

PLANT DESIGN AND ECONOMICS

Table of Content

CHAPTER	DESCRIPTION		PAGE NO
1 PLANT DESIGN	PART A NOTES		1
	PLANT DESIGN		2
	1.1	Engineering And Design: View Points	3
	1.2	Process Flow Sheet	5
	1.3	Fundamentals of Process Design	6
	1.4	Defining Analysis	7
	1.5	Defining Synthesis	8
	1.6	Tools of The Design Process	9
	1.7	Process Design	10
2 EQUIPMENTS DESIGNING	2.1	Heat Exchanger	11
		2.1.1 Classification of heat exchangers	12
	2.2	Thermal Design Considerations	16
		2.2.1 Shell	16
		2.2.2 Tube	16
		2.2.2.1 Tube pitch, Tube layout and tube count	17
		2.2.2.2 Tube passes	17
		2.2.2.3 Tube sheet	18
	2.3	Schedule Number	18
	2.4	Birmingham Wire Gauge (BWG)	18
	2.5	Baffles	20
		2.5.1 Fouling Considerations	20
		2.5.2 Selection of fluids for tube and the shell side	21
	2.6	Process (Thermal) Design Procedure	21
	2.7	Design Problem	23
	2.8	Compressors	33
		2.8.1 Types of compressors	33
		2.8.1.1 Positive displacement type	33
		2.8.1.2 Dynamics compressors	33
		2.8.1.3 Reciprocating compressor	34
		2.8.1.4 Screw compressors	35
		2.8.1.5 Centrifugal compressors	35
		2.8.2 Type selection criteria	35
		2.8.2.1 Axial compressors	35
		2.8.2.2 Centrifugal compressors	36
		2.8.2.3 Reciprocating compressors	36
		2.8.2.4 Rotary compressors	36
	2.8.3 Design criteria	36	

2.9	Pressure Vessel Design	41
	2.9.1 Classification of Pressure Vessels	41
	2.9.2 Calculation of Stress For Pressure Vessels	41
	2.9.2.1 For Cylindrical Pressure Vessels	41
	2.9.2.2 For Spherical Pressure Vessels	42
	2.9.2.3 For Conical Pressure Vessels	42
	2.9.2.4 For Ellipsoid Pressure Vessels	42
	2.9.3 Design of Thin Walled Vessels Under Internal Pressure	43
	2.9.3.1 For Cylindrical Vessels	43
	2.9.3.2 For Spherical Vessels	43
	2.9.4 Heads And Closures	43
	2.9.4.1 Design of Flat Heads	43
	2.9.4.2 Design of Hemispherical Heads	44
	2.9.4.3 Design of Ellipsoidal Heads	44
	2.9.4.4 Design of Torispherical Heads	45
	2.9.4.5 Flanges on Domed Heads	45
2.10	Vessel Supports	45
	2.10.1 Saddle Supports	46
	2.10.1.1 Stress in The Vessel Wall	47
	2.10.2 Skirt Supports	47
	2.10.2.1 Skirt Thickness	48
	2.10.3 Bracket Supports	48
2.11	Absorption	50
	2.11.1 Types of Absorption	50
	2.11.1.1 Physical Absorption	50
	2.11.1.2 Chemical Absorption	50
	2.11.2 Types of Absorber	50
	2.11.3 Comparison Between Packed And Plate Column	50
	2.11.4 Packing	51
	2.11.4.1 Type of Packing	52
	2.11.4.2 Size of Packing	52
	2.11.5 Designing Steps For Absorption Column	52
	2.11.6 Selection of Column	53
	2.11.7 Design of Absorber	53
2.12	Pumps	60
	2.12.1 Centrifugal Pumps	60
	2.12.1.1 Slip Factor	65
	2.12.1.2 Losses in a Centrifugal Pump	65
	2.12.1.3 Characteristics of a Centrifugal Pump	66
	2.12.1.4 Cavitation in centrifugal Pumps	70
	2.12.1.5 Matching of pump and system	73

		characteristics	
		2.12.1.6 Effect of Speed Variation	74
		2.12.1.7 Variation of Pump Diameter	75
		2.12.1.8 Pumps in Series and Parallel	75
		2.12.1.9 Specific Speed of Centrifugal Pumps	76


3 PROCESS ECONOMICS	3.1	Introduction	78
	3.2	Debits and Credits	79
	3.3	Cost Accounting Methods	79
		3.3.1 Accumulation, Inventory and Cost-of-Sales Accounts	79
	3.4	Cost Estimation	80
		3.4.1 Fixed and Working Capital Investment	80
		3.4.1.1 Fixed Capital	80
		3.4.1.2 Manufacturing Fixed Capital Investment	80
		3.4.1.3 Nonmanufacturing Fixed Capital Investment	80
		3.4.1.4 Working Capital	81
		3.4.2 Types of Capital Cost Estimates	81
		3.4.3 Cost Index	82
		3.4.3.1 Estimating Equipment Costs By Scaling	82
		3.4.3.2 Marshall And Swift All Industry And Process Industry Equipment Indexes	82
		3.4.3.3 Engineering News Record Construction Index	83
		3.4.3.4 Nelson Farrar Refinery Construction Index	83
		3.4.3.5 Chemical Engineering Plant Cost Index	83
		3.5 Estimation of Total Product Cost	83
		3.5.1 Manufacturing Costs	84
		3.5.1.1 Direct Production Costs	84
		3.5.1.2 Fixed Charges	84
		3.5.1.3 Plant Overhead Costs	84
		3.5.2 General Expenses	84
		3.5.2.1 Administrative Expenses	85
		3.5.2.2 Distribution And Marketing Expenses	85
		3.5.2.3 Research And Development Expenses	85
		3.5.2.4 Financing Expenses	85
		3.5.2.5 Gross Earnings Expenses	85
		3.6 Interest And Investment Costs	85
		3.6.1 Types of interest	85
	3.6.1.1 Simple Interest	85	

		3.6.1.2 Ordinary And Exact Simple Interest	86
		3.6.1.3 Compound Interest	86
		3.6.1.4 Nominal And Effective Interest Rates	86
		3.6.1.5 Continuous Interest	87
3.7		Present Worth And Discount	87
3.8		Annuities	88
		3.8.1 Ordinary Annuity	88
		3.8.2 Relation Between Amount of Ordinary Annuity And The Periodic Payments	88
3.9		Continuous Cash Flow And Interest Compounding	88
3.10		Present Worth of an Annuity	88
3.11		Perpetuities And Capitalized Costs	89
3.12		Taxes And Insurance	89
		3.12.1 Types of Taxes	89
		3.12.1.1 Property Taxes	90
		3.12.1.2 Excise Taxes	90
		3.12.1.3 Income Tax	90
3.13		Insurance	90

4 DEPRECIATION	4.1	Depreciation	93
	4.2	Types of Depreciation	93
		4.2.1 Physical Depreciation	93
		4.2.2 Functional Depreciation	93
	4.3	Basic Terms	93
		4.3.1 Depletion	93
		4.3.2 Service Life	93
		4.3.3 Salvage Value	93
		4.3.4 Present Value	94
	4.4	Methods For Determining Depreciation	94
		4.4.1 Straight Line Method	94
		4.4.2 Declining Balance Method	95
		4.4.3 Sum of Years Digit Method	95
		4.4.4 Sinking Fund Method	95
		4.4.5 Comparison of Straight Line, Multiple Straight Line, Sum of Years Digit And Declining Balance Methods For Determining Depreciation	97
	4.5	Profitability, Alternative Investments And Replacements	97
		4.5.1 Mathematical Methods For Profitability Evaluation	97
	4.6	Rate of Return on Investment	98
4.7	Discounted Cash Flow	98	
4.8	Capitalized Costs	99	

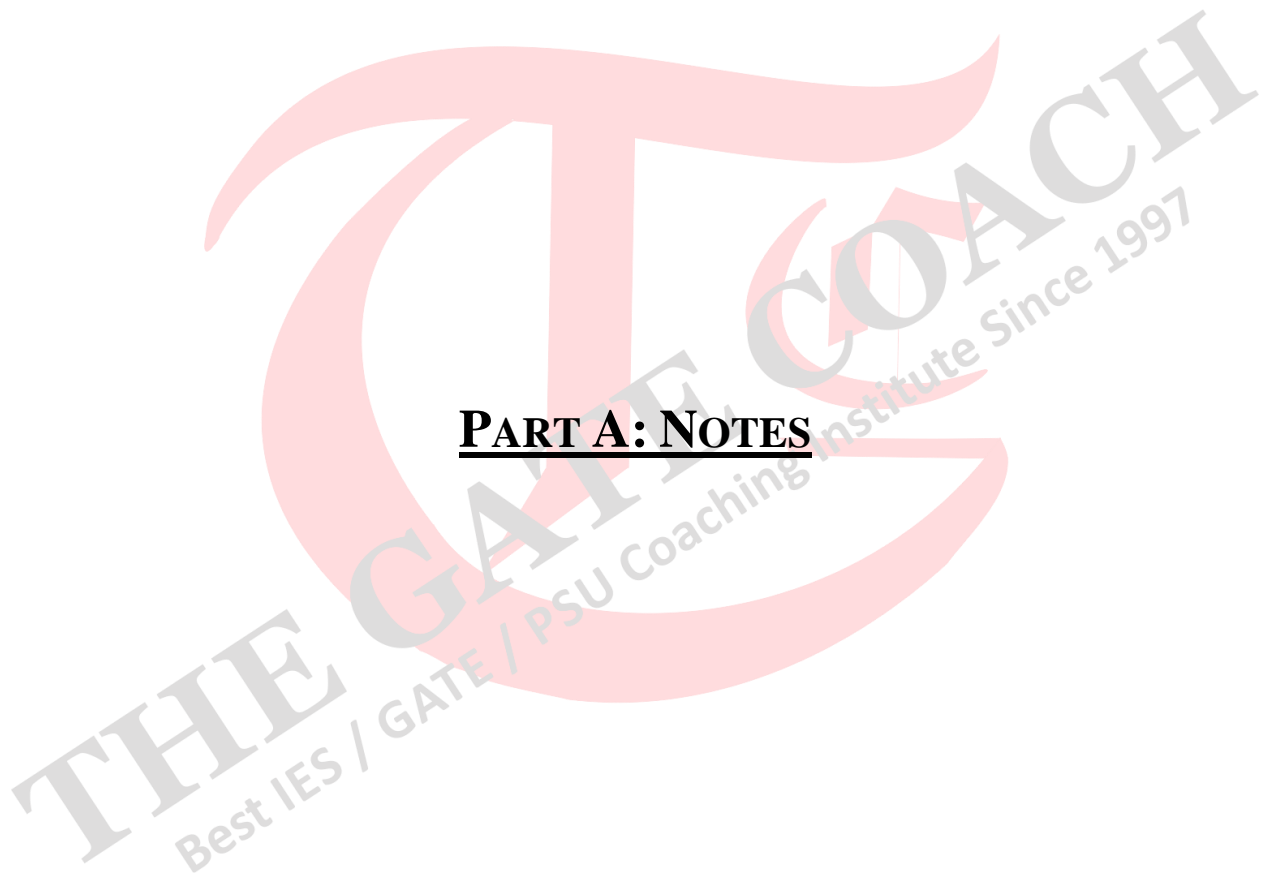
	4.9	Payout Period	99
	4.10	Optimization in Design	100
	4.11	General Procedure For Determining Optimum Conditions	100
		4.11.1 Procedure With One Variable	101
		4.11.2 Procedure With Two or More Variable	102

MULTIPLE CHOICE QUESTIONS	PART B	MULTIPLE CHOICE QUESTIONS	103
	LEVEL 1		104
	LEVEL 2		111
ASSIGNMENT	PART C	ASSIGNMENT	119
	UNSOLVED QUESTIONS		120-122



THE GATE COACH
 Best IES / GATE / PSU Coaching Institute Since 1997

PART A: NOTES



PLANT DESIGN



CHAPTER 1

PLANT DESIGN

1.1 ENGINEERING AND DESIGN: VIEW POINTS

It is necessary to examine the nature of design. Lockyer (1993) gives a good general summary.

Design is a most essential component of our society - it is the art or profession of creating a plan for something yet to be. The “something” can be a work of art, a manufactured product, a societal system, a business system, or the structure of an organization. It generally integrates theory and practice, and requires knowledge, skill and imagination in order to be successful.

The purpose of engineering is to create new material wealth. We attempt to accomplish this goal in chemical engineering via the chemical (or biological) transformation and/or separation of materials. Process and plant design is the creative activity whereby we generate ideas and then translate them into equipment and processes for the production of new materials, or for significantly upgrading the value of existing materials. In any particular company, we might try to generate new ideas:

- To produce a raw material currently being purchased
- To convert a waste by-product to a valuable product
- To create a completely new material (synthetic fibers, food, bioprocessing)

To find a new way of producing an existing product (a new catalyst, a bioprocessing alternate)

- To exploit a new technology (genetic engineering, process compression, expert systems)
- To exploit a new material of construction (high-temperature or high-pressure operation, specialty polymers for membranes)

It is necessary to extend the above to include the many aspects of engineering that are directed to meeting other concerns of society rather than just the creation of wealth. This includes, among other examples, waste treatment and energy conservation. When this first became an issue (coinciding with the escalation in crude prices), efforts to conserve energy often resulted in a significant return on the investment. However once all the “easy” revisions were made, many energy conservation revamps had to be justified on societal or environmental bases since there was little hope that they would ever justify the capital expense on purely economic grounds.

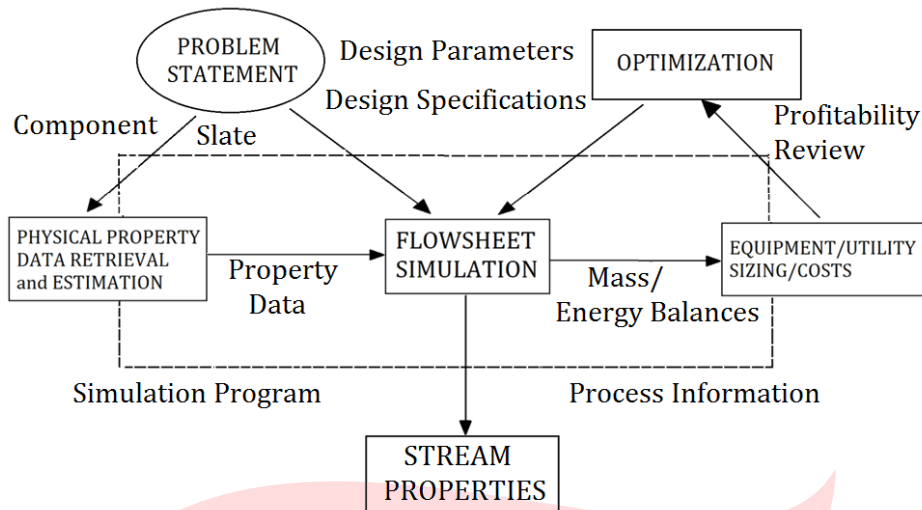


Figure 1.1. The tasks of Process Design.

Figure 1.1 summarizes the Process Design or Analysis task, and whether one is using a computer or slide rule, the principles remain the same. The initial step is the problem statement. What is to be designed and what is it meant to do? This statement must give the component slate and the design specifications. The component slate refers to all material that goes in, exists in the system, and comes out as product (reactants, by-products, products, and wastes). Design specifications are a lot more involved. What is the unit capacity? Is there a build-up consideration? What are the feed stocks, reactants and products? What utilities are available and what are the characteristics of these utilities? For example, what is to be used for cooling – water or air? Is there a need for refrigeration? What are the environmental constraints?

One of the most critical areas in any Process Design or Analysis problem is the question of physical and thermodynamic properties. (You are going to get tired of hearing this.) If the physical property data or the thermodynamic property data is questionable, even the most elegant flow sheet simulator in the world will not provide reliable information. The principle of GIGO (Garbage In = Garbage Out) is very true at this stage. It may not be exciting stuff, but accurate and reliable data is critical. The more sophisticated programs, such as ASPEN, PRO/II or HYSYS, have a very large amount of information within their system data banks. However, there will still be many situations when additional data must be supplied. Fortunately, these programs incorporate many of the most effective and up-to-date estimation routines, which can provide remarkably reliable estimates for many physical properties.

Reliable data, coupled with an appropriate statement of the problem, allows the flow sheet simulator to reach a solution. The solution of the flow sheet is then expanded with specific details of the units, including sizes, costs, and required utilities. These details

can be optimized, along with the technical aspects of the design. The flow sheet simulation may be revisited, as opportunities for refinements are identified, and an iterative process leads to an acceptable design. This point is never really a “finished” design, as the loop could be endless.

The stream property package of a design program is very important. It is essential information for the engineering specialists who have to carry out the mechanical design and construction phase of any project. The heat and material balances produced are necessary for these specialists also. The bulk of the equipment and utility sizing and costing is likely carried out as an independent exercise from the simulator itself, as we will do in our project this year. Some of this information can be imbedded in the actual simulator in an analogous fashion to the physical and thermodynamic properties.

Flow sheet simulation has many other applications over and above the initial design process. In recognition of this fact, the name of the course includes the term “analysis”. In today’s economy, where investment in the petroleum and chemical industries is minimal, you will likely encounter these systems more often in analysis than design situations.

All forms of information can be displayed. For example, an on-line simulator and operational management system on a process unit can actually carry out on-line rating studies, instead of being used for design purposes. This allows an operator to call up the flow sheet for a particular part of the process on the console for analysis. Possibly, a fractionation column is heavily loaded and the operator wants to see how close the column may be to flooding. This situation can have dire consequences for product quality; hence, strict monitoring is necessary. An on-line simulator is capable of performing this task by constantly scanning the unit for data and updating its calculations. It should be able to provide the data concerning the approach to flooding in essentially real time.

1.2 PROCESS FLOW SHEET

In any design, the most important document by far is the process flow sheet. It is essentially the shorthand summary of all the vital information concerning the design. Most design manuals may be left to gather dust on some obscure library shelf, whereas the process flow sheets are used in many aspects of the construction, start-up and operation of the unit.

As can be seen in Figure 1.1, there is usually a certain amount of feedback in the design process. This is essential to achieve an optimum design. Generally, this is done off-line, but many systems have some ability to optimize automatically. This aspect of process design is receiving more attention all the time. The same applies for existing processes, which are applied to older units to upgrade their performance and increase their

competitiveness. Case studies are generally required to satisfy the inevitable “what-if” s of the management, the market research groups, the operating personnel, and of course, those people who must concern themselves with the environmental aspects of the system.

1.3 FUNDAMENTALS OF PROCESS DESIGN

A typical scenario for a Chemical Process Design and subsequent involvement of the design personnel follows.

1. Board of Directors Design Problem	2. Discovery of Possible New Projects
3. Feedback and Customer Reaction	4. Planning and Organizational Design
5. Preliminary Process Design	6. Layout and Three Dimensional Modeling
7. Construction	8. Startup and Commissioning
9. Plant Operation	10. Debottlenecking
11. Decommissioning	

The final design process (steps 6 and on) is usually a linear exercise. However, it is not carried out without a significant amount of preliminary analysis and synthesis in order to ensure that an optimum choice has been made. In the Chemical Process Industries (CPI), and in particular petroleum refining, a great number of designs are comparable to one buying a print rather than original. Most clients have no interest whatsoever in being innovative. They want a package that has been thoroughly de-bugged, which usually means that it is “Number 312 out of a series of 1000”.

It is necessary to introduce the complementary concepts of Analysis, Synthesis and Design. Figure 1.2 on the following page comes from an article by Malone and Doherty in Foundations of Computer Aided Design.

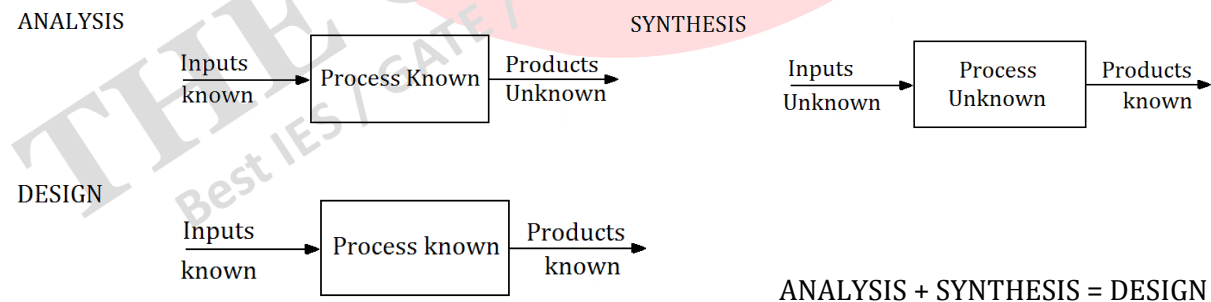


Figure 1.2. The complementary concepts of analysis, synthesis and design.

The innovation and creativity of design often take place in the analysis and synthesis stage. These stages are essential before one can proceed to the final design stage. In the field of fine arts, most artists will produce preliminary sketches and or maquettes of the finished piece. This is comparable to the synthesis stage – visualizing and planning what the final product will be. The amount of analysis and synthesis is directly related to the

“maturity” of the process. The success rate of new processes is only about 1 to 3% at the research stage, 10 to 25% at the development stage, and 40 to 60% at the pilot plant stage. This must be compared with buying an “off the shelf” package for a process unit. The research phase usually requires a great deal of analysis and synthesis before the process can be moved to the development phase.

At first, we will concentrate on the preliminary stages, Analysis and Synthesis. It goes without saying that one must have a thorough grounding in the fundamentals of chemical engineering and the related sciences. The ability to think “analytically” is essential, and there must be sufficient understanding of mathematics so that one can express physical situations in mathematical terms. Few practicing engineers can function effectively without being familiar with computer hardware and software.

1.4 DEFINING ANALYSIS

What do we mean by analysis? Fractionation is a unit operation that is employed almost universally in our profession. One of the most critical issues involved in the design of a fractionation system is the selection of the appropriate method for estimating vapour/liquid equilibrium. It must be emphasized at this point that most appropriate does not mean a method that allows one to achieve a simple and straightforward convergence of a simulator model. “Most appropriate” means a method that most closely represents the actual behaviour of the system. In this case, analysis of the output is essential to be sure that we’ve done what we set out to do.

One of the major criticisms of new graduates in engineering is that they very often regard the output from a sophisticated process simulator such as PRO/II or HYSYS as almost gospel. Although these programs are immensely powerful and important tools, it is absolutely essential that they be “calibrated” against reality for them to be of use. This is where the question of analysis comes in. All of the thermodynamic methods for estimating vapour/liquid or liquid/liquid phase equilibria are simply mathematical extensions of the simple ideal gas law. These extensions, be they Generalized methods, Equations of State, or Liquid Phase Activity Coefficient methods, are attempts to better represent the actual behaviour of the system. It has been said, perhaps somewhat facetiously, that all the many volumes that have been written concerning phase equilibria and the countless PhD’s that have been awarded, have resulted in simply many proposed procedures that are nothing more than glorified curve fitting routines.

For many systems, years of experience with actual operating units, backed up by a great accumulation of plant operating data, has allowed design engineers to select a method that will give acceptable to excellent representation of the system in question for most common operating temperature and pressure regions. When one must deal with a

new system, and of course the number of possible systems is infinite, as is the number of operating regimes that one must deal with, there is always some measure of risk in selecting an appropriate thermodynamic method. There are some guidelines that will allow the designer to select a reasonable first method. For example, relatively ideal mixtures at high pressure and temperatures generally can be represented by one of the more common equations of state, Redlich - Kwong, or Peng-Robinson. On the other hand, it is well known that highly non-ideal mixtures at low temperatures and pressures can only be adequately represented by activity coefficient procedures.

If the design is one of many that have been built and operated previously, this is not normally an issue. If it is a novel development, there is a very real need to analyze the data quite closely to ensure that the predictions are a good representation of reality. This analysis can take the form of experimental determination of binary data, statistical analysis of plant data, or even pilot plant data. Often data from similar systems can be analyzed and used to give direction as to the best approach.

Analysis is certainly not restricted to engineering. The business world depends on critical analysis for the success of most activities. Market research depends on analysis of masses of data, as does profitability analysis of any enterprise. There are some quite exciting new concepts and technology available for analysis of systems. The question of complex and chaotic systems and the mathematics used to describe these systems is an emerging area of analysis that would appear to have the potential to allow us to examine systems that have in the past appeared to be completely unpredictable. Although the subject is most fascinating, we must leave it for another time.

1.5 DEFINING SYNTHESIS

What do we mean by synthesis? Synthesis is the process of converting an abstract description into a more refined description. It is a drawing together of what is known about the possibilities for the process, the desired outcomes, and theoretical knowledge that lays the foundation for the work. In order to accomplish any of the diverse design requirements, there is never one simple straightforward "design". Design is nearly always a matter of compromise. Hazelrigg suggests that the engineering design process should be regarded as a decision-making process rather than a problem-solving process. Problem solving implies a linear process where, given the data and appropriate equations or methods, one can plug in the data and crank out a "correct" answer.

In the case of a "design", what makes one design a good design and another a bad design? These concepts are value judgments and they depend to a very large degree on what are the controlling criteria. If you are working for a corporation a "good" design often means a design that makes a profit. A firm understanding of the principles of

microeconomics is an essential for any practicing engineer who has a design responsibility. There are other social imperatives that must be taken into consideration in addition to simply making a profit. A superb design that makes a good profit but emits an identifiable amount of an environmental Bête noire such as Dioxin would not be acceptable.

When you take the various criteria into consideration and couple this with the unavoidable uncertainties in the design process, it should be obvious that there is no one “correct” design. The usual approach to cope with this situation is PROCESS SYNTHESIS, where the designer constructs several preliminary design options. By a system of comparison and elimination, a choice is made as to what the “final design” will look like. Unfortunately, there is usually a lag of some three to five years between having made a decision to proceed with a “Process Design” and the eventual start-up of a process. Depending on the nature of the process, there can be a great deal of risk associated with this design choice. For a well-established, well-known process such as a crude tower in an oil refinery, the risk is probably not that significant. On the other hand, for the first of a kind unit to produce a new polymer, the risk can be very considerable.

1.6 TOOLS OF THE DESIGN PROCESS

Some comments regarding computer hardware and software are in order at this point. The evolution of the tools available to the practicing professional engineer over the last forty years, from slide-rules and nomographs to extremely powerful hardware and software has happened at an unprecedented rate of change. Most if not all practicing professionals will have the occasion to use computers in their everyday work. Not everyone will have the need to use some of the more powerful tools available, but it is essential that the young engineer at least have a working knowledge of these systems. It should also be obvious that some individuals are better suited for this aspect of engineering than others.

There are some important issues to keep in mind that you might call “street smarts”. First, it must be recognized that there is an appropriate tool for the task at hand. It has often been observed that young professionals tend to err on the side of using much more “horse-power” than is required. There are many occasions particularly in the analysis and synthesis phase of a project where ‘Back of the Envelope’ calculations are all that is necessary. Since the unit cost of using a sophisticated system has become almost inconsequential, it is all too easy to delude oneself into thinking that a more sophisticated routine will give a better answer than some quick calculations, using no more than a pencil, paper and possibly a pocket calculator.

There certainly is a place for the very powerful systems available such as PRO/II, HYSYS, Maple, and MatLab, however one must appreciate that these systems are simply an

adjunct to our own ability to think and question. As these systems evolve and become increasingly powerful, as they must do, this problem will become even more acute.

What is the role of programming languages such as FORTRAN, and C++? Many engineers who were exposed to computers in the sixties learned FORTRAN as a matter of survival. FORTRAN is considered by many to be like a weed; others systems such as C++, Pascal and so on will come along, but FORTRAN will always be there somewhere. Does a practicing engineer need to be expert in the use of these languages? Alternate programming systems such as spreadsheets have become so powerful that they can handle a great number of problems that used to require knowledge of a language such as FORTRAN. Systems such as Maple, Mathematic, and MatLab, and MathCad provide a mathematical suite that was unheard of only a few years ago. Many are of the opinion that it would be preferable to spend the time examining the higher level systems than programming languages.

The vital skills involved in the decision-making process may be engineering, but engineers must borrow from other fields such as mathematical optimization, probability theory, stochastic risk assessment, microeconomics, utility theory, forecasting and regression analysis, decision analysis, operations research and games theory.

1.7 PROCESS DESIGN

Process design can be defined as the design of processes for desired physical and / or chemical transformation of materials. Process design is central to chemical engineering, and it can be considered to be the summit of that field, bringing together all of the field's components.

Process design can be the design of new facilities or it can be the modification or expansion of existing facilities. The design starts at a conceptual level and ultimately ends in the form of fabrication and construction plans.

Process design is distinct from equipment design, which is closer in spirit to the design of unit operations. Processes often include many unit operations.