

PROCESS SYNTHESIS

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INTRODUCTION

In the words of Webster, *synthesis* is "the combining of often diverse conceptions into a coherent whole" and *analysis* is "an examination of a complex, its elements and their relations." Synthesis refers to the more inventive aspects of engineering and analysis to the more scientific. Both are required in the development of industrial processes.

Since World War II engineering education has moved strongly towards analysis, with the introduction of courses which analyse individual process operations and phenomena. Transport phenomena, unit operations, process control, thermodynamics and other engineering science courses greatly strengthened engineering education by showing how things are and how they work.

Unfortunately, there was not a parallel development in the teaching of synthesis. The teaching of how things ought to be rather than how they are. This deficiency has been recognized for years, but the remedy awaited the development of sufficiently general principles about which to organize educational material.

The dominance of engineering science reveals a natural tilt in the educational landscape towards course material which possesses a natural organization. At the University, well organized and easily taught material rises to the surface.

A course in transport phenomena has the natural organization of the equations of change, thermodynamics has the first, second and third laws, unit operations can be organized about the various processing operations and so it is with the courses which dominate. This kept synthesis in the background in spite of the important role synthesis plays in the practice of engineering. Methods of synthesis were not well organized and easily taught, and for this reason synthesis could not rise to the surface.

In the late 1960's and early 1970's, research in process synthesis established the broad outlines of this field and it became apparent that a careful interlacing of synthesis and analysis is a

proper way to approach process development. In these theories of process development, each synthesis step defines an analysis problem the solution of which provides data required for further synthesis steps. Further, it became apparent that this organization of alternating synthesis and analysis steps begs the development of educational material for the early stages of engineering education.

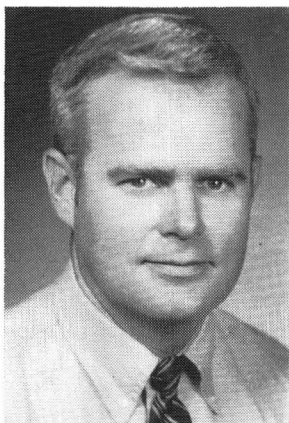
In this report we examine the development of a first course in engineering in which synthesis and analysis are taught simultaneously. Elementary new principles of process synthesis are combined with the classic analysis techniques of material and energy balancing. Emphasis is on the development of process technology rather than on the analysis of existing processes.

RESEARCH IN PROCESS SYNTHESIS

Research in process synthesis has been adequately reviewed elsewhere and it would be a distraction here to go into any great detail.* However, a brief discussion of the broad ways of thinking found in the research literature is necessary to set the stage for the educational developments. This, then, is a most superficial review of the emerging research leading to principles for the development of the process flow sheet. Three approaches to process synthesis are apparent; problem decomposition, evolution and optimization.

In process synthesis by *optimization* a combined design is proposed which is known to be redundant, containing process equipment and material flows in a greater number and diversity than is reasonable. However, somewhere hidden within the combined process design is an economically reasonable process. The desired process flow sheet is exposed by the methods of mathe-

*J. E. Hendry, D. F. Rudd, J. D. Seader, *AIChE J.* (to appear)



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Specializing in research on methods of process design, Professor Rudd has been a frequent consultant and lecturer in industry. In addition to contributions to the research literature, he is co-author of *Strategy of Process Engineering* and the forthcoming *Process Discovery*. In his books he has integrated modern mathematical concepts, a knowledge of industrial processes, and recent advances in econometrics to produce a novel treatment of process design and analysis.

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mathematical programming which trim away all but the flow sheet sought. This approach to design synthesis has been quite successful in specific problems such as heat exchanger network synthesis.

In process synthesis by *evolution* one begins with a reasonable design, a base design, which may not be the economically optimal one. Methods are then developed to detect the weak parts of the design, pointing to reactors which ought to be replaced, separation operations which ought to be reordered and so forth. From the base design there evolves better process designs.

Process synthesis by problem *decomposition* takes a completely different look at the problem, leading to the natural organization sought in the teaching of process synthesis. In decomposition a synthesis problem is decomposed into a sequence

Science aims to analyze natural phenomena, and engineering aims to synthesize preferred situations from natural phenomena.

of smaller and simpler problems which when solved generate the flow sheet for the original process development problem. The success of this approach depends on the accuracy with which the simpler problems can be identified. J. J. Siirola and G. J. Powers are largely responsible for the development of this approach.

In brief outline, flow sheet synthesis by problem decomposition occurs by the solution to these basic problems. First the chemical reaction path is established. This is the sequence of reactions which best transforms the raw materials into the products on the industrial scale. The second problem is one of species allocation in which a mapping of material flow is proposed from raw material and reaction site sources to product, waste and reaction site destinations. During species allocation the easiest set of separation problems are sought. The third problem is the selection of the physical and chemical phenomena which best accomplish the separation problems which arose from the species allocations. The final problem is task integration in which the several separate reaction and separation phenomena are integrated by the reuse of energy and material.

In the following section we give a glimpse of the detailed approach to process synthesis by problem decomposition, and emphasize the teaching of these methods as the first course in engineering.

TEACHING PROCESS SYNTHESIS

We now focus attention on undergraduate education in engineering, which in recent history, has a strong emphasis on the analysis of specific processing phenomena and operations. Our concern is to complement these courses with an introductory course which shows how these specific fields fit into the larger plan of process development. Along with this orientation, certain basic methods of engineering synthesis and analysis are taught.

We have had several years of classroom experience with this approach at the freshman and sophomore level. In mid 1973 Prentice-Hall Inc. will publish *Process Synthesis* by D. F. Rudd, G. J. Powers and J. J. Siirola.* The chapters in this book are now reviewed.

*D. F. Rudd, G. J. Powers, and J. J. Siirola, *Process Synthesis*, Prentice-Hall, Englewood Cliffs N.J. (1973).

Engineering of Process Systems

First the students become acquainted with a bit of the history of processing to see how chemistry is used, how materials are separated and how economy is reached by the reuse of material and energy. In class we discuss the recovery of nitrogen from the atmosphere for use as a fertilizer, the conversion of vegetable protein into meat analog foods for human consumption and the treatment of sewage at the South Lake Tahoe plant, the most advanced sewage treatment facility in the world.

On their own, as home problems, the students prepare a short history of important process innovations. One project is to report on the events which led from Sir Alexander Fleming's discovery of penicillin to the massive process development campaign to provide enough penicillin to accompany the troops during Eisenhower's landing in Europe. A second project begins with this beer recipe from "Hints to Brewers," 1702.

"Thames water, taken up about Greenwich at low tide, when it is free of all the brackishness of the sea and has in it all the fat and sillage from this great city of London, makes a very strong drink. It will of itself ferment wonderfully, and after its due purgation and three times stinking, it will be so strong that several sea commanders have told me that it has often fuddled their murriners"

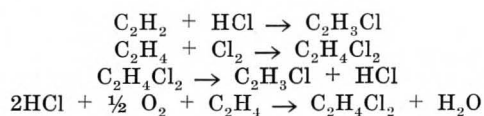
and traces the development of the activated sludge process for sewage treatment.

The students get a feel for processing, and discover the role that the engineer plays in supplying society's needs for food, water and other material items.

Reaction Path Synthesis

The first major subproblem in process synthesis involves the selection and analysis of the chemistry of processing. The chemistry links the products of processing with cheap and readily available materials, and generates wastes and by-products with which we must contend. In this course we do not teach chemistry; we teach the assessment of chemical change.

For example, given these reactions which lead to vinyl chloride,



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the students learn to select the reaction sequences which require for each two molecules of vinyl chloride,

- two molecules of ethylene, one of chlorine and oxygen. This reaction path is to generate no by-products other than water.
- one molecule of ethylene, one of acetylene and one of chlorine. No by-products are allowed for this path.

The students also learn the basic principles of economic screening of the reaction paths they synthesize. The idea is that the products must be more valuable than the reactants if a reaction path is to be of any commercial interest.

Home problems include an analysis of the chemistry involved in these areas: the recycle of pickling liquor waste, acrylonitrile from propylene, titanium by chlorination, waste recycle in the solvay process, sodium bicarbonate by the solvay chemistry, superphosphate fertilizer, leaching copper ores, caustic manufacture the leBlanc process, soap manufacture, nitrogen fixation, fire retardant production, urea synthesis, and so forth.

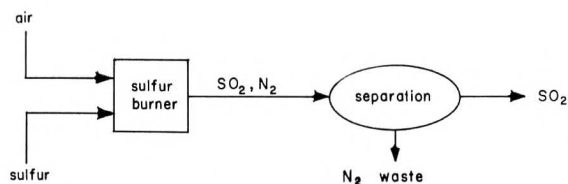
In summary, the students are acquainted with the chemistry of processing, synthesize alternate reaction paths from given chemistry and perform early economic screening of the chemistry.

Materials Balancing and Species Allocation

Once the chemistry of processing is at hand, the problem arises of supplying the reactor feeds and disposing of the reactor effluents. This leads to the next major subproblem in process synthesis, species allocation. The purpose of species allocation is to identify the routes that the several species involved ought to take to support the chemistry and at the same time lead to the simplest separation problems. Given the needs of the chemistry, we allocate species for easy separation.

As a trivial example, suppose we are to manufacture sulfur dioxide by the direct oxidation of sulfur. Air and sulfur are the reactant sources and pure sulfur dioxide is needed as the product. A cold inert gas is needed to lower the reaction temperature. Figure 1 shows two allocations, one recycling sulfur dioxide as the inert and the other using nitrogen as the inert. The one allocation leads to the need to separate nitrogen from oxygen, a difficult problem and the other leads to the separation of sulfur dioxide from nitrogen, an easy problem. This illustrates how the engineer assesses the nature of separation problems and uses this information to impose the proper material flow on the emerging process flow sheet.

Allocation 1



Allocation 2

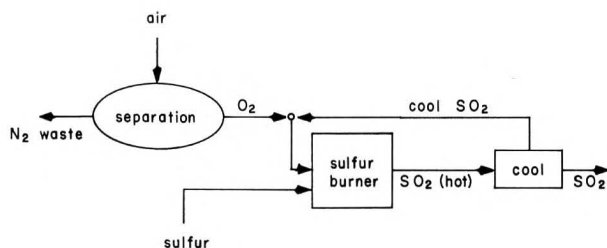


Fig. 1. Alternate Species Allocations During Sulfur Oxidation.

Before anything can be taught about species allocation as a technique in process synthesis, the students must have skill in material balancing. We spend the bulk of this chapter on material balancing, and it is only towards the end of the chapter that the idea is introduced that the real purpose of material balancing is to identify those allocations which involve easy separations.

Typical problems on material balancing and species allocation involve sugar refining, oil and meal from seed, soluble coffee powder production, phosphate rock beneficiation, city refuse composting, fish liver extraction, glycerine desalting, and the manufacture of styrene.

Separation Technology

Species allocation is directed towards the identification of the easiest separation problems which have to be solved to support the process. This leads to the need for an understanding of the means by which materials are separated from each other. One seeks to identify the ways in which the materials differ, and develop equipment to exploit the proper differences. In this chapter we examine some of the separation processes, mainly to get an understanding of how the equipment works.

Equipment separating solids from solids are examined, along with equipment which accomplish separations based on volatility differences, and solubility differences. For example we examine the Nowak-Othmer scheme for separating the redmud waste from the Bayer Process, which

is a mixture of Al_2O_3 , Fe_2O_3 , SiO_2 , TiO_2 , Na_2O and CaO , by taking advantage of the differences in chloride forming affinity of the oxides, differences in volatility of the metal chlorides, and differences in water solubility. All of this orientation in separating technology is supported by material balance calculations and provides the background required to select the basis of separation, discussed in the next chapter.

Typical problems include municipal solid waste recycle, nut meat separation, activated carbon from saw dust, cranberry draining, copper sulfate leaching, desalting sea sand, and the Caban-Chapman process of mercury recovery.

Strategy of Task Selection

Having established the chemistry of processing, outlined the flow of material through the process, and obtained an understanding of the general means of separation, the students are prepared for the study of the heuristic principles of task selection. We examine the ways in which separations ought to be performed to achieve efficient processing.

Techniques are presented for examining the ordered lists of physical and chemical properties of materials to detect the best plan of separation. Table 1 shows the species present in the reactor effluent in the Sinclair-Koppers 500 million pounds per year light olefin process; the species ordering is according to volatility, the property to be exploited to separate the methane and hydrogen for use as fuel, the ethylene and the propylene as products, the ethane and propane for recycle, and the heavies for processing into motor fuels. What principles lead to the discovery of a sequence of distillations to accomplish the separation?

Table 1. Reactor Effluent Ranked According to Volatility. (Sinclair-Koppers 500 million lbs/yr ethylene process)

Species	Amount	Boiling point	Boiling point difference
Hydrogen H_2	18%	-253°C	92°C
Methane C_1	15	-161	57
Ethylene C_2	24	-104	15
Ethane C_2	15	-89	41
Propylene C_3	14	-48	6
Propane C_3	6	-42	42
Heavies C_4^+	8	70	

To be separated into: 1-Hydrogen-methane; 2-Ethylene; 3-Propylene; 4-Ethane-propane; 5-Heavies.

In this chapter we establish the following general principles

1. Of the many differences which may exist between the source and destination of a stream, differences involving composition dominate. Select the separation tasks first. This heuristic is based on the idea that attention should not focus on differences in

pressure, size, temperature, and other bulk properties until after the means of separation has been established.

2. **When possible reduce the separation load by stream splitting and blending.** Here we reduce as much as possible the amount of separation to be performed, as is done in the blending of gasolines to each desired product specifications.
3. **All other things being equal, aim to separate the more plentiful components early.** This reduces the load on the down stream units.
4. **Remove the corrosive and hazardous material early.** The remaining separations can then be done in less elaborate equipment.
5. **The difficult separations are best saved for last.** The extremely expensive separations should not be performed in the presence of material which need not be there.
6. **All other things being equal, shy away from separations which require the use of species not normally present in the processing.** This favors separations driven by the addition or removal of energy, such as distillation, over those driven by the addition and removal of material not normally present in the processing, such as extraction.
7. **Avoid excursions in temperature and pressure, but aim high rather than low. In distillation favor the removal one-by-one of the more volatile components.** This rule derives from the high costs of low temperature and low pressure operation compared to pressure and temperature operation.
8. **Favor the removal of products from the least harsh environment.** For example, the final products in a distillation sequence ought to come from the top of the towers, rather than the bottoms where degradation may occur.

The application of these heuristics to a large extent identifies the separation sections of industrial processes. For example, the student examining Table 1 would arrive at these conclusions.

- a) the boiling points of propane (42°C) and propylene (48°C) are very close, as are the boiling points of ethane (89°C) and ethylene (104°C). Thus the C₂ splitter and the C₃ splitter ought to be last to place the most difficult separations in that position.
- b) to get at the C₂ and C₃ fractions species more volatile and less volatile must be removed. We favor the removal of the more volatile methane and hydrogen to raise the temperature of coolant needed to drive subsequent distillations. This will reduce utilities costs substantially.
- c) the ethylene and propylene ought to be tower top products to insure the removal of degradation products.

These heuristics explain the gross features of the Sinclair-Koppers process the flow sheet of which is shown in Figure 2.

This kind of heuristic reasoning leads to an understanding of the separation sections of a wide variety of processes.

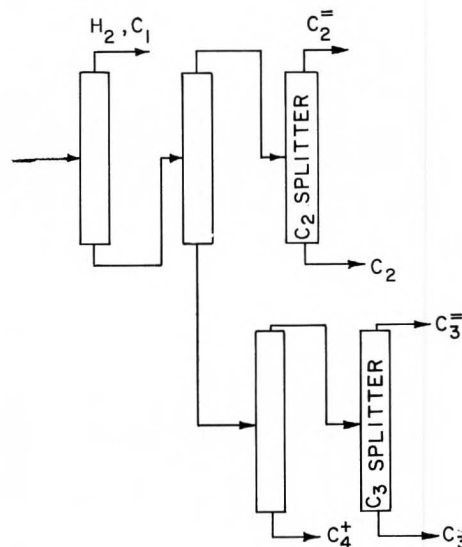


Fig. 2. Sinclair-Koppers Separation Flowsheet.

Typical home work problems involve the processing of cheese whey, crushed rock screening, high purity beryllium from the oxide, detergent manufacture, allyl chloride production, the development of screening circuits and an examination of many other industrial processes.

Task Integration

The skelton of the process has been discovered when the processing tasks were defined in the previous chapters. Many of these tasks involve the addition and removal of energy, and these are costly operations. The last subproblem of process synthesis introduced is task integration where we free the process as much as possible from the purchase of heating and cooling service. We seek to have one task in the process drive other tasks, by the integration of their operation.

Before task integration can be attempted, the elementary principles of energy balancing must be presented. We show how the heat energy added to a system and the work done by a system are related to the enthalpy changes which occur in the material passing through the system. Then, methods of estimating the enthalpy change caused by temperature change, phase change, and chemical change are presented. This gives the quantitative background required for the understanding of the energy management principles to be discussed.

We show how energy management principles are used to supply heat to endothermic reactions, to remove heat from exothermic reaction, and to utilize the energy of product recovery. For example, the endothermic reaction of calcining limestone can be driven by matching it with an exothermic reaction, the combustion of coal: the be-

ginner can calculate how much coal is needed per ton of limestone processed, obtaining a more complete picture of raw material costs in lime production.

The synthesis of networks of heat exchangers to recover sensible energy is discussed using the simple but approximate criteria of avoiding heating and cooling with external sources of these expensive utilities.

Typical problems include freezing of fish fillets, gas desulfurization, energy storage in checker brick regenerators, cost of sugar evaporator operation, and processing of junk cars by freeze milling.

Fresh Water by Freezing

The scope of each of the preceding chapters was limited in turn to a specific aspect of process synthesis. Such limitations are necessary and desirable to present a compact package of knowledge which can be digested without too much difficulty. In practice no field is as clean and orderly as textbooks tend to describe it to be. This is certainly true of the field of process synthesis.

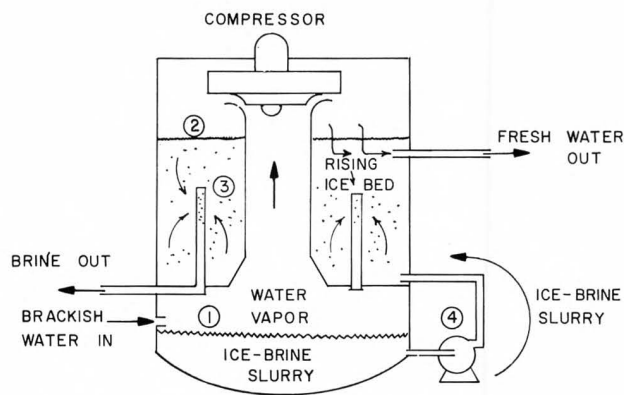
For one thing, few, if any, real problems are equally balanced among the several topics presented in the earlier chapters. Some problems are dominated by the chemistry, others by task sequencing still others by a critical separation, and many by the integration of energy and material use. Further, an experimental program usually parallels process synthesis for rarely is sufficient information to be found in the literature on phenomena to be exploited in a new area of processing. Finally, the early discovery stages of engineering are not sufficiently detailed to arrive at just one process, and several alternatives survive to undergo the detailed engineering studies necessary to determine economic and engineering feasibility.

These things are now brought into focus by tracing the development of a process to obtain fresh water from brackish water. We risk the appearance of contrived spontaneity by condensing the years of work of a number of engineers into a scenario of process discovery. However, it is important for the reader to come close to the act of discovery, even if the discovery is only one simulated by the authors.

This chapter begins with the observation that the *ice crystals formed in brackish water are salt free*, and ends with processes now commercially available for the production of fresh water. This engineering problem is dominated by task integration problems, for it is the cost of energy which dominates the water cost. Figure 3 is a schematic drawing of the vacuum freezing-vapor compression process, the synthesis of which is a problem in task integration discussed in this chapter.

Detergents from Petroleum

In this chapter we apply the principles of process synthesis to the development of part of the technology to convert crude oil into detergents. No new ideas are presented, we apply what we already know. Our attention

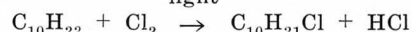


1. Vaporization of sea water at triple point causes ice formation.
2. Vapor condenses on clean ice surface to form fresh water.
3. 5% of fresh water used to wash rising piston of ice.
4. Ice-brine slurry pumped to bottom of ice wash column.

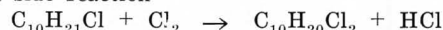
Fig. 3. Vacuum Freezing—Vapor Compression Process.

is focused on the problem of converting a kerosene fraction of the crude oil into an intermediate material, a chlorinated hydrocarbon, which then fits into the large campaign of detergent production.

Given fragmentary conversion data on these reactions



with the side reaction



We seek the technology to produce monochlorodecane economically on a commercial scale. Dominating this process synthesis problem are problems in species allocation and task selection.

To give some idea of the tenor of this chapter, we sketch out part of the development of the final process flow sheets. Figure 4 shows five ways of separating the reactor effluents shown in Table 2 into an HCl waste, Cl_2 -decane recycle, monochlorodecane product, and dichlorodecane waste. How might the beginning student select among these?

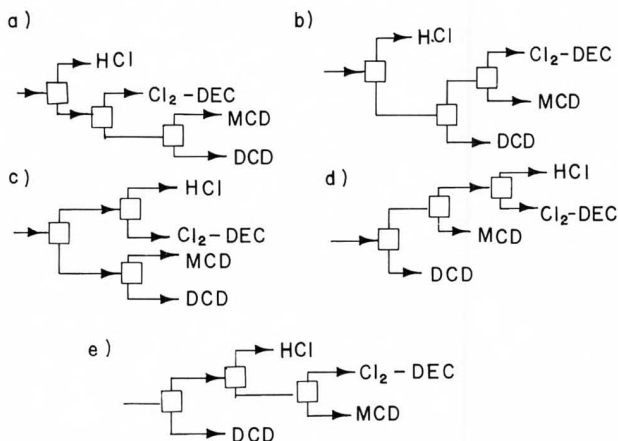


Fig. 4. Alternative Separations.

The dominance of science oriented courses in undergraduate education is caused by the very important role analysis has in engineering . . . The absence of the organizing influence of basic principles of synthesis is possibly the major reason why analysis tended to dominate education.

Table 2. Effluent from Photochlorination Reactor

Species		Moles	Boiling point
Monochlorodecane	MCD	0.95	215°C
Dichlorodecane	DCD	0.05	241
Decane	DEC	4.0	174
Chlorine	Cl ₂	trace	-34
Hydrogen chloride	HCl	1.05	-85

Applying the task selection heuristics

Plans a and c lead to low amounts of material processed

Plans a and b lead to low cooling costs by the early removal of volatile material

Plans a and c reduce processing costs by minimizing the amount of material processed during the most costly separation.

Plans a and b reduce costs by removing corrosive materials early

Plans a and c remove the MCD on a distillate rather than bottoms product

Hence, by applying these simple rules it appears that structure a is favored for a number of reasons. However, much more synthesis must be performed to develop better processing alternatives.

Figure 5 shows eight flowsheets which are synthesized using the principles developed in this early course. Figure 6 shows the economic analysis against which these processes are compared.

Flowsheet 2, which has the separation sequence for the last two columns in Flowsheet 1 reversed, is less attractive than 1 for all values of conversion. The decane is the largest component in the reactor effluent, and is also the lowest boiling component leaving the phase separator. The failure to remove decane early causes the increased cost in this case.

Flowsheet 3 involves the use of decane as a solvent to remove chlorine from the vapors leaving the phase separator. Since the chlorine not converted in the reactor is re-

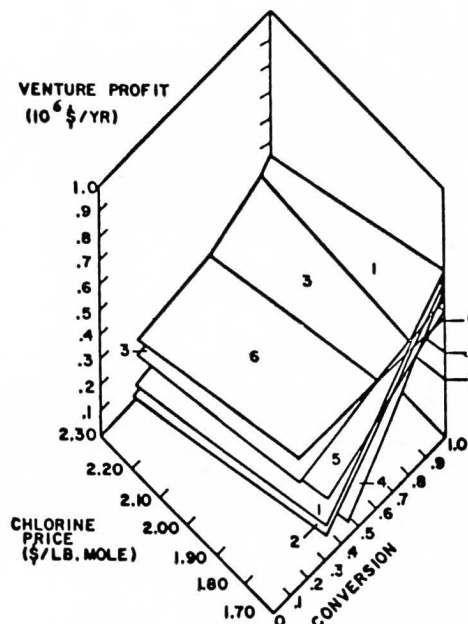


Fig. 6. Venture Profit Surfaces for Monochlorodecane Processes.

cycled, this flowsheet is not nearly as sensitive to conversion or chlorine cost as are Flowsheets 1 and 2. The maximum profit for Flowsheet 3 is not as high as the optimum for Flowsheet 1, but it is much less sensitive to the level of conversion. If uncertainty in the reactor design is large, the selection of Flowsheet 3 may be wise. The addition of a separator to recover unconverted chlorine adds to the equipment and operating costs but gives much greater flexibility in operation.

Flowsheet 4, which utilizes the reverse separation sequence of Flowsheet 1, is decidedly less attractive. The repeated processing of the low boiling components, par-

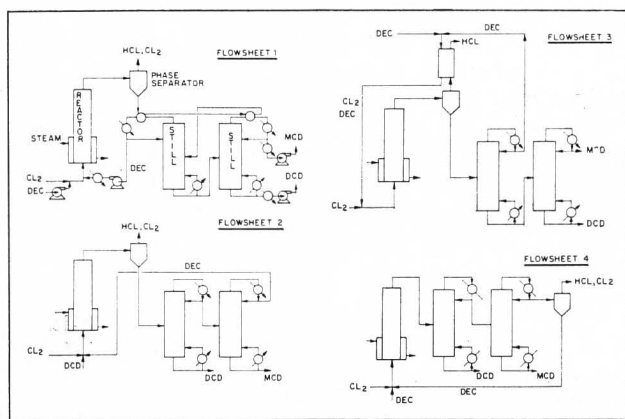
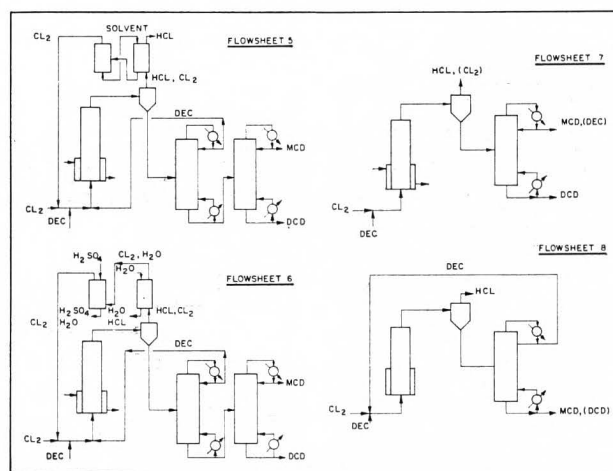


Fig. 5. Flowsheets synthesized using the principles. (Reproduced by permission of Chem. Eng. Prog. 68, No. 9, pp. 91-92, 1972)



ticularly HCl, causes very high equipment and utility costs. The loss of chlorine, as in Flowsheets 1 and 2 makes the profit for this process dependent on reactor conversion and chlorine cost.

Flowsheet 5 shows the same independence of conversion as Flowsheet 3. The profit is less due to solvent costs and the additional separator.

A profit nearly as high as that for Flowsheet 3 is obtained for Flowsheet 6. Flowsheet 6 utilizes water to remove hydrogen chloride from the vapors leaving the phase separator. Wet chlorine returning to the reactor inlet is dried by contacting concentrated sulfuric acid. The low cost of the solvent, water, and the fact that the water need not be regenerated make this alternative very attractive. However, the corrosive nature of the hydrogen chloride-water mixture and the sulfuric acid-water mixture require more expensive materials of construction. The danger of water entering the reactor must also be considered. If the reactor and separators are constructed of carbon steel, any traces of water in the presence of the hydrogen chloride reaction product would lead to rapid failure of these units due to corrosion.

Flowsheet 6 has a higher profit than Flowsheet 3 at low conversion. This because of the large amounts of decane solvent required in Flowsheet 3 for low chlorine conversions.

Flowsheets 7 and 8 are the special cases when conversion is complete. Flowsheet 7 has the advantage of only requiring two separators and no recycle. The high conversions using stoichiometric feed ratios lead however, to the production of large amounts of DCD. Hence, the profit for this alternative is low.

Flowsheet 8 represents the situation when large excesses of decane are utilized. Complete conversion of chlorine is achieved, hence no separation is required for its recycle. A small amount of DCD appears in the product. These advantages are offset by the costs associated with the separation and recycling of large amounts of decane.

In summary, three regions exist when comparing the eight flowsheets over wide ranges of conversion. At low conversions process Flowsheet 6, which utilizes water as a means to separate HCl and chlorine, is best. At intermediate conversion levels, process Flowsheet 3 is best. Process 3 utilizes the feed and recycle decane as a solvent for absorbing chlorine from the waste hydrogen chloride stream. For high levels of conversion, process Flowsheet 1, which discards unconverted chlorine, is optimal.

CONCLUSION

An essential difference between the aims of education in science and in engineering ought not be lost. Herbert A. Simon states in the *Sciences of the Artificial*

Historically and traditionally, it has been the task of the science disciplines to teach about natural things: how they are and how they work. It has been the task of the engineering schools to teach about artificial things: how to make artifacts that have the desired properties and how to design. . . . Everyone designs who devises courses of action aimed at changing situations into preferred ones.

Science aims to *analyse* natural phenomena, and engineering aims *synthesize* from natural phenomena preferred situations. For example, while it may be sufficient for a scientist to develop an understanding of the phenomena of ice formation, the engineer ought to be concerned with use of his knowledge in the development, say, of an artifact which economically can produce fresh water from the sea by freezing.

The dominance of science oriented courses in undergraduate education is caused by the very important role analysis has in engineering, and is also caused by the availability of well organized and carefully planned text material in these areas. The natural organization of methods of analysis lends itself to course development and text preparation.

The absence of the organizing influence of basic principles of synthesis is possibly the major reason why analysis tended to dominate education. It remains to be seen if the course described will bring the proper balance between analysis and synthesis in engineering education. □

LETTERS: (Continued from page 3)

A little checking has revealed that the non-zero value is the result of a reformulation of steam table data published by the ASME in 1967.¹ Recognizing that a stable liquid-vapor equilibrium can't exist below the triple point temperature of 32.018°F, the reference conditions were changed so as to assign the value zero to the entropy and *internal energy* of the saturated liquid phase at the triple point. This, of course, forces the associated enthalpy to be (Pv) units greater or about 0.0003 Btu/lb_m. One can certainly estimate the conditions for the metastable vapor-liquid equilibrium at precisely 32°F through simple extrapolation and obtain values of about -0.0181 Btu/lb_m and -0.0178 Btu/lb_m, respectively, for the internal energy and enthalpy of the liquid phase. The error in the Combustion Engineering tables, then, is the omission of the minus sign together, perhaps, with out spelling out the convention not stating (as does the reference above) that the first entry in the saturation table corresponds rigorously to a metastable state. At least one recently published text² on chemical engineering thermodynamics has copied this error, but the new edition of "Steam Tables" by Keenan, Keyes, et al,³ does note both the negative values and metastability below the triple point.

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1. "Thermodynamic and Transport Properties of Steam," American Society of Mechanical Engineers (1967).

2. Balzhiser, R. E., M. R. Samuels and J. D. Eliassen, "Chemical Engineering Thermodynamics," Prentice-Hall, Inc (1972).

3. Keenan, J. H., F. G. Keyes, P. G. Hill and J. G. Moore, "Steam Tables," John Wiley & sons, Inc. (1969).