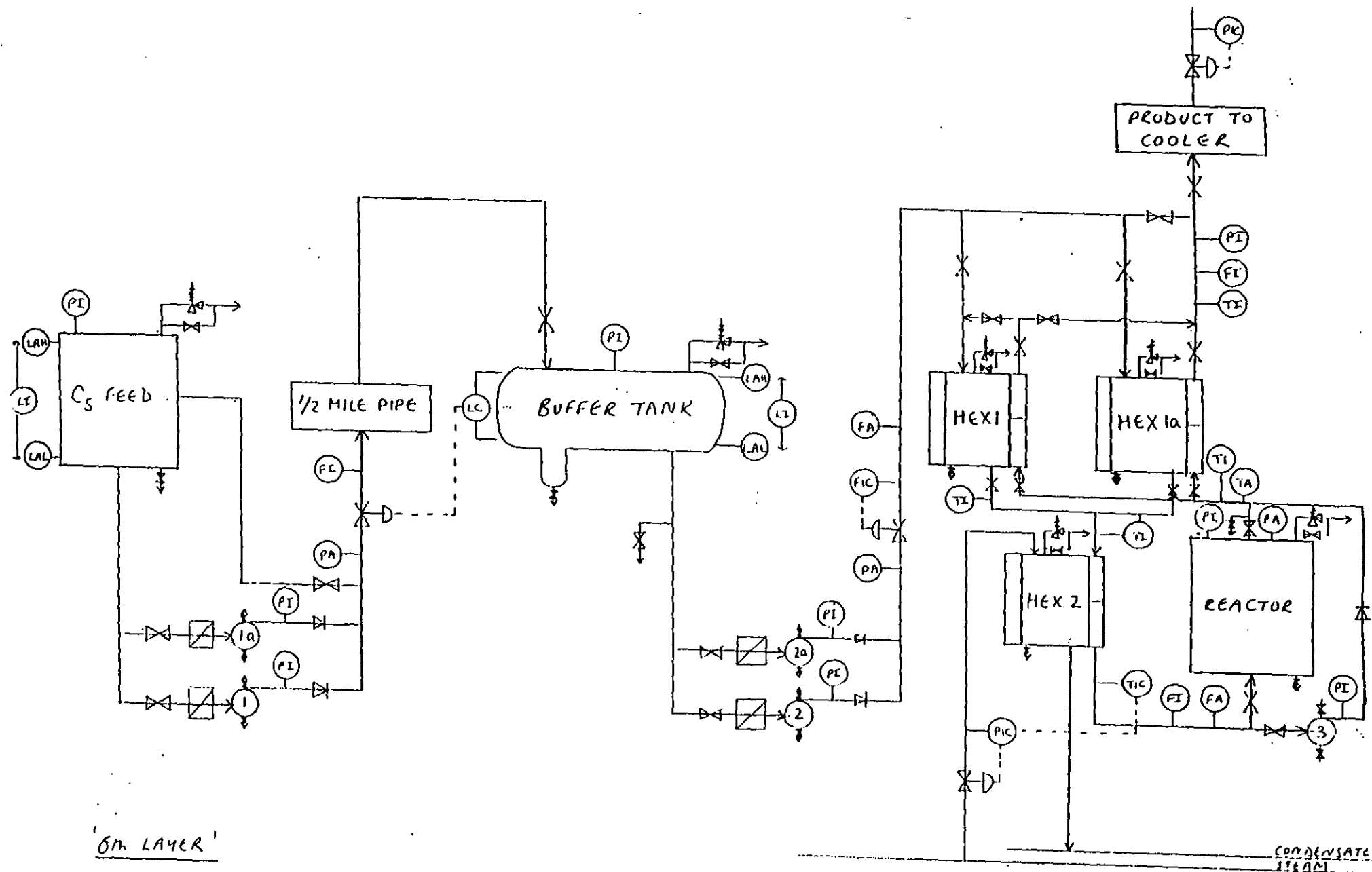
3rd LAYER

4th LAYER

B22



'SM LAYER'



APPENDIX B2 (PART 2) - PAUL BUJAC'S REASONING BASED ON THE APPLICATION OF HIS DESIGN EXPERIENCE TO THE LAWLEY DESIGN PROBLEM

Basis of added equipment

ITEM	PURPOSE	
Waste water drain line on buffer tank	To remove water (to drums?)	P**
Process vent on buffer tank	Breathing, maintain tank at atmos press (to atmos?)	P
Buffer tank overflow	Controlled overflow (to bund?)	U
Fire relief on buffer tank	Limits vessel pressure to within design	U
Fire relief on reactor	Limits vessel pressure to within design	U
Miscellaneous drain points	Draining vessels/lines to?	M
Miscellaneous vent points	Purge to atmos?	M
Steam to HEX 2	Heats reactor inlet stream	P
Condensate ex HEX 2	Drain condensate away	P
Miscellaneous purge points	Decontaminating equipment	M
Level control on buffer tank	Maintains buffer tank inventory	C
Interface level on buffer tank heel	Measures water level	C
Pressure control on final product line	Maintains system as liquid	C
Flow control ex buffer tank	Controls reactor feed/production rate	C

* A key to the letters is provided overleaf

ITEM	PURPOSE	
Temp control on reactor, cascade onto HEX 2 exit temp, cascade onto steam flow control	Controls reactor conversion by temp	C
Analysis of feed ex buffer tank	Check for water in feed and feed comp	D
Analysis of cooled product	Check conversions	C
Temperature measurements ex HEX 1	Check HEX 1 performance, fouling etc	D
Pressure measurement inlet HEX 1	Check HEX 1 fouling	D
Flow totaliser on feed to plant	Accounting, mass balance purposes	D
Isolation valves on feed to buffer tank	Isolation between plant units	U,M
Isolation valve on buffer tank base	Contains inventory	U
Isolation valve on product line	Isolation between plant units	U,M
Thermal insulation on lines around HEXs	Heat conservation and personnel protection	P

NOTES

C Control
 D Diagnostics
 P Process
 M Maintenance
 U Upsets

Data not yet added

Pipe specifications

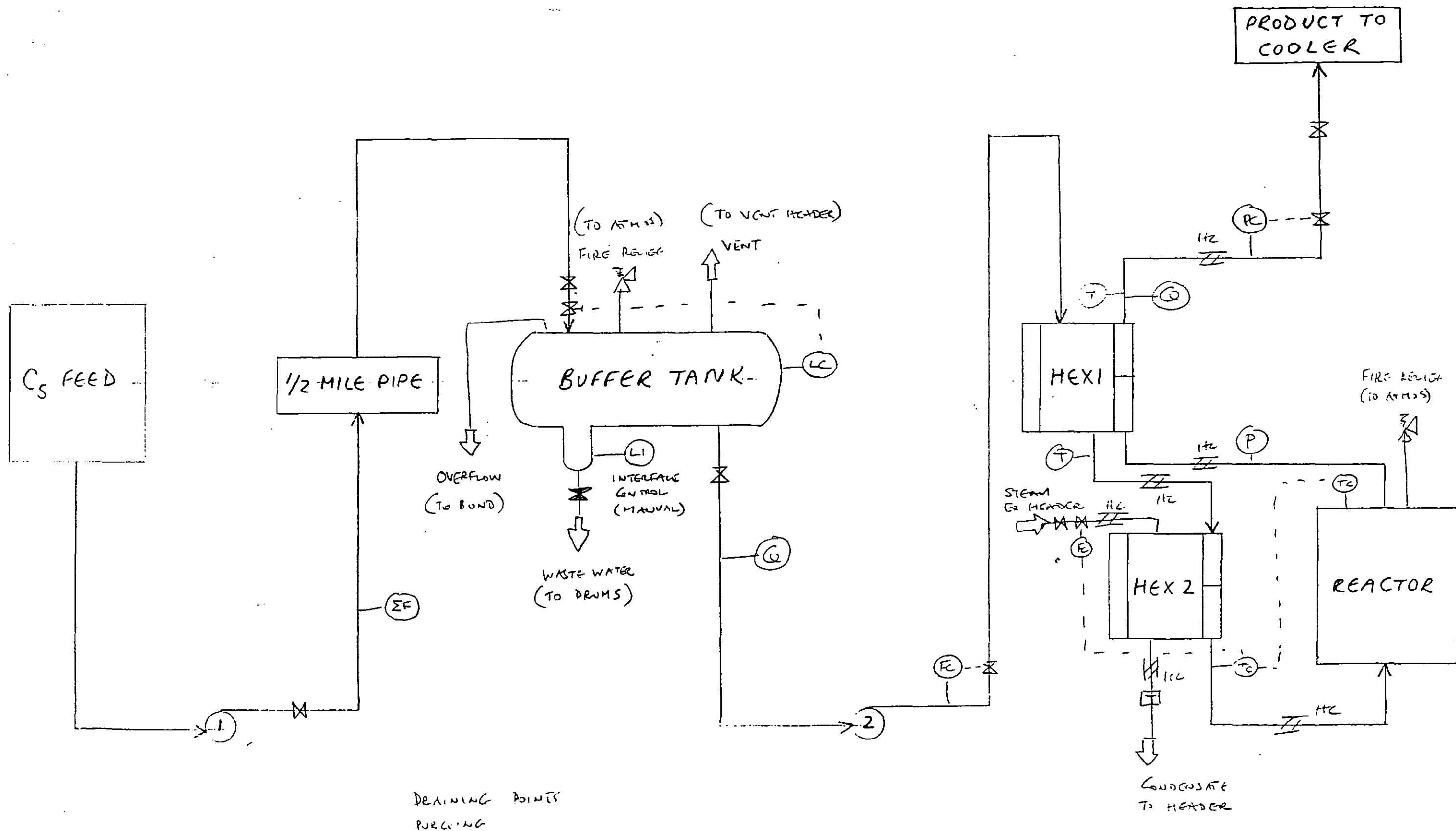
Details around pumps (local isolation, drains etc)

Details around instruments (local isolation, sensors, transmitters etc)

Service, condensate, vent, effluent headers

TRIP/ALARM SYSTEMS

Thermal/hydraulic relief



APPENDIX B3 - MATRIX OF DESIGN OBJECTIVES AND SOLUTIONS

(Note this matrix is intended to illustrate the philosophy of defining the line diagram design problem in terms of objectives and solutions - it is not intended to provide a complete analysis of the problem)

[illegible]

[illegible]

Drains						✓	✓								
Vents						✓	✓								

[illegible][illegible][illegible][illegible][illegible][illegible][illegible]

APPENDIX C1 (PART 1) - EXAMPLE DECISION SUPPORT DOCUMENT FOR EQUIPMENT TYPE SELECTIONS

HEAT TRACING

Tracing is the application of an outside source of heat to piping or equipment. It is required to maintain the temperature of the fluid at or above a certain minimum for various process or physical reasons.

Reasons for applying heat tracing

- Freeze protection
- Maintaining low viscosity
- Preventing condensation
- Preventing crystallisation

Freeze protection

Freeze protection may be required for water, aqueous solutions and certain organic fluids to prevent freezing or precipitation or separation.

The following conditions favour the need for freeze protection:

- Ambient temperature is likely to fall below freezing point of material
- Material expands on freezing
- Material in lines is likely to be stagnant
- Material leakage is undesirable
- Process stops.

If a line contains an expendable fluid such as cooling water and a minimum flow can be maintained through its entire length, those portions containing the running flow need not be traced.

When considering freeze protection it is important to look at the worst case temperature, i.e. the highest freezing point of all the different compositions / combinations of process fluids which may be present during either production or transitional operations such as start-up and shutdown.

When calculating the power required for freeze protection there is a need to ascertain whether the heating will purely be used to retain heat or whether the heating may also be relied upon to melt / reheat the frozen process fluid in the event of maloperation.

Maintaining low viscosity

Liquids such as heavy oils do not freeze in cold conditions but their viscosities increase considerably. This can cause an excessive pressure drop in a line or result in a reduced

flowrate. It can also lead to malfunctions in equipment. Heating the material will decrease the viscosity in most cases.

It should be borne in mind that high-viscosity materials do not transmit heat well when they are cold. Thermal currents of warmer material through the cooler portions are slow to form and the poor heat transmission can give rise to localized overheating.

Preventing condensation

Tracing may be needed for gas flows containing water or organic vapours which could condense within the line or equipment if the ambient temperature falls below the dew point of the vapour mixture.

Situations requiring prevention of condensation include those where:

- the condensate is corrosive, as in the case of water vapour condensing from hydrogen chloride or sulphur dioxide
- there is no facility to remove the condensate from the piping or equipment
- the condensate could damage machinery
- the condensate could freeze and cause large pressure drops or operational difficulties
- condensate slugs could upset the process or damage pipework.

Preventing crystallisation

Similar to freeze protection.

Types of tracing

- Steam
- Electric
- Other

Factors affecting choice of tracing

- Attainable temperature levels and accuracy required
- Safety
- Installed and operating costs
- Availability of design tools
- Availability of energy sources
- Need for connection to central monitoring and control system
- Need for reheating / melting
- Reliability / robustness of system
- Scale and complexity
- Current plant practice.

Steam tracing

A steam tracing system consists of steam supply piping from the steam main to the traced pipe, the steam tracing tubing, steam traps and piping from the traps to the condensate return system. Steam at the temperature required by the process is fed to the tracing at several points

along the length of the traced piping and condensate is withdrawn from the tracing tubing at several locations.

Plus	Minus	Interesting
High heat output	Energy inefficiency	Single-line, multiple-line or wound tracing may be used
High reliability	Poor temperature control	Steam is normally at low pressure (25-150psig)
Fewer safety concerns	High installed costs	Generally not thermostatically controlled
Opportunity to utilise waste steam	High maintenance costs	Reliable temperature control is not possible below 250°F
More robust		Above 250°F, control to +/-50°F is available at no extra cost
		Some fluids may be sensitive to the temperature of the saturated steam at the pressure of the steam in the tracing tubing
		It may then be necessary to use pipe-skin temperature sensors which control tracing steam to segments of the piping
		The problem of high temperature may be avoided by isolating the tracing tubing from the piping with fibreglass rope

Electric tracing

An electric tracing system consists of a power supply system, an electric cable placed against the pipe under the thermal insulation and any control or monitoring system that may be used. There are a number of different types available, the most common being:

- **Constant resistance wire** - this has a nearly constant-wattage output of heat per unit length of wire for a given voltage regardless of the temperature which the wire might attain in its position between the pipe or equipment and the insulation

- **Self-regulating tracing wire** - continuously varies its heat output in response to variation in the temperature of the pipe, support or valve

When considering electric tracing it should be borne in mind that the tracing wire could be damaged if at any time the temperature of the fluid in the pipe gets hotter than the tracing. This could happen, for instance, during start-up, if the system is steam purged and reaches a temperature higher than any seen in production.

Plus	Minus	Interesting
General		
Lower installed and operating costs	More complex design procedures	Electric tracing is usually the preferred system for applications under 250°F Control accuracies of +/- 5°F are attainable Usually thermostatically controlled
Reliability	Lower power output	
Good temperature control		
Energy efficiency		
Constant resistance		
	There is a limited service temperature for tracing wire assemblies Concern should be given to the possibility of overheating a process fluid if the fluid in a section of piping is stagnant	This tracing may be used at temperatures from -50-1100°F depending on the type of sheathing Additional wattage per foot of pipe can be obtained by using multiple tracer lengths in parallel or by wrapping the tracer around the pipe in a spiral fashion Parallel tracers are normally used since it is difficult to spiral long lengths of tracer wire
Self-regulating		
Can compensate for heat loss more rapidly than constant wattage units Can be overlapped without causing overheating or burnout if an extra amount of heat is required near the heat sinks (valves, pipe supports and instruments)	Inherent characteristic of in-rush current can lead to additional costs of high-amperage circuit breakers, heavy wiring and large transformers	Favoured in low temperature applications Typical uses include freeze protection of water or aqueous solutions or to ensure that a maximum fluid viscosity is not exceeded

Plus	Minus	Interesting
Self-regulating (cont'd)		
Can be cut to length in the field, providing extra flexibility and safety margins for the overall system performance		

Other

A number of tracing fluids other than steam may also be used, for instance hot water, ethylene glycol, water and heat transfer oils.

Jacketing

There are some situations in which steam or electric tracing cannot provide sufficient heating while at other times cooling of the piping and equipment is required. In these cases, the piping or equipment may be jacketed. Alternatively, 'hot boxes' may be used around pumps and valves to provide a local warm environment.

Piping is jacketed by centring the process line inside a larger diameter pipe with a heating or cooling medium flowing through the annulus. Hot boxes, which are often easier to maintain than conventional insulation, simply comprise an insulated heated box.

Equipment must be specified with a special external jacket if required.

The heat transfer fluids used include:

- steam
- special heating oils
- tempered water
- brines
- glycols

Temperature control

Temperature control may be:

- Manual
- Automatic

Manual

In the case of freeze protection, steam may be applied manually as the calendar season approaches when there is danger of reaching the lower temperature limit. If a big steam system is being used, the heat use may be limited further by only switching the steam on overnight if appropriate. The steam is then shut off during those months when the ambient temperature is expected to be above the lower limit.

Automatic

- Automatic control may be either thermostatic or regulating.
- Self-actuating temperature control valves may be used in the case of steam tracing.
- Electric and / or pneumatic control systems are the alternative.

Sensing

Three main methods of temperature sensing and control are available:

- **Point sensing** - the different flow paths in a complex piping network, such as the flow versus no-flow segments of the piping system, are considered separately and individual sensors and heater circuits are provided for each flow path.
- **Ambient sensing** - the ambient sensor turns all the heating circuits on or off as soon as the ambient temperature passes the setpoint.
- **Dead-leg sensing** - a pipe with the following characteristics is selected and a sensor and controller are used to control the desired temperature:
 - smallest diameter in piping network to be maintained at a given temperature
 - permanent, no-flow position: either non-flowing section of piping network or separately constructed piece of pipe.

All heater circuits installed on other pipes with different diameters in the network are turned on or off through a contactor based on the signal and setpoint of the controller on the dead-leg. All heating cables remain on until the dead-leg meets its temperature requirements, regardless of the flow conditions of the different pipe sections

Plus	Minus	Interesting
Point sensing		
Energy efficient Effective for simple, long runs of pipes	Increases the number of circuits substantially for complex piping systems, leading to much higher installed costs and reduced reliability	Most common technique
Ambient sensing		
Minimises the number of circuits and installed cost	Energy consumption is greater than for point sensing unless self-regulating heaters are used	Most common technique used for protection against freezing

Plus	Minus	Interesting
Ambient sensing (cont'd)		
		The amount of heat provided to each pipe is proportional to its heat loss, regardless of whether it contains flowing or stagnant fluids
Dead-leg sensing		
Simple to design Leads to fewer circuits, resulting in higher reliability and lower installed costs		Good for freeze protection as well as for broad-range temperature control of complex systems To minimise wide temperature variation among the various pipes, self-regulating heaters are recommended Temperature ranges can approach those of point sensing

Heat transfer aids

In order to overcome inadequate heat transfer, any installation for maintaining more than 50-90°C should be installed with a heat transfer aid.

In the case of electric tracing, the simplest and most common heat transfer aid is aluminium tape with a high-temperature adhesive that is installed longitudinally over the cable and pressed down firmly.

Heat transfer cement is an alternative aid which may also be used with steam tracing. The cement is more efficient and also keeps cables cool. It is often applied to the irregular surfaces of flanges where it is difficult for the cable to remain in contact with the pipe / vessel wall.

Another method of improving heat transfer which is suitable for both electric and steam tracing is tack welding. The weld stops the tracing from falling off the pipe and a significant amount of heat is transferred through the weld material.

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Kenny TM, Steam Tracing: Do It Right, Chem Eng Prog, Aug 1992, 40-44

Lam V & Sandberg C, Choose the right heat-tracing system, Chem Eng Prog, March 1992, 63-67
Lonsdale JT, Little NJ & Bradford DL, Heat Tracing: Steam or Electric?, Chem Eng Prog, Dec 1995, 41-45
Patas JE, Take a Cool Look at Your Heat-Tracing Needs, Chem Eng Prog, Oct 1990, 45-46
Radle J, Steam Tracing Keeps Fluids Flowing, Chem Engng, Feb 1997, 94-97
Sandberg C, Heat tracing: steam or electric?, Hyd Proc, March 1989, 107-110

**APPENDIX C1 (PART 2) - EXAMPLE DECISION SUPPORT
DOCUMENT FOR EQUIPMENT CONFIGURATION SELECTIONS**

PUMP SETS

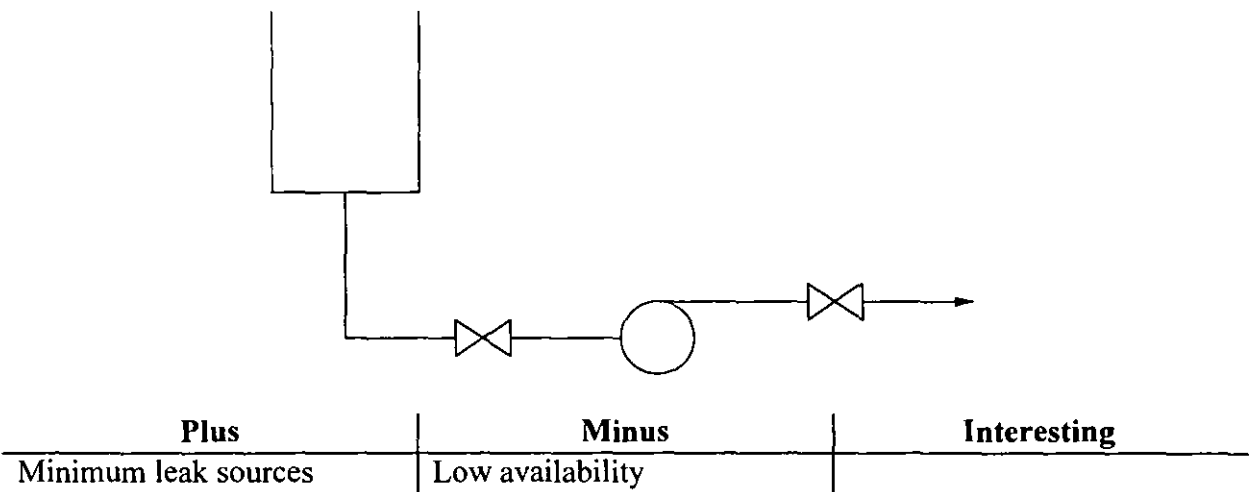
This document presents possible alternative configurations for pump sets incorporating any or all of the following:

- sparing / duplication
- kickback lines
- non-return valves.

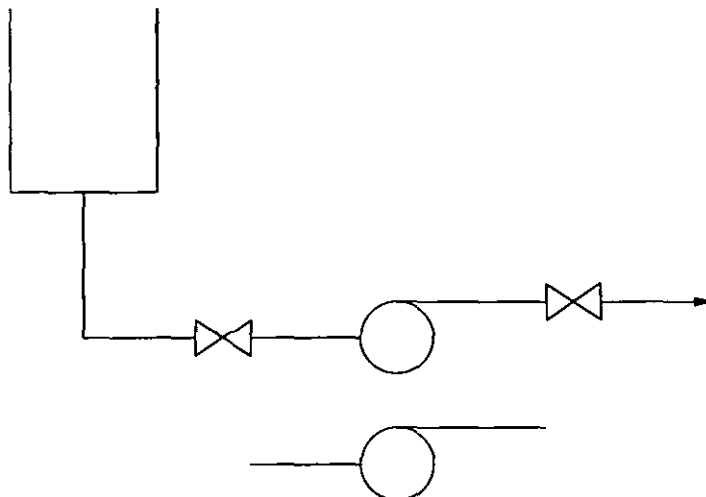
An illustration of each configuration option is given, followed by a table indicating the positive, negative and ‘interesting’ aspects of the particular arrangement shown.

1) Sparing / duplication

a) Single installed pump

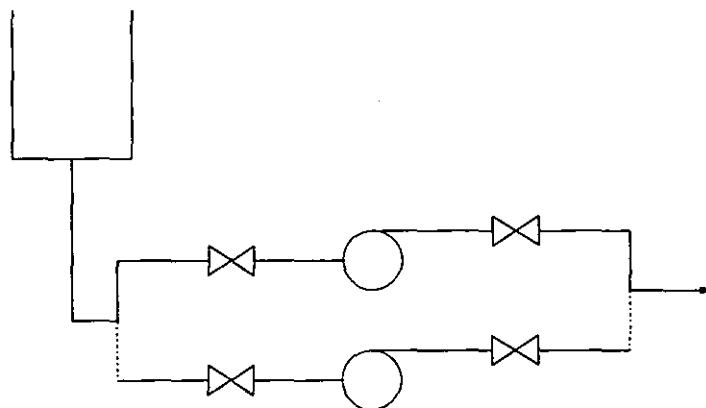


b) Single installed pump with warehouse spare



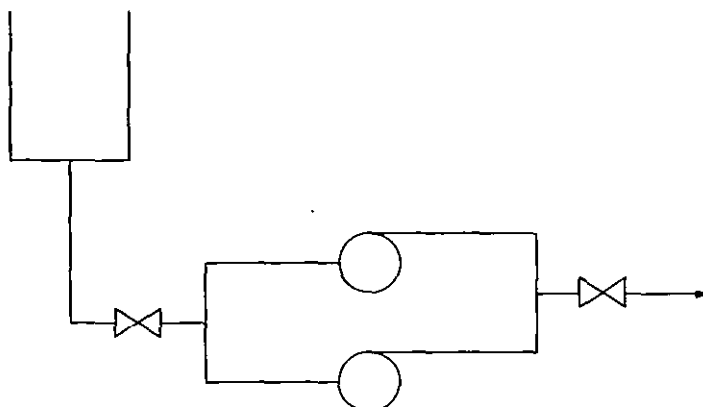
Plus	Minus	Interesting
Minimum leak sources Increased availability	Not suitable for hazardous areas	

c) Single installed pump with local uninstalled spare



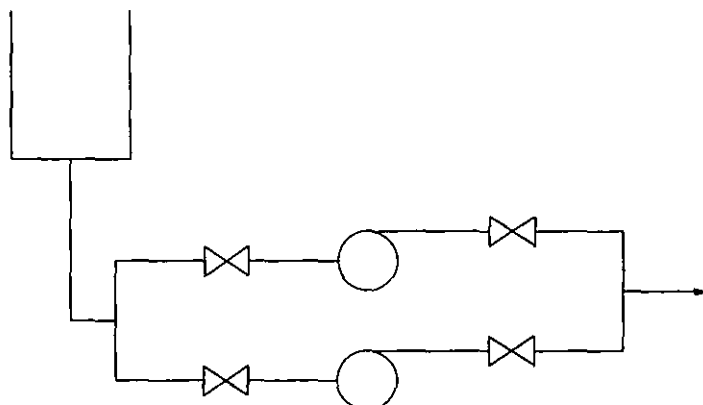
Plus	Minus	Interesting
Minimum leak sources Good availability	Not suitable for hazardous areas if pump needs to be changed without total shutdown	May eliminate need for intermediate storage

d) Duplicated pump with common isolation



Plus	Minus	Interesting
Excellent availability Suitable for hazardous areas	Stagnant pockets may cause problems, e.g. degradation of equipment Reverse flow will occur in the off pump if centrifugal Increased maintenance requirements Increased leak sources Increased inventory Increased complexity	May eliminate need for intermediate storage May lead to slack maintenance practice May increase pressure relief requirements

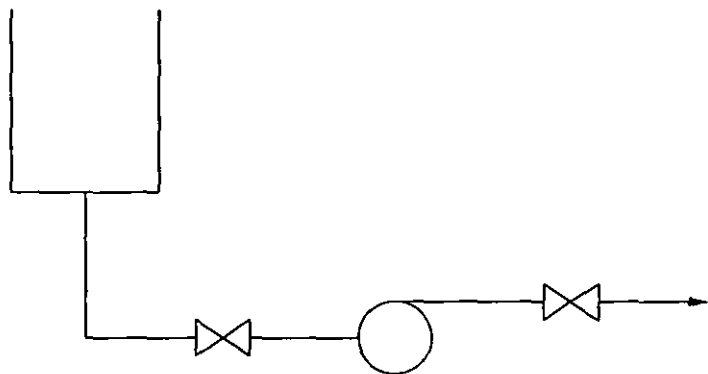
e) Duplicated pump with dedicated isolation



Plus	Minus	Interesting
Excellent availability Suitable for hazardous areas	Stagnant pockets may cause problems, e.g. degradation of equipment Increased maintenance requirements Increased leak sources Increased inventory Increased complexity	May eliminate need for intermediate storage May lead to slack maintenance practice May increase pressure relief requirements May lead to thermal expansion in the off pump

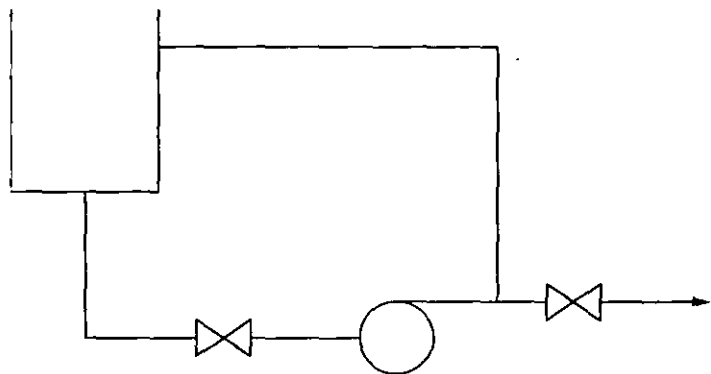
2) Kickback lines

a) No kickback line



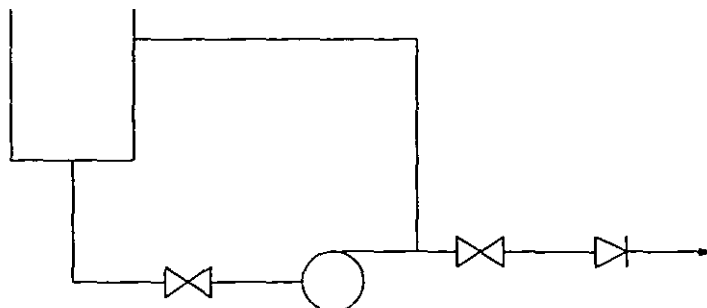
Plus	Minus	Interesting
Minimum leak sources	No protection against overheating due to dead-heading	

b) Simple kickback line



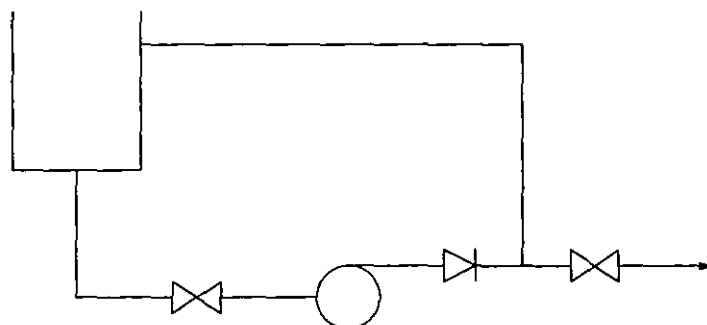
Plus	Minus	Interesting
Protects pump from overheating due to dead-heading Enables operators to check that the pump is working correctly (without dead-heading it) before bringing it on-line	Increased leak sources May introduce a reverse flow path to feed vessel May cause problems with isolation of pump / feed vessel	Kickback lines are often fitted with a restriction orifice to limit the flow through them Kickback lines generate fluid mixing Dead-heading for any length of time is more likely to occur on pumps with intermittent duties as it is not easy to alarm these for failure

c) Kickback line with reverse flow protection of pump and feed vessel



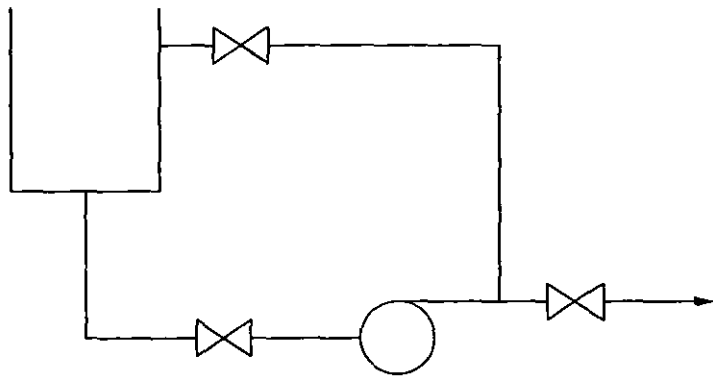
Plus	Minus	Interesting
Protects pump from overheating due to dead-heading Enables operators to check that the pump is working correctly (without dead-heading it) before bringing it on-line Reduces probability of reverse flow from downstream through pump or kickback line	Increased leak sources May cause problems with isolation of pump / feed vessel	Kickback lines are often fitted with a restriction orifice to limit the flow through them Kickback lines generate fluid mixing Dead-heading for any length of time is more likely to occur on pumps with intermittent duties as it is not easy to alarm these for failure

d) Kickback line with reverse flow protection of pump only



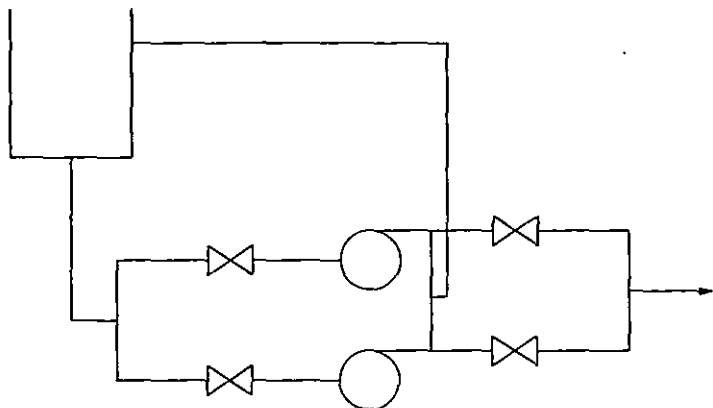
Plus	Minus	Interesting
Protects pump from overheating due to dead-heading Enables operators to check that the pump is working correctly (without dead-heading it) before bringing it on-line Minimises possibility of reverse flow from downstream through pump	Increased leak sources May introduce a reverse flow path to feed vessel May cause problems with isolation of pump / feed vessel May inhibit drainage of kickback line, depending on location of drain points	Kickback lines are often fitted with a restriction orifice to limit the flow through them Kickback lines generate fluid mixing Dead-heading for any length of time is more likely to occur on pumps with intermittent duties as it is not easy to alarm these for failure

e) Kickback line with isolation



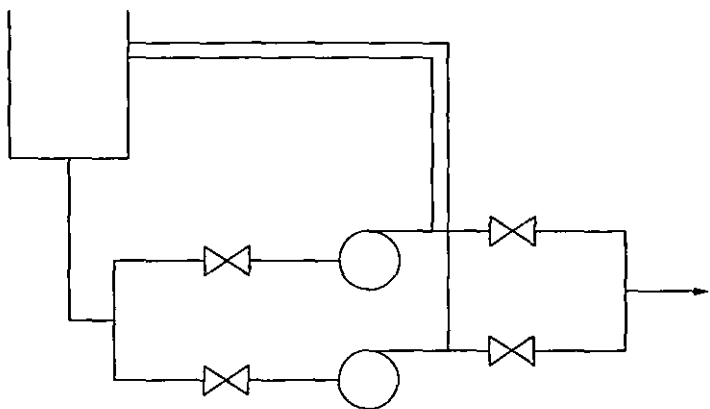
Plus	Minus	Interesting
Protects pump from overheating due to dead-heading Enables operators to check that the pump is working correctly (without dead-heading it) before bringing it on-line Feed vessel is isolatable independent of pump	Increased leak sources Increased complexity May introduce a reverse flow path to feed vessel Kickback isolation valve may be left shut and invalidate purpose of kickback line	Kickback lines are often fitted with a restriction orifice to limit the flow through them Kickback lines generate fluid mixing Dead-heading for any length of time is more likely to occur on pumps with intermittent duties as it is not easy to alarm these for failure

f) Duplicated pumps with common kickback line



Plus	Minus	Interesting
Protects pumps from overheating due to dead-heading Enables operators to check that the pump is working correctly (without dead-heading it) before bringing it on-line	Increased leak sources Increased complexity May introduce a reverse flow path to feed vessel May cause problems with isolation of pump / feed vessel Reverse flow may occur in the off pump	Kickback lines are often fitted with a restriction orifice to limit the flow through them Kickback lines generate fluid mixing Dead-heading for any length of time is more likely to occur on pumps with intermittent duties as it is not easy to alarm these for failure

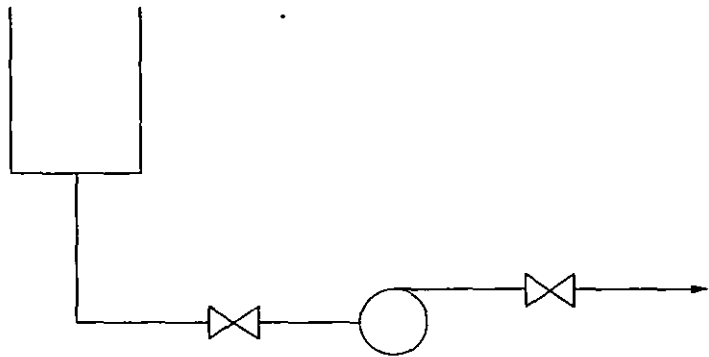
g) Duplicated pumps with dedicated kickback line



Plus	Minus	Interesting
Protects pumps from overheating due to dead-heading Enables operators to check that the pump is working correctly (without dead-heading it) before bringing it on-line	Increased leak sources Increased complexity May introduce a reverse flow path to feed vessel May cause problems with isolation of pump / feed vessel	Kickback lines are often fitted with a restriction orifice to limit the flow through them Kickback lines generate fluid mixing Dead-heading for any length of time is more likely to occur on pumps with intermittent duties as it is not easy to alarm these for failure

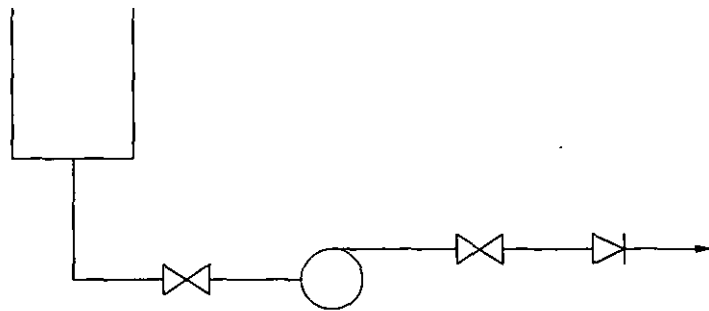
3) Non-return valves

a) No non-return valve



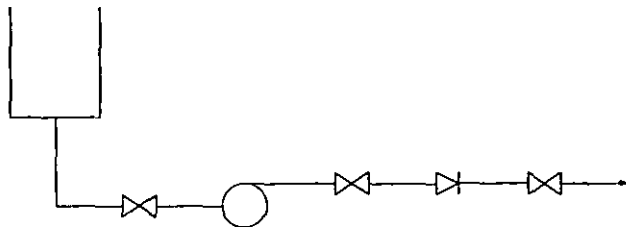
Plus	Minus	Interesting
Minimum leak sources	No protection against reverse flow	

b) Non-return valve isolatable from pump but not process



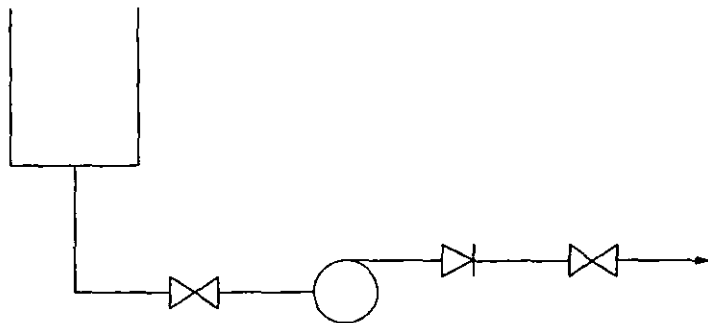
Plus	Minus	Interesting
Non-return valve helps to protect pump against reverse flow	Increased leak sources Non-return valve may inhibit drainage of pump delivery line Non-return valve cannot easily be maintained / replaced	

c) Non-return valve isolatable from pump and process



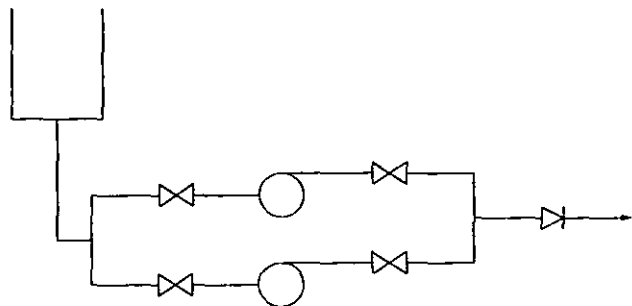
Plus	Minus	Interesting
Non-return valve helps to protect pump against reverse flow Non-return valve helps to protect against failure of pump delivery isolation during maintenance / replacement Non-return valve may easily be maintained / replaced	Increased leak sources Increased complexity Non-return valve may inhibit drainage of pump delivery line	

d) Non-return valve and pump isolatable from process but not from each other



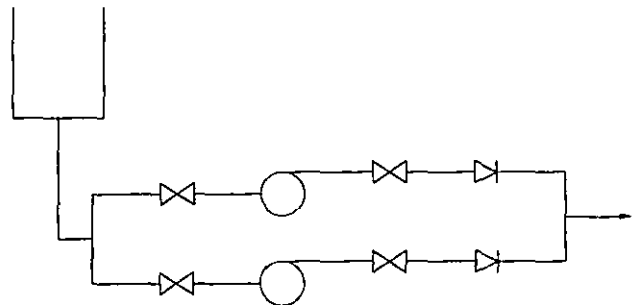
Plus	Minus	Interesting
Non-return valve helps to protect pump against reverse flow Non-return valve may easily be maintained / replaced	Increased leak sources Increased complexity	

e) Duplicated pumps protected from process by common non-return valve



Plus	Minus	Interesting
Non-return valve helps to protect pumps against reverse flow from downstream	Increased leak sources Increased complexity Non-return valve may inhibit drainage of pump delivery line Non-return valve cannot easily be maintained / replaced Non-return valve does not protect pumps from driving each other backwards in the event of isolation failure	

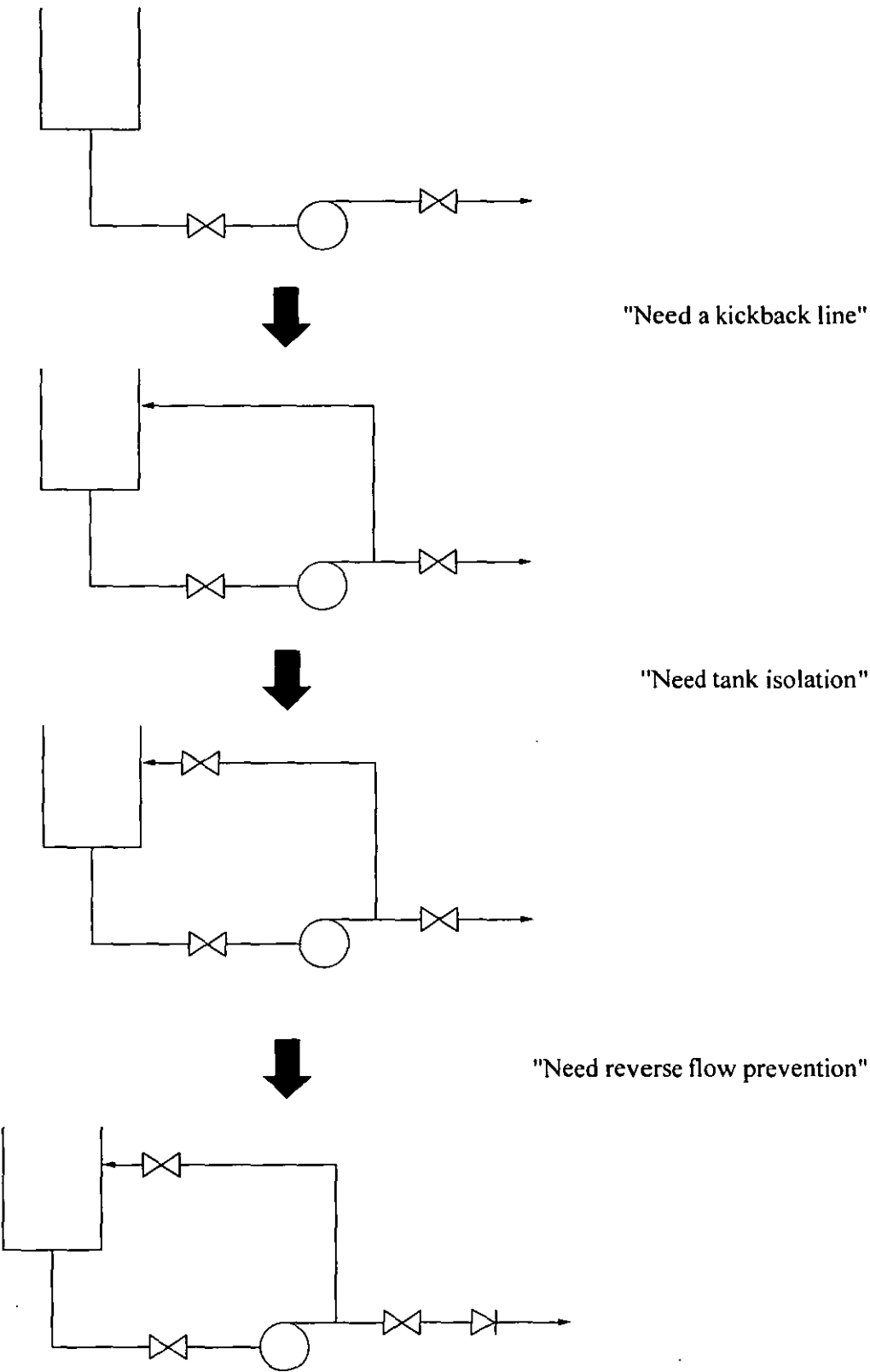
f) Duplicated pumps protected by dedicated non-return valves



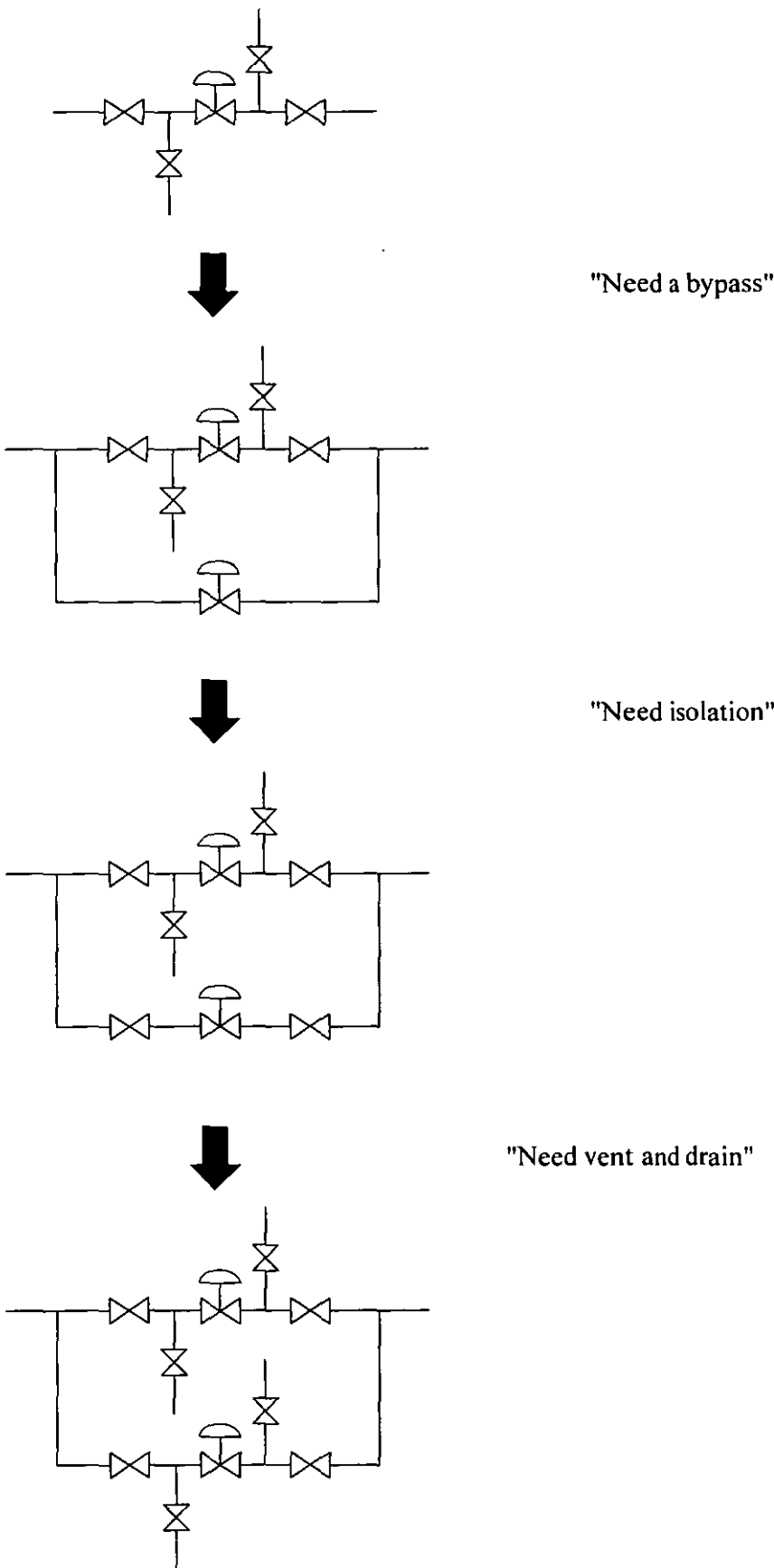
Plus	Minus	Interesting
Non-return valves help to protect pumps against reverse flow from downstream Non-return valves protect pumps from driving each other backwards in the event of isolation failure	Increased leak sources Increased complexity Non-return valves may inhibit drainage of pump delivery line Non-return valves cannot easily be maintained / replaced	

APPENDIX C1 (PART 3) - MODIFICATION CHAINS

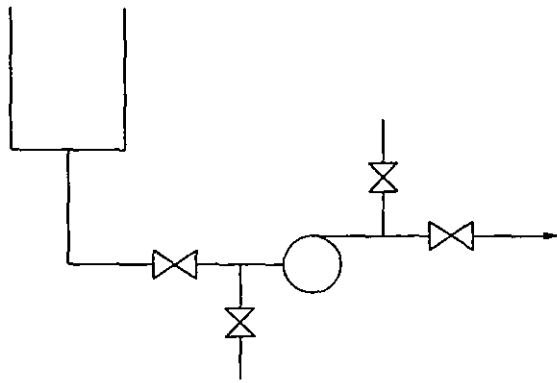
1) The kickback line



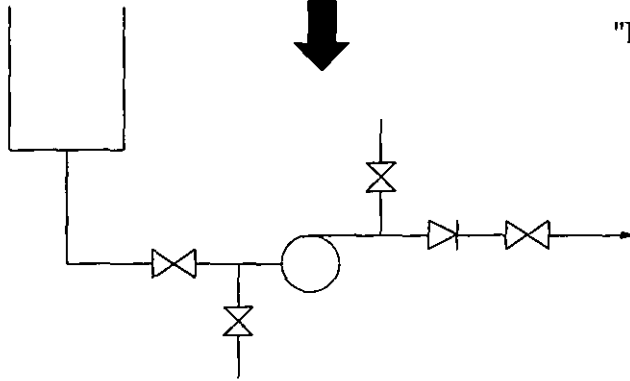
2) **The control valve bypass**



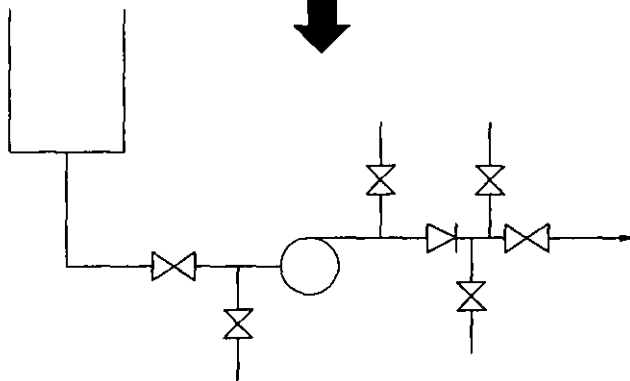
3) The non-return valve



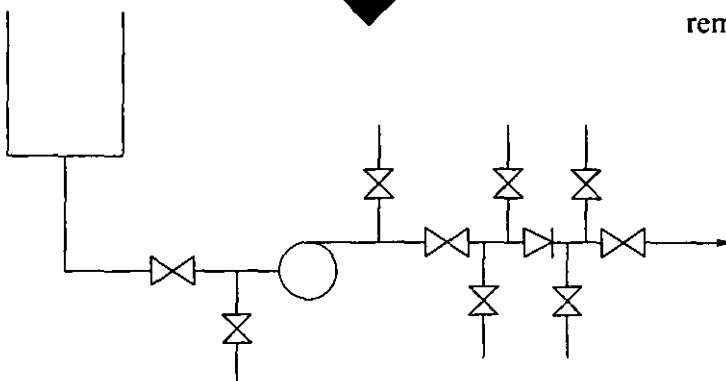
"Need reverse flow protection"



"Need to drain and vent line"



"Need to isolate pump from non-return valve for separate removal"



APPENDIX C2 (PART 1) - INHERENT SAFETY GUIDEWORDS

ECONOMICS

- Line size and material of construction may affect the decision to incorporate certain instrumentation, isolation valves or the location of instrumentation or the choice and location of control valves
- Consider the cost of spares plus associated secondary equipment such as pipework, valves etc.
- Line size and material of construction may affect the decision to install bypass lines and associated equipment

AVOID

- Extremes of velocity
- Obstructing pump suction lines with valves / intrusive instrumentation
- Overspecification
- Locating vessels with large or hazardous inventories at elevated positions
- Locating valves or instruments in positions where they will cause flashing of the process fluid
- Inherently unsafe equipment such as bellows or glass or plastic devices such as sight glasses, bulls eyes and sightports for toxic / flammable service
- Hazards, rather than trying to control them

MAKING STATUS CLEAR

- Provide independent facilities for checking that equipment has been drained
- Use figure of 8 (spectacle) plates in preference to spades for isolation
- Use rising spindle valves

SIMPLIFY

- Equipment, e.g. use open tanks
- Use gravity not pumped flow
- Minimal duplication
- Minimal / simple computer control
- Minimal equipment
- Minimal interconnections
- Use dedicated, not multi-purpose plant
- One vessel one job, not one vessel two jobs
- Eliminate reliance on interlocks by changing design so that hazardous condition does not arise
- Avoid complex pipework
- Minimise interdependence of flows

OPERABILITY

- Locate drains and sample points at accessible positions / elevations
- Locate sample points in safe positions and at ambient temperatures and pressures
- Trapped condensate drains require a venting / bypass system for start-up
- Consider the logistics of piping arrangements surrounding equipment and spares e.g. for isolation, drainage and switching
- Can operators be sent out to change spares or are the process conditions such that the spares should be permanently plumbed in (i.e. installed)

PROTECT

- Fire insulation
- Fire safe valves
- Fire walls
- Water cool / deluge
- Layout
- Zoning
- Bunds
- Explosion venting
- Blast walls
- Design for containment
- Design for vacuum
- Materials of construction
- Underground pipelines
- Use restriction orifices to maintain minimum flows as required during emergency shutdowns
- Paint piping or equipment that is to be insulated
- Interlocks
- Fusible links
- Fume / dust extraction

SUBSTITUTE

- Chemicals
- Physical form - e.g. reduce dust explosion hazards by using larger particle sizes or by handling solids as a wet paste or a slurry in water
- Cleaning fluids
- Services
- Heat transfer media
- Equipment
- Materials of construction

INTENSIFY

- Intermediate storage should preferably be small or nil

BEWARE

- Obstructions to purging
- Bypasses can be a source of unrevealed failures
- Inter-vessel overflows can lead to problems with contamination and effluent treatment
- Open or weeping bypasses can defeat control - especially level control
- Reaction forces on vent / sample point arms
- Cooling water additives e.g. nitrates can cause stress corrosion cracking of mild steel
- Nitrogen purging can introduce a risk of asphyxiation
- Environmental factors, e.g. sea spray can cause stress corrosion cracking of stainless steel

GOOD PRACTICE

- When possible, control processes by the use of physical principles rather than by added-on control equipment which may fail or be neglected
- For every control valve and sensor combination it is good to have independent confirmation using a sensor for a different variable that flow is present
- When equipment is prepared for maintenance it is recognised good practice to slip-plate or disconnect lines leading to other equipment items

TOLERANCE

- Set a minimum pipe size for mechanical strength
- Safe equipment opening facilities
- Metal is often inherently safer than glass or plastic
- Expansion loops are more inherently safe than bellows
- Avoid using hose - use fixed pipe
- Consider the need for additional valves to prevent unintentional discharge through a faulty valve

MINIMISE

- Inventory
- Fugitive emissions
- Waste
- Pollution
- Energy usage
- Number of leak sources
- Use of hazardous materials
- Residence time of hazardous materials
- Quantity of nitrogen introduced as purge
- Water hammer
- Frequency of shipments / loading / unloading

MODIFICATION CHAINS

- Isolation / maintenance
- Reverse flow paths
- Relief sizing
- Draining / venting / purging / switching
- Thermal expansion

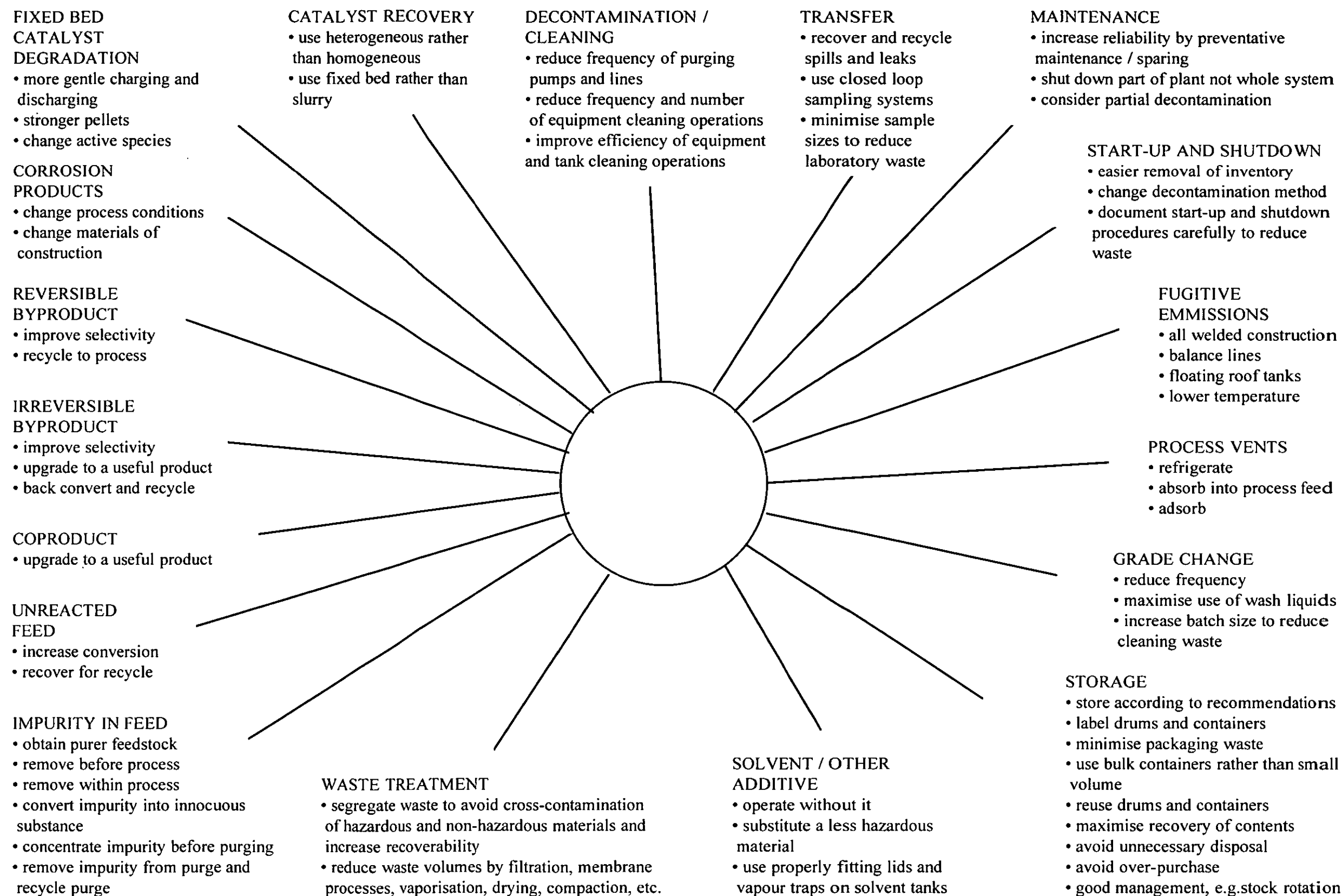
DIVERSIFY

- Ordinary and emergency devices should normally have completely independent action
- If a trip style system is used as a controlling device it cannot be regarded as a protection
- If duplicated non-return valves are required then use different types or different brands
- Do not rely on alarms or trips on sensors used for control - if there is sufficient incentive to include an alarm then use an extra, separate sensor

MODERATE

- Use restriction orifices to moderate flows in case of regulator failure
- Consider altering operating temperatures to avoid risk of flashing, autopolymerisation etc.
- Consider storing materials under less hazardous conditions, e.g. use dilution, refrigeration etc.

APPENDIX C2 (PART 2) - WASTE MINIMISATION GUIDEWORDS



APPENDIX D1 - PROCESS DESCRIPTION FOR MASTERCLASS EXERCISE

Authors: Paul Bujac/Duncan Woodcock

Date: 13 Nov 97

1 PROCESS DESIGN BASIS

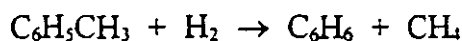
This plant is design to manufacture 66 000 tpa of benzene by the catalytic hydroalkylation of toluene. The feeds (toluene and hydrogen) are available on site and the product benzene is exported by road tanker. Benzene specification is 99.95% and a plant availability of 90% has been assumed.

2 PROCESS DESCRIPTION

2.1 Reaction Chemistry

The process chosen is the high pressure (25 barg), high temperature (590 - 650 C) exothermic hydroalkylation of benzene over a chromia-alumina catalyst.

The primary reaction is



Other reactions include the reversible formation of diphenyl



and non-reversible heavies formation.

Optimum performance, minimising heavies, is achieved by operating with a significant H_2 excess (eg H_2 :toluene 5:1). Typical per pass conversion is 70 - 85% with an overall yield of some 95 - 98%. The catalyst fouls slowly and requires regeneration by burning off heavies with air.

2.2 Block Diagram

Figure 1 shows the fundamental process blocks and main process flows. As well as the need to operate with the reactor feeds rich in H_2 , other constraints are the purging of byproduct methane (with an associated loss of H_2) and byproduct heavies (with associated losses of toluene and diphenyl). These purge streams are used as fuel and some of the value is recovered.

2.2.1 Feed import/storage

Toluene is supplied from an adjacent plant by pipeline. A buffer stock of 2 days requirements is provided in an atmospheric stock tank. Hydrogen is also available on site at the required pressure (30 barg).

2.2.2 Feed systems/pre-heating/reaction/primary separation

The feeds to the reaction section (toluene and H_2) are each composed of fresh feeds and recycles. The toluene feed (toluene from the stock tank and recovered toluene including some diphenyl and heavies from distillation) is pumped at high pressure from the liquid feed drum into the presaturator. The toluene is vaporised by heat exchange with the crude product and by steam. Fresh H_2 and recycled H_2 (from the primary separation via the recycle compressor and containing some CH_4) are also fed into the vaporiser. An intermittent purge is taken from the base of the presaturator and fed into the crude product line to prevent the build up of heavies.

The mixed vapour feed is then preheated to 600 C, first by heat exchange with the reactor off gas, and then by a gas fired furnace, before entering the fixed bed catalytic reactor. The reaction is exothermic and the gas temperature is controlled by addition of cold recycle H_2 .

The reactor offgases pass through the interchangers and are further cooled to 35 C, by cooling water, to condense out the bulk of the aromatics. The 2 phase mixture is separated in a phase separator. The condensate (benzene, toluene, heavies etc) is fed forward to distillation. The non-condensables (H_2 and CH_4) are recompressed and recycled. Some of the recycle is purged to the Works fuel header to remove the byproduct CH_4 (as a H_2/CH_4 mixture).

The catalyst becomes fouled with tars and requires intermittent regeneration. This will be achieved by feeding a preheated mixed nitrogen/air stream through the offline reactor. The regeneration offgas is fed to the preheater to complete the combustion of any hydrocarbons/CO etc.

2.2.3 Benzene distillation

The crude condensate is fed to the distillation column. This unit separates a pure overhead benzene product from both recycle toluene, taken as a sidestream, and heavies, the bottom stream. The reflux has limited sub-cooling and any lights are purged into the fuel header. The heavies are pumped into the works liquid fuel system. The column operates at 0.3 barg, using cooling water on the condenser and IP steam on the reboiler.

2.2.4 Product storage/export

Benzene from the still is cooled and stored in an atmospheric pressure stock tank and exported from the plant by road tanker.

3 PROCESS FLOW DIAGRAMS AND MASS BALANCES

See figure 2 and table 1.

4 FEEDSTOCKS, RAW MATERIALS, UTILITIES AND EFFLUENTS

4.1 Feedstocks

Toluene is imported by pipeline from an adjacent plant.

Hydrogen is available at suitable pressure also on an adjacent plant.

4.2 Raw Materials

Catalyst

4.3 Utilities

Steam (conditions etc)

Natural Gas

Process air

Instrument air

Nitrogen

Cooling water

4.4 Effluents

CH₄/H₂ purge from the recycle and still vent to the works LP fuel gas header

Heavies purge to the works fuel system

5 CONTROL AND OPERATING PHILOSOPHY

5.1 Primary control objectives

- a. To achieve demand make of in specification benzene
- b. To maintain inventories within process and storage tanks
- c. To maintain optimum reactor performance by controlling the feed rates, compositions and temperature into the reactor
- d. To purge out byproducts
- e. To optimise individual equipment performance

5.2 Operating states and transitions

Four stable operating states have been identified.

- a. Shutdown under maintenance
- b. Operating under total recycle
- c. Production
- d. Catalyst regeneration

These states and acceptable transitions are shown in figure 3.

5.3 Control systems

5.3.1 Feed import/storage

Control of the toluene feed maintains an adequate inventory in the stock tank. Compressed H_2 feed rate is controlled to maintain the total system pressure.

5.3.2 Feed systems/pre-heating/reaction/primary separation

The toluene feed (fresh toluene plus recycle) is flow controlled into the presaturator. The level in the vessel (essentially the toluene boilup rate) is controlled by the IP steam feed. The temperature of the gas leaving the furnace is controlled by adjusting the gas supply to the heater. The reactor temperature is controlled by the addition of cold recycle gas.

There is no direct control on the reactor offgas cooling. The level in the primary gas/liquid phase separator is controlled by varying the feedrate to the still. The recycle gas purge is flow controlled with the flowrate set by analysis.

5.3.3 Benzene distillation

The column operates at constant boilup rate, set by the steam flow to the reboiler. The reflux rate is set by the column profile. Any lights are purged out by operating the reflux condenser warm (temperature control via cooling water flow) and by pressure control. The product takeoff is controlled by the level in the reflux drum. The sidestream toluene recycle is removed under sump level control. A flow controlled purge of heavies is taken from the still base; the flowrate set by analysis.

The level in the recycle liquid feed drum is maintained by fresh input of toluene from the stock tank.

5.3.4 Product storage/export

The level in the product stock tank is maintained by setting the daily production rate.

6 RELIEF, BLOWDOWN AND DRAINAGE PHILOSOPHY

SECTION	PRELIMINARY REQUIREMENTS
Toluene storage	Fire relief on stock tank Bunding around stock tank
Vaporiser	Fire and process relief Local area drains to safe area
Preheater, reactor, heat exchangers, recycle	No relief
Primary separator	Fire relief Local area drains to safe area
Still and associated equipment	Fire relief Still designed to contain lockin pressure due to steam heating Local area drains to safe area
Recycle drum	Fire relief Local area drains to safe area
Benzene storage	Fire relief on stock tank Bunding around stock tank

7 MATERIALS OF CONSTRUCTION

Carbon steel throughout plant but alloy steels in high temperature areas.

8 HAZARDS

8.1 Flammability

All the streams are flammable.

8.2 Toxicity

All the process liquids are toxic with low occupational exposure limits.

9 ANALYTICAL REQUIREMENTS

- a. Recycle gas to set purge rate by controlling CH_4 content in H_2
- b. Crude product to monitor reactor conversion
- c. Benzene product
- d. Heavies to set purge rate and control heavies composition in still base

10 EQUIPMENT LIST

See table

Table Equipment List

Ref No.	Name	Function	Process P/T	Size
C311	Benzene Column	Separates lights, benzene, toluene recycle and heavies purge	1.1 bara 84/160C	2m diameter 20m T/T
D211	Phase Separator	Separates cooled reactor exit stream into vapour and liquid streams	21 bara 35C	1m diameter 3m T/T
D311	Benzene Column Reflux Drum	Stores inventory of reflux for Benzene column.	1.1 bara 84C	1m diameter 3m T/T
D312	Liquid Feed Drum	Helps to control liquid feed inventory	1 bara 115 C	1m diameter 3m T/T
E211	Presaturator	Vaporises liquid feed at its partial pressure in the mixed reactor feed	24 bara 140C	1m diameter 5m T/T 3.3MW
E212	Feed-Effluent Heat Exchanger	Superheats mixed reactor feed by interchange with reactor exit stream	23 bara 650/140C	11.2 MW 250m ²
E213	Furnace	Superheats mixed reactor feed to reactor inlet temperature	23 bara 560/600C	1.3MW
E214	Reactor Exit Cooler	Cools and reactor exit stream before phase separation	21 bara 150/35C	3.4MW 70m ²
E311	Benzene Column Condenser	Condenses benzene overheads	1.1 bara 84C	1.9MW 30m ²
E312	Benzene Product Rundown Cooler	Cools benzene product upstream of storage tank	1.1 bara 84/35C	0.2MW 10m ²
E313	Benzene Column Reboiler	Provides reboil for Benzene column	1.2 bara 160C	2.3MW 70m ²
E314	Toluene Recycle Cooler	Cools toluene recycle to allow operation of D312 at 1 bara	1.2 bara 120/35C	0.1 MW 5m ²
E315	Residues Rundown Cooler	Cools residues stream before discharge to site liquid fuel system	1.2 bara 160/35C	0.04MW 1m ²
P311	Benzene Column Reflux Pump	Returns reflux to top of Benzene Column	84C	
P312	Liquid Feed Pump	Boosts pressure of liquid feed to vaporiser pressure	1/25 bara 35C	20KW
P313	Residues Rundown Pump	Pumps residues stream to site liquid fuel system	1/2 bara 35C	
P411	Benzene Product Export Pump	Pumps benzene product from T411 to tanker	20C	
R211	Hydrodealkylation reactor	Adiabatic packed bed reactor that converts toluene to benzene	23 bara 600/650C	2.5m diameter 6m T/T
T111	Toluene Storage Tank	Stores toluene feed	ambient	300m ³
T411	Benzene Product Storage Tank	Stores benzene product	ambient	250m ³
X211	Gas Recycle Compressor	Boosts pressure of gas recycle to vaporiser pressure	21/25 bara 35/52C	0.2MW

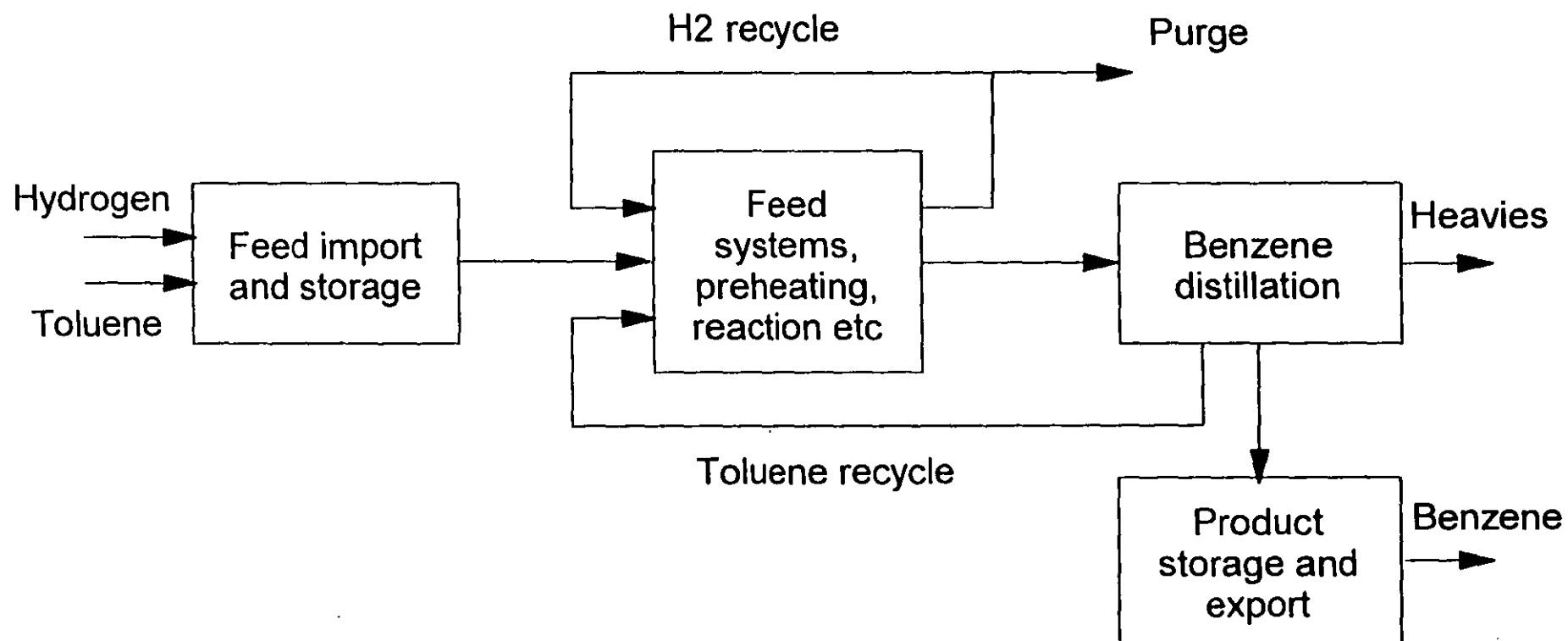


Fig 1 Block Diagram

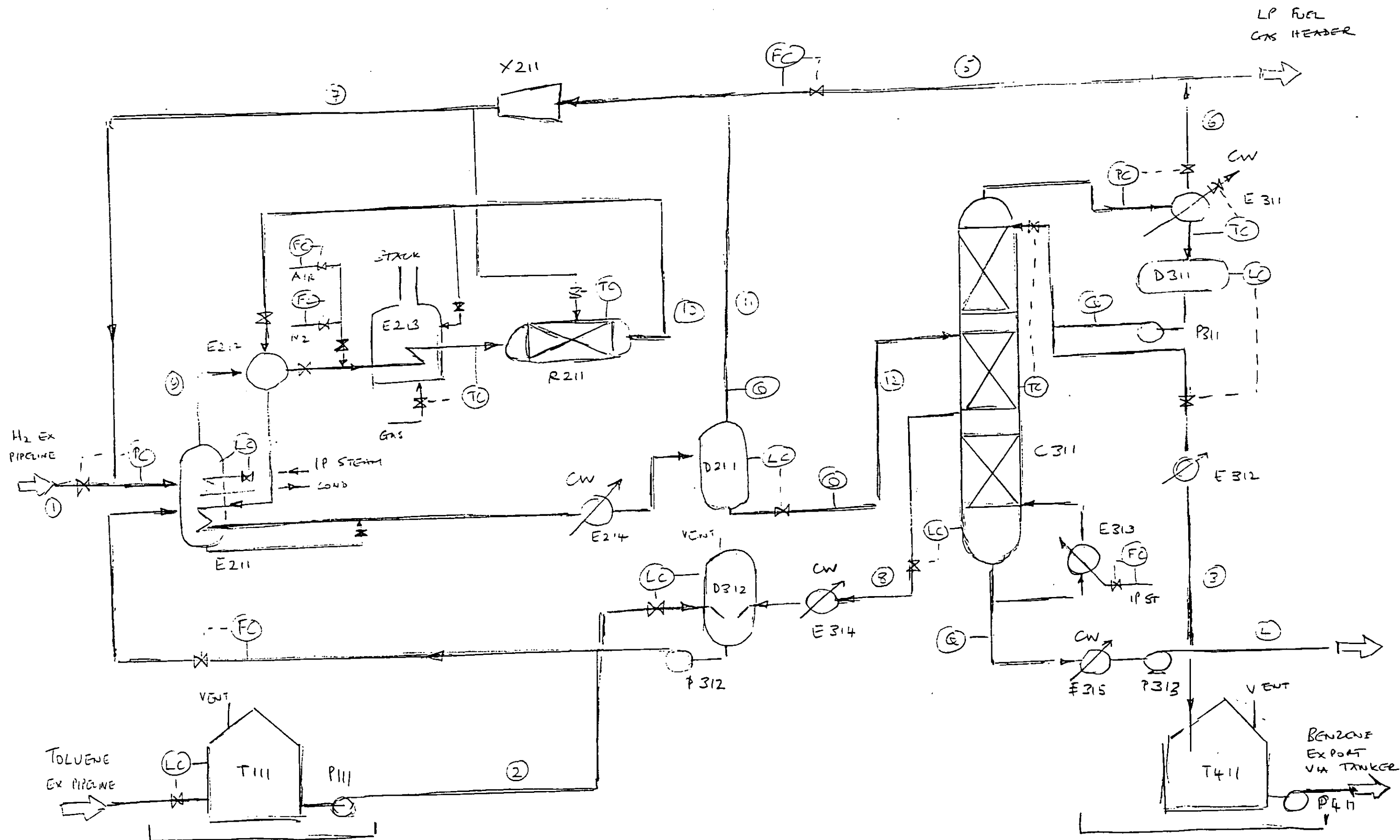


FIG 2

BENZENE PFD - PREMIUM

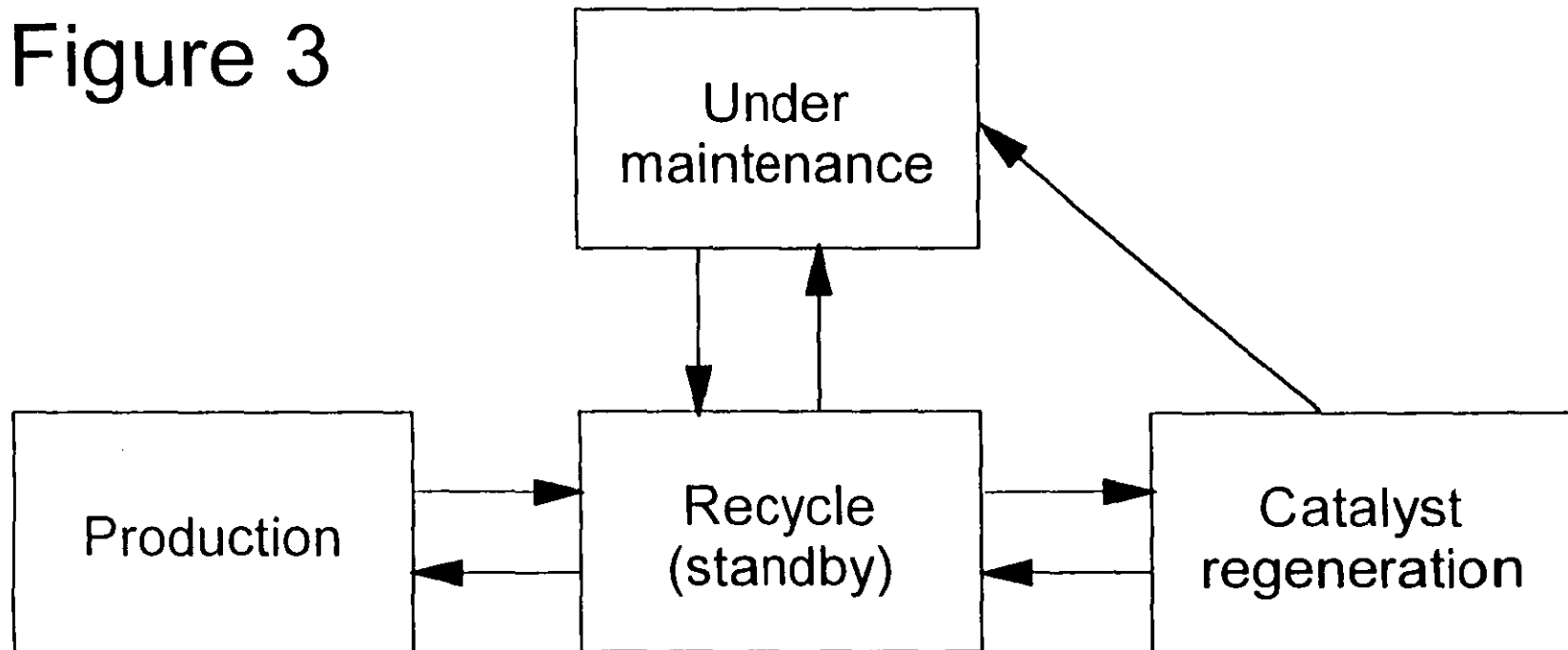
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TABLE MASS BALANCE

Kgmol/h	Molwt	1	2	3	4	5	6	7	8	9	10	11	12
H ₂	2	167.7				65.3	0.9	517.3		685.0	583.5	582.6	0.9
CH ₄	16	3.4				98.0	6.9	776.0		779.4	880.9	874.0	6.9
Benzene	78			100.0		1.4	0.1	11.1		11.1	112.6	12.5	100.1
Toluene	92		11.7		8.0	0.2		1.6	33.3	146.6	43.1	1.8	41.3
Heavies	[92]				2.0						2.0		2.0
Total		171.1	111.7	100.0	10.0	164.9	7.9	1306.0	33.3	1622.1	1622.1	1470.9	151.2
Temp	C	20	20	35	35	35	50	52	35	140	650	35	35
Pressure	bara	30				20.5	1.5	24.5		24	24	21	21

Kg/h	Molwt	1	2	3	4	5	6	7	8	9	10	11	12
H ₂	2	335				131	2	1035		1370	1167	1165	2
CH ₄	16	54				1568	110	12416		12470	14094	13984	110
Benzene	78			7800		109	8	866		866	866	975	7808
Toluene	92		1076		736	18		147	3064	13487	3965	166	3800
Heavies	[92]				184						184		184
Total		390	1076	7800	920	1826	120	14464	3064	28193	28193	16290	11904
Temp	C	20	20	35	35	35	50	52	35	140	650	35	35
Pressure	bara	30				20.5	1.5	24.5		24	24	21	21

Figure 3



APPENDIX E1 - PAPER ON INTERMEDIATE REPRESENTATION

INTERMEDIATE REPRESENTATION IN LINE DIAGRAM DEVELOPMENT (REPRESENTING DESIGN INTENT)

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Current methods for developing engineering line diagrams from process flow diagrams encourage the designer to add specific equipment at each decision. This can steer the design away from the optimal solution in terms of safety, health, environmental acceptability, operability and cost. An alternative method is proposed which allows the designer to specify more fully the *design intent* for the process. This is achieved by elaborating on the functional requirements of the plant. The designer can then specify equipment which best achieves those requirements. This paper identifies some objectives in engineering line diagram development that would benefit from this *intermediate representation*. Possible representations are described. Problems associated with representing *design intent* in a practicable way are discussed.

KEYWORDS Drawing, design intent, representation, process flow diagram, engineering line diagram.

INTRODUCTION

Process Flow Diagrams (PFDs) and Engineering Line Diagrams (ELDs) are critical stepping-stones in the design of any process plant. The PFD is a conceptual, or function-based, diagram which outlines the process route in sufficient detail for material and energy balances to be performed. By contrast, the ELD is an equipment-based diagram which represents the type and interconnection of all process hardware required on the plant.

Current practice in the development of ELDs from PFDs is more art than science. Public literature^{1,2} deals extensively with the subjects of how to draw a PFD or ELD and what information is to be included. However, there is a distinct lack of information or guidance on how to make the transition from function-based diagram to equipment-based diagram. Scott's^{3,4} work on ELD development is a notable exception.

The usual approach to ELD development is to add specific equipment with each decision. Thus each step in the ELD development consists of a decision to add equipment either to replace the functions represented on the PFD or to permit additional operations (such as start-up, etc.). Indeed, the symbols currently used in these drawings constrain the designer to do this. This constraint can lead to premature conceptions of the design solution. At the same time, only a statement of the specific equipment is carried forward - not the intent of that equipment. Overspecification and late changes in design often occur as a result of this approach.

INTERMEDIATE REPRESENTATION

An alternative approach is proposed in which the designer can expand on the detailed functions which need to be performed before specifying the equipment required to achieve them. Thus, in the process of ELD development, provision for additional functions such as maintenance, start-up and shutdown (which would not be shown on the PFD) will be explicit. Once the *design intent* has been expressed more fully in terms of functions, the designer can specify equipment which best achieves the stated intentions. In this way, solutions are found in the context of the extended functional description rather than by considering items of equipment individually. Hence, all interactions and possible multiple or ancillary functions can be identified. The expansion of the functions represented in the PFD to those which must be provided for in the ELD is termed, here, *intermediate representation*.

CLASSIFICATION

Several candidates for intermediate representation have been identified and classified according to their common features. These classes are defined below, together with an example of each class and the predicted benefits of their intermediate representation.

The five classes are represented in Fig. 1.

1) SECTIONAL CHARACTERISTICS

The common feature of problems in this class is that the designer wishes to assign a particular characteristic to all equipment within a section of the plant.

For example, insulation may be required on a column and all of its ancillary equipment.

A method for the intermediate representation of sectional characteristics would provide three benefits. The need for maintenance of individual equipment characteristics (with the attendant opportunities for error) is avoided. Change (or refinement) of the sectional requirement is simpler. Extension of the section to include other equipment is straightforward.

2) VARIABLE EQUIPMENT

The designer wishes to specify the function required but not to prescribe the equipment that will be used.

For example, the designer may wish to show that pressure relief will be required on a given vessel but may not want to decide (yet) whether a relief valve or bursting disc is more suitable.

Use of symbols denoting function (not form) avoids the foreclosure of options, whereas the use of standard hardware symbols implies a specific solution. If a pressure relief valve symbol is used to illustrate that pressure relief is required, it may later be assumed that a relief valve is the preferred method of relief.

3) VARIABLE LOCATION

The designer wishes to specify the function required but not the precise location.

For example, temperature indication is required between two points but no specific location is required.

Intermediate representation improves the opportunity of finding multiple equipment functions and of avoiding overspecification. Taking the temperature indicator illustration in

Fig. 2(c) as an example, it might be possible to eliminate the need for two temperature indicators by putting a single temperature indicator on the entry to the junction rather than having one on each of the two exit lines.

4) VARIABLE EQUIPMENT AND LOCATION

The designer wishes to specify the function required but neither the equipment to be used nor the precise location.

For example, flow from one vessel to another is to be prevented.

The use of intermediate representation allows the designer to defer decisions until all pertinent design factors are apparent. Taking the example of reverse flow prevention there might, for example, be cases when the specification of non-return valves would lead to unnecessary drainage complications which could easily be avoided by choosing a siphon breaker as the reverse flow prevention method. By making the intention (such as prevention of flow between two vessels) explicit it is also easier to recognise a decision which violates that intent. The benefits which apply to classes 2 and 3 also apply to this class.

5) ISOLATION

The designer wishes to isolate one or more equipment, or to alter the paths available for flow. This shares the same features as class 4, but is classified separately because:

- a) isolation of a number of lines will be considered together, as any item(s) to be isolated will normally have at least two associated flow lines (input and output)
- b) isolation is required for a number of different reasons, for example, isolation for maintenance, isolation for on-line spares, so the opportunity to meet multiple objectives with a single piece of equipment is particularly common.

Keeping track of the different reasons for isolation should allow the designer to be more confident in deciding where one piece of equipment can be used to meet multiple objectives. The benefits which apply to class 4 also apply to this class. For example, specific representation of the need for isolation on all lines to or from a vessel helps the designer to identify when a later decision will violate existing isolation strategies.

Further examples of problems in each class are given in Fig. 1.

POSSIBLE SOLUTIONS

Some proposals for intermediate representation are given here.

The representation of design intent for problems in the first class - sectional requirements - should not pose any great problems. All that is required is a box or other outline, and a qualifying statement. A possible representation is shown in Fig. 2(a). A single boundary is manipulated so that the extent of the boundary is clear. Additions to the section of the plant highlighted will by default acquire the sectional characteristic but exceptions may be made where appropriate.

The intermediate representation of the second class of problems - those with variable equipment type - simply requires the introduction of a new set of generic symbols. For instance, if pressure relief is required on a vessel, this may be represented as in Fig. 2(b). In fact a number of generic symbols for functions in PFDs are already in general use, so this proposal is an extension of current practice.

The major challenge lies in the representation of candidates which come into classes 3, 4 and 5 where location is a variable. There is no obvious way of doing this in a manner which will be simple and clear. Fig. 2(c) illustrates an example problem in class 3. In this case it is desired to show that temperature indication is required but its location with respect to the junction is not constrained. What is needed is a way to represent the fact that location can be left undecided, to provide for a more flexible response in later decisions. One solution for some of the candidates in class 4 might be to use highlights on lines, for example a *shadow* line could be used to mean no return flow is to be permitted (Fig. 2(d)). Alternatively, a similar problem might be solved by introduction of a symbol attached to a vessel with a qualifying statement such as 'no return flow to vessel A' (Fig. 2(e)).

A number of the solutions to the intermediate representation problem, presented above, rely on methods which can best be achieved using computer aided design (CAD) tools. Sectional requirements are particularly suited to CAD. Perhaps before CAD tools were available any intermediate representation would have been considered to be too time-consuming to be of benefit.

CONCLUSION

One of the major drawbacks of current methods for ELD development is the loss of clarity of design intent. This is brought about by an early commitment to specific process hardware, induced by the use of standard symbols.

New symbols and other forms of representation are proposed here which allow the designer to expand on the conceptual ideas provided in the PFD before progressing to the specification of equipment in the ELD. In this way, the design intent is more easily carried forward until all the functional intentions have been declared. The designer can then specify equipment which achieves these intentions.

Several candidates have been identified for intermediate representation and these have been classified as follows:

- 1) Sectional characteristics
- 2) Variable equipment
- 3) Variable location
- 4) Variable equipment and location
- 5) Isolation

Suitable representation of classes 1 and 2 is relatively straightforward, while representation of variable location (classes 3, 4 and 5) requires further investigation.

Potential benefits are foreseen in terms of generating simpler, cheaper and more inherently safe designs. These benefits include:

- emphasis on the importance of functions, by deferring specification of process hardware so that the problem is considered as a whole and the foreclosure of options is avoided,
- the introduction of 'function symbols' as a form of intermediate representation of the problem, making it clearer which decisions have been made and which have not, and making it easier to identify decisions which conflict with earlier decisions,
- deferring the specification of hardware solutions until all the interactions are known, so that there is an improved opportunity to perform multiple functions with fewer equipment and to minimise the incidence of late changes.

These benefits of intermediate representation combine to help the designer to find the optimum solutions in terms of safety, health, environmental impact, operability and cost.

ACKNOWLEDGEMENT

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FIGURES

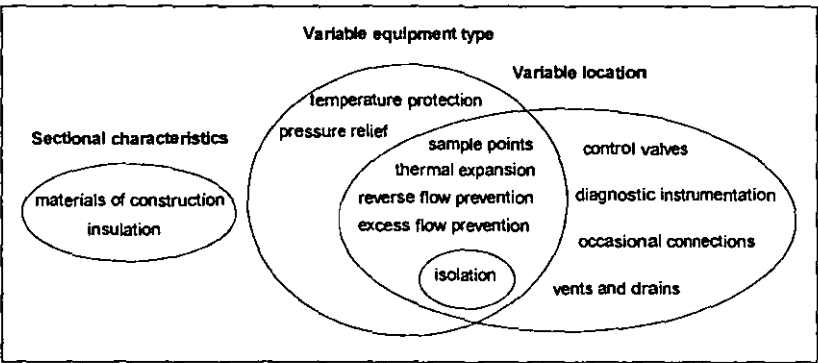


Fig. 1 Classification of candidates for *intermediate representation*

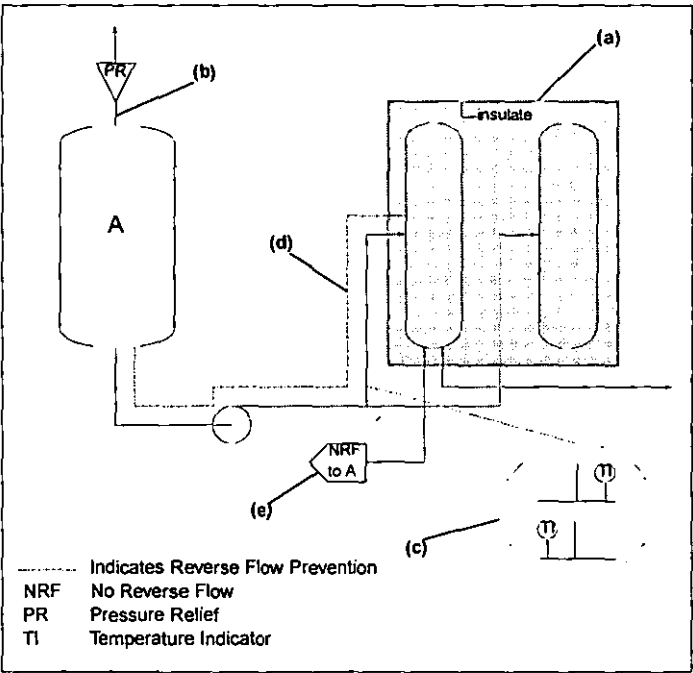


Fig. 2 Example illustrations of *intermediate representation*:
(a) Insulation as an example of allocation of Sectional Characteristics
(b) Possible symbol for pressure relief function
(c) An example illustrating the problem of conveying variable location
(d) Possible representation of the need for reverse flow prevention
(e) Alternative notation for reverse flow prevention

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