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This is the 14th Graduate Issue to be published by CEE and distributed to chemical engineering seniors interested in and qualified for graduate school. As in our previous issues, we include articles on graduate courses and research at various universities and announcements of departments on their graduate programs. In order for you to obtain a broad idea of the nature of graduate work, we encourage you to read not only the articles in this issue, but also those in previous issues. A list of the papers from recent years follows. If you would like a copy of a previous Fall issue, please write CEE.

Ray Fahien, Editor, CEE
University of Florida

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OXIDATIVE DEHYDROGENATION
OVER FERRITE CATALYSTS

JOE W. HIGHTOWER
Rice University
Houston, TX 77001

A complete study of heterogeneous catalytic reactions should include the reaction pathways, kinetics, mechanisms, rate limiting steps, nature of the active sites, solid state effects, deactivation, and transport properties. It is normally very difficult to obtain reliable information about all these factors for a single system. However, in the case of butadiene production from n-butene via catalytic oxidative dehydrogenation, we have been able to approach this objective. The purpose of this paper is to summarize results obtained during the last several years with ferrite catalysts [1, 2].

CATALYTIC ROUTES TO BUTADIENE

Two major catalytic approaches have been used commercially to prepare butadiene. The first is direct dehydrogenation over a chromia/alumina or promoted iron oxide catalyst [3, 4], viz.

\[ C_4H_8 \rightarrow C_4H_6 + H_2 \quad K_{371}C^{-10^{-4}} \] (1)

Although the reaction is relatively selective, it suffers from being thermodynamically limited (requires high temperature and low partial pressures), endothermic (requires addition of costly heat), and coke-forming (loss of hydrocarbons). A second approach involves addition of oxygen to the feed hydrocarbon stream to remove the hydrogen as water, viz.

\[ C_4H_8 + \frac{1}{2} O_2 \rightarrow C_4H_6 + H_2O \quad K_{371}C^{-10^{13}} \] (2)

\[ \rightarrow CO_2 + H_2O \quad K_{371}C^{-10^{210}} \] (3)

In contrast to straight dehydrogenation, this reaction (2) is essentially irreversible and autothermal. Unfortunately, the addition of gaseous oxygen can lead to deep oxidation (total combustion to CO₂ and H₂O, as illustrated in reaction (3)). This reaction of course decreases the yield of butadiene. In fact, from the equilibrium constants given in Eqs. (2) and (3), it is obvious that only CO₂ and H₂O would be the products if thermodynamics alone were controlling the product selectivity. Of the several catalysts that give good selectivities (>90% butadiene at low conversion), ferrites are among the most notable. Ferrites are well-crystallized spinel oxides (or partially inverted spinels) that have the general formula

\[ M Fe_2O_4 \] (4)

where M can be any of a number of alkaline earth or transition metal ions, e.g. Mg, Ca, Co, Cu, etc. The work described herein will be limited to magnesium ferrite.

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CHEMICAL ENGINEERING EDUCATION
REACTION PATHWAYS

When oxygen and butenes are passed over MgFe₂O₄, both the desired butadiene and some by-product CO₂ are formed. The CO₂ may come directly from burning butene (reaction II) or from burning the product butadiene (reaction III), as illustrated by the scheme

\[
\text{C}_4\text{H}_8 \xrightarrow{(1)} (\text{C}_4\text{H}_6) \xrightarrow{} \text{CO}_2
\]

By adding a small amount of very highly radioactive butadiene to the reactant butene/O₂ mixture and examining the radioactivity in the CO₂ as a function of time, one can quantitatively determine the relative reaction rates [5]. If none of the radioactivity appears in the CO₂, the rate ratio \( r_{\text{III}} / r_{\text{II}} = 0 \). For maximum production of butadiene in this case, one would want to carry out the reaction at the highest possible conversion. On the other hand, if all the CO₂ were formed by burning butadiene, the initial specific activity of the CO₂ (after correction for the different number of C atoms in the two molecules) would be exactly the same as that of the butadiene from which it was exclusively formed. The rate ratio \( r_{\text{III}} / r_{\text{II}} \) in this case would be infinity.

In our case with magnesium ferrite [1] the rate ratio \( r_{\text{III}} / r_{\text{II}} \) is about 1.5 at approximately 50% conversion of the butene. This implies the existence of an optimal degree of conversion in order to maximize butadiene yield. Too high a conversion will raise the product butadiene concentration to the point where it will be rapidly combusted to CO₂. Moreover, a plug flow reactor will give a much higher selectivity to butadiene than will a CSTR. It is also advantageous to add the reactive oxygen a little at a time at various points along the reactor bed instead of carrying the entire lot of O₂ all the way through the reactor where it can cause combustion. Steam also helps to moderate the exothermic reaction and minimize hot spot formation.

KINETICS

Over MgFe₂O₄, the major OXD reaction (2) is zero order in oxygen and near first order in the partial pressure of n-butene. Neither CO₂ nor butadiene affects the rate significantly in the pressure range studied. The reaction orders were determined by varying the partial pressures one at a time (making sure not to get into the explosion regime!) and noting the effect on the initial reaction rate. These results suggest a Langmuir-Hinshelwood model with the O₂ and C₄H₈ being adsorbed noncompetitively on neighboring sites. If the O₂ were adsorbed dissociatively, the rate equation can be written as

\[
r_{\text{BD}} = k \theta_0 \theta_B = \frac{K_{02}P_{O2}}{1 + K_{02}P_{O2} + K_{B}P_{B}}
\]

where \( K_{02} \) and \( K_B \) are the adsorption equilibrium constants for O₂ and butene, respectively, and \( k \) is the zero order Langmuir-Hinshelwood rate constant. The \( \theta \)'s are fraction coverage of the respective surface sites by oxygen and butene. When O₂ is strongly adsorbed (i.e. \( \sqrt{K_{02}P_{O2}} > 1 \)) and butene is weakly adsorbed (i.e. \( K_BP_B < 1 \)), the rate of butadiene formation \( r_{\text{BD}} \) reduces to

\[
r_{\text{BD}} = k \theta_B P_B
\]

which fits the observed kinetic data.

At higher partial pressures, terms must be added in the denominator to account for inhibition by steam and butadiene.

MECHANISM, RATE LIMITING STEP

During the OXD reaction at temperatures as high as 400°C, there is very little isomerization of the n-butenes. For example, if the starting hydrocarbon is 1-butene, it remains 1-butene until it either is partially oxidized to butadiene or burned to CO₂. Very few 2-butenes are observed. This implies that the reaction may be relatively simple with two H atoms being removed as shown below.

\[
\text{C} = \text{C} - \text{C} \quad \text{H} \quad \text{H}
\]
A mixture of 1:1 = C₄H₈:C₄D₈ (in presence of a stoichiometric amount of O₂) was used to test this reaction scheme. Indeed there was essentially no scrambling of H and D atoms among the molecules, as the only OXD products formed were C₄H₆ and C₄D₆. Furthermore, the lightweight C₄H₈ molecules reacted about 2.5 times more rapidly than did the heavier C₄D₈ molecules, which indicates a large primary kinetic isotope effect and pinpoints the rate limiting step in the reaction.

\[
\frac{C_4H_8}{C_4D_8} \rightarrow \frac{C_4H_6}{C_4D_6} \quad (9)
\]

Since the C-D bond has a lower zero point energy than does the C-H bond [6], such an isotope effect would be expected if cleavage of a carbon-hydrogen bond were involved in the rate limiting step. In other words, C-D bonds are more difficult to break than are C-H bonds.

This kind of information is useful in development of more active catalysts. If one could include in the catalyst recipe a pinch of C-H bond breaking ability and still keep all other parameters the same, a more active catalyst should result. Such information is critical in establishing the point where additional research may be productive.

ACTIVE SITES

Much previous research has clearly established that this type of general reaction involves an oxidation/reduction cycle with some component of the catalyst being alternately oxidized and reduced [7-9]. Chemical intuition would suggest that it is the iron switching between the Fe²⁺ and Fe³⁺ states that provides this property. Magnesium is not easily reduced. Such a switch might occur if oxygen were alternately added to and removed from the surface. In other words, a reduced Fe²⁺ might react with gaseous O₂ to form an oxide surface species, viz.

\[
Fe^{+2} + \frac{1}{2}O_2 \rightarrow Fe^{+3}O^- \quad (10)
\]

These O⁻ ions might then dissociate the C-H bonds in butene to form an adsorbed C₄H₆ species and an OH⁻ ion. A second such hydroxyl ion formation would result in adsorbed C₄H₆ (perhaps negatively charged) which can release an electron to reduce the Fe³⁻ back to Fe²⁺ and finally desorb into the gas phase as butadiene. Two OH groups might coalesce to split out H₂O and regenerate the site on which more O₂ can adsorb.

Evidence for this sequence of events comes from some electrical conductivity measurements made with a cobalt ferrite catalyst [10]. Since electrical conductivity is primarily a surface phenomenon, we postulated that there should be notable changes in this parameter as the catalyst is transformed from the oxidized to the reduced state. To test this, a pellet of the catalyst was prepared by compressing the powder in an infrared pellet press. Two electrical leads were attached, and the pellet was placed inside a reactor connected to a vacuum system through which different gases could be admitted.

The pellet was first exposed to oxygen and evacuated at about 400°C. Presumably this left the catalyst surface in a fully oxidized state, Fe³⁺. The conductivity was low and remained low during the evacuation. However, when 2-butene was admitted at the same temperature (see point B, Figure 1), the conductivity rapidly increased. At
From this information one can draw a cyclic representation of the chemistry that is occurring. Let us imagine that the reaction takes place on active centers located near the edge of a crystallite. In the reduced state a surface oxygen ion is missing (anion vacancy, □). If the lattice were to be continued in the vertical direction, another iron atom would be located above the oxide layer (cation vacancy ▲),...

the same time, a small amount of butadiene was observed to form in the reactor. The amount corresponded approximately to 1 butadiene molecule/surface O atom (assuming the surface is covered with O" ions each occupying 10Å² of surface space). This would leave the surface in a "reduced" state according to the equation

$$\text{Fe}^{3+} + C_4H_8 \rightarrow \text{Fe}^{2+} + C_4H_6 + H_2O$$

By moving in the direction of a more "metallic-like" reduced surface, one might expect the material to be a better conductor than in the oxide state, as was observed. The slow increase in the conductivity after the initial rapid rise may have been due to slow removal of bulk O atoms.

Addition of O₂ (Point D) quickly returned the catalyst to its oxidized condition, which it retained during brief evacuation.

At Point E a stoichiometric mixture for the OXD reaction (C₄H₈:O₂ = 2:1) was admitted, and both reactions (2) and (3) proceeded. Because the deep oxidation reaction (3) requires a lot of oxygen, the gaseous O₂ is depleted before the butene is all consumed (Point F). At this point, reactions (2) and (3) cease, and the catalyst is reduced by the unreacted butene, as in reaction (11). Accordingly, the conductivity increases rapidly. Note that so long as there is any gaseous O₂, the catalyst remains in the fully oxidized state. This is evidence that oxygen is very strongly adsorbed.

**OXD REACTION CHEMISTRY**

From this information one can draw a cyclic representation of the chemistry that is occurring. Let us imagine that the reaction takes place on active centers located near the edge of a crystallite. In the reduced state a surface oxygen ion is missing (anion vacancy, □). If the lattice were to be continued in the vertical direction, another iron atom would be located above the oxide layer (cation vacancy, ▲), as shown below.

These two vacancies are assumed to be the independent sites suggested by the Langmuir-Hinshelwood kinetics. Butene presumably adsorbs reversibly on the cation sites, and O₂ reacts with the anion vacancy to oxidize the Fe<sup>2+</sup> to Fe<sup>3+</sup>. As the reaction progresses in a clockwise direction (see Figure 2), two H atoms are sequentially removed from the butene and placed on the oxide ions. Reduction occurs when the butadiene is released into the gas phase, and condensation of two hydroxyl groups (along with water removal) returns the catalyst to the reduced state shown in (12).

The fact that no radioactivity appears in the butenes when butadiene-¹⁴C is admitted supports the irreversible clockwise direction within this scheme. The absence of isomerization and H/D scrambling among the hydrocarbon molecules confirms the directional irreversibility.

**SOLID STATE EFFECTS**

So far I've presented only the good news. Unfortunately, the MgFe₂O₄ catalyst slowly loses its activity irreversibly. The deactivation is not caused by coke build-up, and alternate oxidation/reduction cycling during pretreatment will not regenerate the catalyst. This suggests that some

Continued on page 204.
Research on  

NUCLEATE BOILING

RUSSELL MESLER  
University of Kansas  
Lawrence, KS 66045

Research takes an especially exciting turn when it requires us to revise our views of long-held beliefs. Such is the case of recent research results concerning nucleate boiling. Although the picture is by no means complete, it appears possible that we may be changing several of our views concerning nucleate boiling.

Nucleate boiling is a familiar topic to any chemical engineer. All heat transfer texts devote sections to it in which the rudimentary facts are stated. All such treatments advise that nucleate boiling is a complicated subject and that it is not possible to go into a detailed discussion of the subject.

Nucleate boiling is classified as convective heat transfer. It is unusual convection on at least three counts. First, because of the latent heat, great quantities of heat can be exchanged with only a little change in temperature as long as liquid remains on the surface. Second, the density changes resulting from heat transfer are very large compared to usual convection. Third, it is only at a vapor-liquid interface that heat can be absorbed and vapor generated.

It is perhaps this third aspect that is most responsible for making nucleate boiling so inscrutable. Most of the vapor-liquid interface in boiling is provided by bubbles, but where do bubbles come from? Bubbles have short lives, escaping once they become large. A large source of nuclei is required.

It is important to recognize that liquids often resist the tendency to form bubbles. In the organic chemistry laboratory it is well known that liquids in a glass flask will superheat above their usual boiling point. Suddenly, when ebullition does start, the boiling is so vigorous that the contents of the flask are likely to be expelled and wind up on the lab bench. The solution to the problem is the use of a boiling chip to reduce superheating and maintain steady ebullition.

The phenomenon of superheating is attributed to the action of surface tension. The pressure inside a small static spherical bubble is higher than outside by twice the surface tension over the radius, $2\sigma/r$. Such a static bubble would be in unstable equilibrium. If it were only slightly smaller, the increased pressure would tend to collapse it and if it were slightly larger, it would tend to grow and rise and thus escape.

The action of a solid on the stability of small bubbles is well exemplified by boiling chips. A boiling chip is able to retain gas or vapor on its surfaces and thus provides a vapor-liquid interface deep in the liquid able to generate vapor when the liquid becomes supersaturated. The vapor breaks away as bubbles rising to the surface but leaving behind some vapor from which the next bubble can grow.

Nucleate boiling is often characterized by the tendency for bubbles to rise repeatedly from certain points on the surface when boiling at low heat flux. These points are described as nucleation sites. They are thought to act as boiling chips...
by stabilizing a vapor-liquid interface on the surface.

Usually nucleation sites become active only after the surface temperature rises significantly above the boiling point. It is possible with very smooth surfaces to achieve even higher superheats before ebullition occurs, as in a glass flask. Once ebullition starts more nucleation sites become active, often with only a slight increase in surface temperature. It is only at low heat flux that the individual bubbles and nucleation sites can be effectively studied. At just a modest heat flux bubbles begin to merge and with just a bit more heat flux the commotion becomes so great that it is impossible to discern much detail at the center of activity. Views near the edge of a boiling surface may not be representative of the rest.

Because of the visual difficulty of studying bubbles at even modest heat fluxes most of the studies of bubbles have been made at low heat fluxes. The results of these studies have then been extrapolated to explain nucleate boiling at higher heat fluxes where applications are common.

At high heat fluxes more vapor is generated. In escaping the surface it pushes back the liquid and establishes a vapor region just above the surface. This leaves a film of liquid on the surface that becomes especially important in the transfer of heat. Exceeding what is called the peak heat flux leads to the drying off of the surface. Without liquid the surface is unable to lose heat fast enough and the surface temperature rises unless the heat supply is reduced.

A surprising fact is that higher heat fluxes are possible if the depth of liquid on the surface is a few mm rather than much deeper. Nucleate boiling is limited in its ability to transfer heat. Exceeding what is called the peak heat flux leads to the drying off of the surface. Without liquid the surface is unable to lose heat fast enough and the surface temperature rises unless the heat supply is reduced.

An important fact is that higher heat fluxes are possible if the depth of liquid on the surface is a few mm rather than much deeper. Nucleate boiling is limited in its ability to transfer heat. Exceeding what is called the peak heat flux leads to the drying off of the surface. Without liquid the surface is unable to lose heat fast enough and the surface temperature rises unless the heat supply is reduced.

**PHASE TRANSITION PROCESSES**

Boiling is not the only process involving a phase transition in which nucleation is important. Another is crystallization. In crystallization, crystal nuclei initiate crystal formation.

There are a number of similarities between crystal nucleation and vapor bubble nucleation. Both crystals and vapor bubbles will grow on surface imperfections such as scratches and pits. Crystallization also exhibits tribonucleation. Crystallization is initiated by rubbing or dragging a stirring rod along the bottom of a beaker. Vapor nuclei can be produced in the same fashion.

There is another source for crystal nuclei for which no similar source of vapor bubbles has been reported. It is called secondary nucleation and is the production of nuclei from the break-up of larger crystals. This source of nuclei is the most important one in industrial applications.

**SEARCH FOR SECONDARY NUCLEATION**

The reason secondary nucleation has never been seriously considered for nucleate boiling is probably because it was not easy to see how any of the abundant vapor could be returned to the liquid to serve as nuclei. Without a process for the return of vapor to the liquid it was impossible to see how secondary nucleation could occur in nucleate boiling.

The first clue to a process for secondary nucleation came in research on boiling in a thin liquid film. Nucleate boiling was studied on the outside of a vertical, steam-heated, copper tube. High speed motion pictures showed that when a bubble burst, bubble nuclei appeared where the bubble had just burst.

The next clue came in an experiment with superheated water in a glass tube. An air bubble was formed in the water and was allowed to rise and burst at the surface. Soon after it burst, clusters of bubble nuclei appeared beneath the surface and these nuclei grew and coalesced to form a vapor bubble. When this bubble burst it too produced a cluster of nuclei beneath the surface. Viewing the high speed motion pictures of the event gave the impression that nuclei came from the top film of the bubble crashing upon the surface following the bursting of the bubble.

**DROP-FORMED VORTEX RINGS**

At this juncture a study of the tendency for small drops to entrain bubbles seemed appropriate. With just the simplest experiments using only an eye dropper and a beaker it was obvious that drops do entrain bubbles. With this encouragement high speed motion pictures were taken of drops falling several feet into water. It was soon learned that entrainment occurred...
not upon initial impact but later when the splash fell back upon the surface. This led to experiments with short falls where it was learned, by dying the drop, that when a dyed water drop strikes a water surface it usually produces a vortex ring. Furthermore, with optimized lighting it was seen that the vortex rings carry tiny bubbles on their axes as they plunge beneath the surface. See Figures 1 and 2.

Drop-formed vortex rings were news to us. Once one knows about them it’s not difficult to find that they’ve been known a long time. They were described in an 1858 paper by W. B. Rogers [16] before he founded MIT. They are not mentioned in most texts on fluid mechanics, except for Sommerfield [17] and Batchelor [18]. A recent book *Bubbles, Drops and Particles* [19] includes no mention of them. Apparently few researchers have had occasion to learn of them.

We found that researchers at Los Alamos were not familiar with them. They developed a technique to solve the Navier-Stokes equations numerically with a computer [20, 21] and applied their method to the prediction of the behavior of a drop striking a pool of water. They could only solve for short falls. They compared their results to experiments with drops falling from greater heights. They found agreement and concluded that their method was sound, unaware that drops falling from short distances behave differently [22].

Now that drop-formed vortex rings have been recognized as providing a mechanism for secondary nucleation, it is pertinent to consider how important secondary nucleation might be. Vortex rings are capable of providing nuclei away from the interface. The tiny bubbles are carried within the rings wrapped in layers that come from near the surface and the impinging drop that likely have temperatures close to saturation. The tiny bubbles are shielded from the local environment through which they are carried. If they escape to a hotter environment they can begin rapid growth. The fact that clusters of bubble nuclei are seen later beneath the surface when a bubble bursts on a superheated pool fits these circumstances.

When a bubble bursts on the surface, does its top film form drops that in turn form vortex rings? A bubble about 2 cm in diameter was blown from a detergent solution colored with food dye and placed on the surface of clear water. It was ruptured soon after placement and a picture was taken looking down on the surface. The picture showed tiny rings and bubbles where the miniscus had been [15]. Apparently the rings were vortex rings.

Another interesting aspect is the behavior of a vortex ring as it approaches a wall. It plows right in and spreads out, giving the impression that the tiny bubbles it might carry would be delivered very close to the wall. If the wall was a heater surface the tiny bubbles would seem to be delivered to a region of high temperature.

Although it goes unnoticed by current texts, it is possible to improve the performance of nucleate boiling by the simple means of boiling in thin liquid films. An early indication of this came from Japanese engineers who studied nucleate boiling on a horizontal surface with varying depths of liquid covering the surface [23, 24]. At depths below 5 mm, surface temperatures were lower and were lowest just before the surface dried off with the surface only partially covered with liquid.
They offered no explanation for the observation but did note that nucleation increased at lower liquid depths. Others have reported similar results [25, 26]. Boiling in thin liquid films offers an ideal opportunity for secondary nucleation to occur. When boiling thin liquid films, bubbles burst from the top of the film not far from the heater surface. Drops formed when a bubble bursts should be drawn into the film on the surface. Vortex rings formed by these drops would be well positioned to carry entrained bubbles to the surface. Near the surface the entrained bubbles would be exposed to the highest temperatures around. Whether secondary nucleation is indeed responsible for the better performance of boiling in thin liquid films cannot be said at present but it seems like a good bet. This would seem to be a likely candidate for further research.

One advantage of boiling from thin liquid films is that nucleate boiling can be achieved at lower surface temperatures and at lower heat fluxes. This is especially important in low heat flux applications where, judging only from boiling from submerged surfaces, nucleate boiling would not seem possible.

Nucleate boiling from thin films can be improved even more by the addition of traces of surfactants to water. This was reported by the Japanese and also more recently in desalination equipment [23, 27, 28]. Preliminary experiments in our laboratory show that surfactants increase nucleation, apparently from secondary nucleation.

There have been numerous studies of nucleate boiling on horizontal or vertical tubes or on vertical flat surfaces [28, 29, 30]. These studies have generally indicated better performance than nucleate boiling on submerged surfaces and the improvement has generally been attributed to the flow in the film. Not one of these studies has made any recognition that similar improvements occur when nucleate boiling occurs in thin liquid films on horizontal surfaces where there is no imposed flow.

Most texts on heat transfer describe flow boiling as being different from nucleate boiling on a submerged surface. In flow boiling, liquid is progressively converted to vapor so that a number of flow regimes exist along the flow. The predominant flow regime is annular flow with a liquid film on the wall. Early work hypothesized that in the annular flow region heat transfer was so good that it must be forced convection and that, consequently, nucleate boiling was suppressed [31].

The support for this hypothesis has recently been reanalyzed and found not to support the hypothesis [32]. Annular flow would seem to offer an ideal situation for secondary nucleation to augment nucleate boiling heat transfer.

In vigorous boiling on a submerged surface the view of the bubble activity is obscured. Extrapolating results on bubble nucleation at lower heat fluxes suggests that at higher heat fluxes more surface sites come into play. An alternate hypothesis is that at high heat fluxes secondary nucleation supplies the additional nuclei. The circumstances would seem to permit secondary nucleation in the same way as has been suggested for nucleate boiling in thin films. At high heat fluxes vapor does push the liquid away leaving the surface wet with a film of liquid. It would seem possible for drops to form from bubbles bursting from this film or perhaps from all the commotion above the surface. Drops striking the film would be well positioned to cause secondary nucleation. Current literature mentions only the former hypothesis, so the latter has not been ruled out. Who can say which hypothesis is more nearly correct? More research can help decide.

Secondary nucleation can also offer alternate hypotheses for two other characteristics of nucleate boiling. When heat flux is plotted against surface temperature excess over saturation, one obtains what is often called the boiling curve. The upper portion of the curve often moves in a parallel fashion to higher or lower temperature differences because of aging or other obscure reasons. It is usually said that changes in the nucleation characteristics of the surface are responsible for the shift. An alternate hypothesis is that changes in nucleation on the surface effects only the lower portion of the curve and that secondary nucleation ensues to move the rest of the curve.

The other characteristic is hysteresis in which surface temperatures are higher as the heat flux is increased but lower as it is decreased. On increasing heat flux it sometimes occurs that after bubbles begin to coalesce the surface temperature suddenly falls. The usual explanation for this is that new nucleation sites have acquired vapor and became active. The alternate hypothesis is that when bubbles begin to merge a new flow regime is established which favors secondary nucleation.

CONCLUSIONS

Secondary nucleation definitely occurs in
nucleate boiling. Indications are that drop-formed vortex rings are responsible for entraining tiny bubbles to serve as nuclei for secondary nucleation. How important secondary nucleation is in submerged boiling remains to be shown, but it seems likely to be responsible for the improved performance of nucleate boiling in thin liquid films with and without surfactants. Research opportunities abound in evaluating these new developments.

ACKNOWLEDGMENTS

Most of the research on nucleate boiling has been supported by the National Science Foundation. A sabbatical leave spent at Berkeley Nuclear Laboratories in England with R. B. Duffey helped to develop some of the research. Kenneth Carroll, Tom Yu, Ted Bergman, Gregg Mailen and other students are in large measure responsible for our progress.

REFERENCES

In Memoriam

WILLIAM H. CORCORAN

William H. Corcoran, 62, Institute Professor of Chemical Engineering at the California Institute of Technology, died while vacationing in Hawaii on Saturday, August 21, 1982. Bill is survived by his wife of nearly 40 years, Martha, son Will Corcoran, Jr. and daughter, Sally Corcoran Fisher, and six grandchildren. To describe the accomplishments and contributions of Bill Corcoran to chemical engineering, engineering education, and to his friends and colleagues would require many, many pages. During his life, Bill Corcoran attained virtually every honor and recognition available to an engineering educator, while, at the same time, truly touching the hearts and minds of all those with whom he came in contact. Ironically, two weeks before his untimely death, Bill Corcoran prepared a short essay entitled “My Career as a Chemical Engineer.” As a tribute to Bill Corcoran we now reprint that essay:

My Career as a Chemical Engineer

My professional work began before World War II as an employee of Cutter Laboratories in Berkeley, California. Here my interest in pharmaceuticals and biomedical engineering was sharpened and never left me. In World War II I was involved with a very excellent group of people at the California Institute of Technology. We were responsible for the work on processing of double-base propellant and interior ballistics of all rocket motors used by the Navy. One year of that program also concurrently dealt with ordnance work on the atomic bomb. The rocket program was very successful, and in my very biased opinion it contributed in a major way to the quality of our munitions program in World War II.

Subsequent to World War II I went back to graduate school, courtesy of the National Research Council. I have never forgotten the nice fellowships they afforded me, and today I have an association with the National Research Council by way of its Commission on Engineering and Technical Systems. That is a pleasure and allows me to partially pay back the debt I owe them. After receiving my Ph.D. degree in 1948, I returned to Cutter Laboratories in Berkeley where for four years I was Director of Technical Development. The work included process development on pharmaceuticals and biologicals, including fermentation studies on penicillin and deep-culture growth of useful organisms for manufacture of vaccines. In addition we did significant work on disposable medical equipment and mass parenteral solutions. My interest in biomedical and bioengineering was further intensified by that experience.

In 1952 I returned to the California Institute of Technology as an Associate Professor of Chemical Engineering and except for a two-year period from 1957 to 1959 I have been associated with the California Institute of Technology ever since. In the period of 1957 to 1959 I was Vice President and Scientific Director for Don Baxter Incorporated, a subsidiary of the American Hospital Supply Corporation. Here my biomedical work continued.

My work at Caltech in research has related to studies of nitric acid-nitrogen dioxide-water systems, pyrolysis of hydrocarbons, flow systems, including work on artificial heart valves, and desulfurization and supercritical extraction of coal.

Teaching has been a major interest during my professional career, and I have especially enjoyed the teaching of my Senior design course entitled “Optimal Design of Chemical Systems.” I have learned so much in the teaching of the course that I can hardly believe what has happened, and I do have some hopes that the students learned at the same time. In terms of breadth of opportunity for a professor I can't think of a course more designed for a professor's development.

In other professional activities I spent 10 years as Vice President for Institute Relations at the California Institute of Technology while still maintaining my programs of teaching and research. In 1978 I had the privilege of being President of AIChE. Currently I have the pleasure of working with the Accreditation Board for Engineering and Technology and will be the President for a two-year term ending in 1984.

Along the way I have had the great fortune to act as a consultant for the American Hospital Supply Corporation and the Bechtel Corporation and as a Director of Superior Farming, the KTI Corporation, and Phytogen Incorporated, a genetic engineering firm. There has not been one dull second. If I had my life to relive, I would do exactly what I had done previously and probably would make the same mistakes. Hopefully not. It has been a great life, with thanks to all the people with whom I have associated but with special thanks to my wife Martha who understood from time zero the nature of the profession and has been a very interested observer and participant in my professional activities.
A number of aspects of effects of diffusive mass transfer are currently being investigated at Clarkson College of Technology. The growth of crystals as it is affected by diffusion is being studied by Professors William Wilcox and Gordon Youngquist. A major investigation of the role of mass transfer in corrosion is being carried out by Professor Der Tau Chin. Finally, the role of multi-component diffusion and chemical reaction in the classical operations of distillation, absorption and condensation is under investigation by Drs. Ross Taylor and Ralph Weiland. These latter studies form the subject of this article.

It is a fact that mass transfer is a rate process driven by concentration gradients (more precisely, by gradients of chemical potential). Nevertheless, the vast majority of commonly used design methods are based on equilibrium models that completely neglect the influence of finite rates of mass transfer. For example, the equilibrium stage model of distillation for binary, nonreacting systems (the McCabe-Thiele method) is well known to all students of chemical engineering [1, 2]; however, in practice, binary distillation takes place almost exclusively in the undergraduate laboratory. Real separations involve multi-component mixtures (three or more species) and this presents a real complication that is the subject of some of our recent research efforts.

In addition to the problems posed by the multicomponent nature of most separation processes, chemical reaction presents a set of unique difficulties all of its own. The development of procedures for the analysis and design of such operations forms the second thrust of our efforts. Despite the fact that a great deal of work has been published on chemically reactive mass transfer [3, 4], it is remarkable that so little has been reported on the application of this extensive fundamental work to the design and analysis of separation processes of industrial scale.

Finally, when multicomponent mass transfer is combined with chemical reaction and heat transfer some really intriguing problems arise. An example is the condensation of multicomponent vapors when two or more species can react together in the condensed phase. Nothing at all appears ever to have been written about this aspect of mass transfer and a study of it forms the third part of our general efforts.

In what follows it will be most convenient to discuss these three main threads of our research somewhat separately.

MULTICOMPONENT DIFFUSIONAL SEPARATION PROCESSES

Considerable effort has been devoted to the construction of algorithms for calculating the equilibrium separation in multicomponent, multi-stage systems and many ingenious computational procedures have been devised. The formulation of the material and energy balance equations in tri-
diagonal and block tridiagonal matrix form (thereby permitting efficient methods of solution) has proved particularly efficacious in this area [1, 2].

While the principle advantage of equilibrium models is their (relative) simplicity, the primary disadvantage is that they are fundamentally unsound; distillation, absorption, and so on are certainly not equilibrium operations. If any successful non-equilibrium model of multicomponent stagewise processes is to be developed, it must be based on sound mass transfer principles. This is where the complications set in because the calculation of mass transfer rates in multicomponent systems is considerably harder than it is for binary ones.

Diffusion in multicomponent mixtures is complicated by the coupling that exists between the individual concentration gradients. The rate of diffusion of one species is dependent not only on its own concentration gradient but on all the other concentration gradients as well. Now, these individual concentration gradients may have vastly different magnitudes and signs. Thus, a possible consequence of the coupling between the gradients is that a particular species may permeate in opposition to its own concentration gradient, or may not transfer at all even though a gradient for it exists. A further possibility is that a species with no concentration gradient in a particular medium may be transported through that medium at significant rates. These “interaction” phenomena, which cannot take place in binary mixtures, are called reverse diffusion, a diffusion barrier and osmotic diffusion, respectively [5-7].

Practical consequences of diffusional interaction phenomena include individual point efficiencies in tray distillation not all being equal and not being constrained to lie between zero and one, both of which conditions hold for binary mixtures. Based on a film model of steady-state one-dimensional mass transfer.

There are, currently, four such methods able to predict the occurrence of the various interaction phenomena and which are applicable to mixtures with any number of constituents regardless of the relationship between the fluxes (for example, transfer through a stagnant gas or equimolar counter transfer).

In chronological order of their development they are:

2. The method of Krishna and Standart [12] based on an exact solution of the Maxwell-Stefan equations. It is worth noting that all of the eight or so separately published exact solutions of these equations (see [6] for sources) are simply different forms or special cases of a single fundamental result [13].
3. An “alternative linearized theory” proposed recently by Krishna [14, 15].
4. A simplified method developed by Taylor and Smith [16].

All of these methods make use of the properties of matrices. Methods 1 and 2 usually require iteration on the fluxes, involve matrix computations and may suffer convergence problems. Methods 3 and 4 are explicit in the fluxes. Methods 1 and 2 have been used to predict efficiencies and Numbers of Transfer Units in distillation and applied to the simulation of condensers [6]. The rather limited number of experimental results

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**Practical consequences of diffusional interaction phenomena include individual point efficiencies in tray distillation not all being equal and not being constrained to lie between zero and one, both of which conditions hold for binary mixtures.**
that are available confirm that interaction effects may sometimes be significant indeed [6, 8, 17-21]. Methods 1 and 2 predict, often to a very satisfactory degree, the experimentally measured rates of mass transfer whereas models which neglect interaction effects, based on the concept of an effective diffusivity, are inadequate. Methods 3 and 4 have not been tested yet and this is something we are working on.

Engineering design based on the matrix methods is necessarily computer based because of the length and complexity of the calculations involved. Theoretical papers on mass transfer frequently make claims to the effect that the inclusion of this or that model into existing design procedures is straightforward (see, for example, ref. 15). In fact, the combination of design equations with advanced models of mass transfer is not at all straightforward because of the nature of the computations that are required.

Recent research has led to the development of stable and efficient algorithms for computing intra-phase mass transfer [20-23]. This, of course, is only a part of the overall problem because mass transfer in real systems necessarily involves two distinct phases. The more practical problem of computing rates of inter-phase mass transfer has been the subject of only very recent investigation [24, 25]. A number of different computational algorithms have been developed and these have proven markedly superior to previously published procedures. A large part of the problem here is that the models require extensive physical property data that are not always accurately known and the estimation of which occupies a very major portion of the total time required. Currently under way is a computational study to investigate the sensitivity of the models to uncertainties in basic data.

It is, of course, possible to compute mass transfer rates (which are the quantities really required in design calculations) much more rapidly from the explicit methods 3 and 4. It is, therefore, of some interest to know when an approximate method can be used and what level of confidence can be ascribed to its predictions.

We have recently compiled statistical informa-

Diffusion in multicomponent mixtures is complicated by the coupling that exists between the individual concentration gradients.
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Required mass transfer rates are estimated from a model that combines stage hydrodynamics and multicomponent mass transfer. This model can be as simple or as complicated as desired [30].

CHEMICALLY REACTIVE SEPARATIONS

Separation operations involving mass transfer with chemical reaction are typified by a number of processes for gas purification, particularly those for the removal of acid gases. Coal gasification processes produce copious amounts of carbon dioxide which will have to be removed from the gas mixture, and in coal liquefaction part of the product is gas containing much CO₂ which lowers its heating value. Many gas purification processes employ chemically-reactive solvents which must be reused; thus, there are two important parts of such processes, namely gas absorption and solvent regeneration.

It turns out that the absorption step usually is of relatively low cost; the solvent regeneration step, however, is very costly indeed and dominates the economics, accounting for well over 80% of the operating costs [31]. With this in mind, the surprising fact is that it is the gas absorption step (at least for a single transferring component) that has been extensively studied [3, 4]. By contrast, the solvent recovery or stripping operation has remained virtually unexplored from either a fundamental or practical viewpoint and is totally lacking in design methods. If the process could be understood in a fundamental way to the extent that the dependence of stripping column performance on plant operating variables was predictable, then the real possibility of plant optimization in terms of reducing energy costs would exist. Thus, the ultimate objective of this aspect of our research is to develop design and analysis procedures founded on a fundamental understanding of the basic physicochemical processes taking place.

Previous literature dealing with gas desorption from chemically-reactive solution is sparse indeed and most of it addresses the problem merely as a sideline to a study of the absorption step of some new process. Notable exceptions are the experiments of Ellis et al [32] and McLachlan and Danckwerts [32], although the former shed little light on the fundamentals. It is really only in the past year or so that the results of serious efforts to understand this important operation have begun to be reported. The stripping of an already absorbed species from chemically reactive solvents purely by the action of heating (and this is the industrially common situation) has recently been examined from a theoretical standpoint by Astarita and Savage [34] who incorporated the classical two-film theory. The key result of their analysis was the delineation of the conditions under which absorption theory (which is well developed) can be applied to desorption.

In a companion paper, Savage et al. [35] reported absorption and desorption rate data for the CO₂—hot carbonate system and interpreted the results in terms of their theory. Unlike all previous studies, one of the more positive aspects of their work is that it was done in an apparatus of well-defined geometry and characterizable hydrodynamics so that, by and large, chemical kinetics could be nicely separated from mass transfer effects. The range of solution loadings covered, however, was insufficient to establish the influence of this variable. Unfortunately, the data were interpreted on the basis of negligible gas phase resistance to mass transfer; whereas, at least for the CO₂—monoethanolamine system, this resistance is dominant over a certain range of conditions [36].

Based on the work of Rawal [36] who assumed that the equilibrium model of Olander [37] applied to the stripping of carbon dioxide from monoethanolamine solutions (this now seems justified in the light of ref. 34), we have recently elaborated on a design procedure for packed stripping columns using this process [38]. The primary aim of this work was the prediction of column performance from first principles, based solely on physicochemical parameters and equilibrium data specific to the system. For this purpose, the ability to apply chemical absorption theory, although important, is only one component of the overall analysis. The reversibility of the chemical reactions is critical in chemical desorption. This necessarily introduces thermodynamic relations as an integral part of the theory. Furthermore,
heat effects cannot be ignored because a substantial amount of heat must be supplied to effect the decomposition of the solvent-gas compound and the liberation of the freed gas from solution. The implication is that vapor and liquid rates vary significantly throughout the column, although the column itself operates substantially isothermally.

We have recently completed an experimental study of this operation [38] done in a small (6-in. diameter) reboiled packed column (Fig. 1). While it must be admitted that the comparison between model and experiment in this work tended to be more qualitative than precise, it is useful to note that many of the trends found were rather counterintuitive so that the transport process is by no means a straightforward one. For example, it was predicted theoretically and confirmed experimentally in a fairly rough way that at low solution loadings, increasing liquid rate could actually decrease the overall mass transfer coefficient \( K_{0,La} \). Furthermore, when solution loading was low, the gas-side resistance was found to be of tremendous importance. This was unexpected in view of the fact that \( \text{CO}_2 \) has a very low physical solubility and that it is generally agreed that the mass transfer of sparingly soluble gases is liquid-phase controlled. Other operating variables such as operating pressure, solution loading and amine concentration were found to have surprising effects as well. Many of these results stem from the fact that a change to one operating variable causes changes in a number of parameters at the same time so that intuition cannot be relied upon for guidance. A good model, however, provides unerring advice.

Naturally there are serious problems associated with trying to test fundamental models on large scale equipment at such an early stage of development. One of these is the poor characterizability of packed columns in terms of hydrodynamics, hence, individual film coefficients so necessary to a proper film model of chemically reactive mass transfer. As mentioned earlier in the context of multicomponent mass transfer, errors in basic data can have a profound consequence on model prediction; a sensitivity analysis is presently underway for reactive mass transfer in continuous contacting equipment.

To provide data of greater reliability for testing against these fundamental mass transfer models, we are doing experiments in well-defined flow geometries like single sphere and string-of-spheres columns. Then all of the necessary fundamental data become accurately known, or at least can be independently measured, and a real test of models becomes possible. An obvious extension is to systems in which two or more gases simultaneously absorb and then react with a common nonvolatile solvent. Typical of such systems is the absorption into, and stripping from, alkanolamines of carbon dioxide and hydrogen sulfide. Of particular interest is the selective removal of \( \text{H}_2\text{S} \). Although a moderate amount of equilibrium and physical property data exists for this combination, little or no mass transfer work has been done on the absorption side, and nothing has been reported on solvent regeneration. Yet the natural gas industry in this country is very large indeed and natural gas often contains a lot of both impurities. Experiments and modelling of both aspects of this rather more complex system are underway at Clarkson.

Our studies using model mass transfer devices are aimed at testing theories of the transfer processes which will find ultimate use in simulations of packed columns. Concurrently, we are also Continued on page 200.
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A Course in

FUNDAMENTALS OF PETROLEUM PRODUCTION

F. A. L. DULLIEN
University of Waterloo
Waterloo, Ontario, Canada

O
ev er the past decade an increasing number of graduates of the Chemical Engineering Department and also of some other engineering departments of the University of Waterloo have been hired by various petroleum companies, operating mostly in Alberta. The Faculty of Engineering at the University of Waterloo operates one hundred percent on the cooperative scheme. The students alternate between academic and work terms. An increasing proportion of our students have been hired in their work terms by the oil companies. This situation created a demand for a senior year elective course in the fundamentals of petroleum production which is also suited to the needs of first year graduate students specializing in some branch of flow through porous media research. There is no petroleum engineering department at the University of Waterloo, but there has been continuous basic research on certain aspects of this discipline for the past sixteen years, under the author's supervision. It was thus logical for the author to propose a course on Fundamentals of Petroleum Production, which was accepted by the Faculty of Engineering in 1978. Since then the course has been taught every year in the winter term.

The purpose of this course is to introduce the average chemical engineer, who has only a minimum of familiarity with the concepts of capillarity and flow through porous media, and none at all with reservoir engineering concepts, to petroleum production engineering. All this has to be accomplished in thirteen weeks (three contact hours per week), because with the coop system the lecture part of a term is only about three months long. Under these constraints the course on Fundamentals of Petroleum Production is limited in scope and, at the same time, conceptually difficult for the students.

TECHNICAL CONTENT

The technical content of the course is best appreciated by perusing the course outline shown in Table 1. The rationale for this approach to the course is presented in the following paragraph. The author does not think that a completely black box-type presentation of the material is in the best interest of either the student or the industry where the student may work. The black box approach pays no attention to the microscopic mechanisms, the interplay of the various forces...
on a microscopic scale and the microscopical geometric parameters of the environment in which the physical phenomena take place. It is true that a typical reservoir engineer is concerned with the control and prediction of macroscopic parameters but it is equally true that the observed macroscopic behavior is, to a large extent, the result of events that occur in small pores and which are determined by microscopic parameters. Staying mum on the microscopic aspects of petroleum reservoirs (an attitude which is quite common in some texts on reservoir engineering) is tantamount to pretending to be completely ignorant of some facts which are very important in determining the outcome of oil recovery operations, particularly when secondary and tertiary recovery are considered. Such an attitude is likely to mislead the student by keeping him ignorant about things that matter a great deal. The purpose of university education cannot be the maintenance of ignorance. This is the reason for starting this course with an introduction to capillary theory.

In the discussion of basic laws of capillarity, attention is drawn continually to the fact that petroleum reservoirs consist of a multitude of tiny interconnected capillaries. A petroleum reservoir is a permeable porous medium, not at all like the water reservoirs most people tend to think of immediately when they hear the word “reservoir.” The major portion of this chapter deals with the capillary pressure curves: primary drainage, imbibition and secondary drainage capillary pressure curves, their methods of measurement in the lab and in the field, capillary hysteresis and the roles played both by the pore structure and the contact angle in bringing about the hysteresis. One of the difficult tasks to be accomplished in this portion of the course is to give the students a “feel” for the physical phenomena, “drainage” and “imbibition.” It has been found indispensable to do a classroom demonstration of these phenomena. Transparent capillary micro-models are very useful for this purpose, as is an experiment consisting of placing a sandstone core plug, saturated with oil, in a beaker of water. The spontaneous imbibition of water into the plug is demonstrated by the appearance of oil drops on the plug’s surface which have been displaced by the water.

The second chapter introduces the student to the fundamentals of flow of a single fluid through a permeable porous medium. The discussion is centered on Darcy’s law and the various types of pressure heads and fluid potentials which are

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**TABLE 1**

Course Outline

1. **CAPILLARITY**
   - Laplace’s equation of capillarity
   - Young’s equation—The contact angle
   - Capillary pressure—Effects of the pore structure and the contact angle
   - Determination of the capillary pressure curve—Saturation
   - Capillary rise—Effects of the pore structure and the contact angle
   - Kelvin’s equation
   - Capillary hysteresis—Effects of pore structure

2. **FLOW OF A SINGLE FLUID THROUGH POROUS MEDIA**
   - Porosity
   - Specific surface
   - Permeability—Darcy’s law
   - Formation factor
   - Macroscopic heterogeneity of pore structure
   - Anisotropy

3. **SOME APPLICATIONS OF DARCY’S LAW**
   - Fluid potential
   - Linear flow vs. radial flow
   - Well stimulation

4. **BASIC CONCEPTS IN RESERVOIR ENGINEERING**
   - Calculation of hydrocarbon volumes
   - Fluid pressure regimes
   - Oil recovery—Recovery factor
   - Volumetric gas reservoir engineering
   - Gas material balance—Recovery factor

5. **PVT ANALYSIS FOR OIL**
   - Definition of the basic PVT parameters
   - Use of the PVT parameters

6. **GENERAL MATERIAL BALANCE EQUATION FOR A HYDROCARBON RESERVOIR**
   - Derivation of the general equation
   - Solution gas drive
   - Gas cap drive
   - Natural water drive
   - Compaction drive

7. **DISPLACEMENT OF OIL BY AN IMMISCIBLE FLUID**
   - Generalization of Darcy’s law for multiphase flow
   - Effective and relative permeabilities
   - The Buckley-Leverett theory of oil displacement
   - Mobility control
   - Tertiary flooding
used in conjunction with this basic law of reservoir engineering and groundwater hydrology. Thus, careful distinction is drawn between the physical meaning of the hydrostatic pressure, $P$ and the “datum pressure” or “psi-potential” $\psi = P + \rho g z$, where $z$ is distance measured vertically upward from an arbitrary datum, $\rho$ is the fluid density and $g$ is the gravitational acceleration constant. Generally, it is the gradient of the datum pressure, $\nabla \psi$, that must be used in Darcy’s law. The heads $P/\rho g$ and $\psi/\rho g = P/\rho g + z$ represent distances in the vertical direction and are much more readily visualized than the corresponding pressures, $P$ and $\psi$. $\psi/\rho g$, the so-called “piezometric head,” is then the sum of the pressure head, $P/\rho g$ and the elevation head $z$. The fluid potential $\Phi$ is also introduced here.

The permeability, $k$, the porosity, $\phi$, and the specific surface, $s$, are the most commonly used macroscopic pore structure parameters. By definition, their value does not depend on the fluids used in the measurement, but it is completely determined by the pore structure of the sample. The important role played by pore structure in determining reservoir behavior is stressed again when discussing the above mentioned parameters. The Kozeny-Carman equation is “derived”, not because it is believed to be generally valid, but mainly to illustrate the kind of efforts that have been made to understand the relationship between flow and pore structure.

Simple integrated forms of Darcy’s law are presented, and the special cases of gas flow, slip flow (Klinkenberg equation) and non-Darcy flow (Forchheimer equation) are discussed.

There follows a brief outline of some field applications of Darcy’s law.

The formation (resistivity) factor is then introduced and the fundamental difference between Darcy flow and electrical conduction in porous media is pointed out. This is manifested by the fact that the electrical conductivity of small pores is the same as that of big pores whereas the fluid conductivity of a pore in creeping flow varies as $A$, the normal cross-section of the pore. Hence a fine-pored medium has a much lower permeability than a coarse-pored of comparable porosity, while the difference between the formation factors of the two materials may be relatively little.

It is pointed out that reservoirs are heterogeneous, i.e. they are characterized by a distribution of permeabilities, and anisotropic, i.e. the permeabilities at a given point are different, depending on the direction of flow.

At this point in the course the students already have a certain idea of the behavior and the pore structure of a reservoir. They are unlikely to confuse it with a water reservoir.

| TABLE 2 |

Recommended Reference Books


The course switches to the subject which is conventionally at the beginning of reservoir engineering texts; the explanation of the basic concepts of reservoir engineering, such as hydrocarbon volumes, fluid pressure regimes, gas recovery factor, gas expansion factor, solution gas-oil ratio, oil formation volume factor, gas formation volume factor, producing gas-oil ratio, etc.

Next, the general macroscopic material balance for a hydrocarbon reservoir is derived, discussed and applied to elucidate the various possible natural modes of petroleum production, the different so-called “drives.”

At the end of the course the fundamentals of immiscible displacement are outlined. In this chapter some of the basic concepts, introduced in the early chapters, play an important role and are thus vindicated from an applications point of view which, of course, is the only point conceded by the average student taking this course.

There are usually four home assignments in this course, one on each of the following chapters: 1, 2-3, 4-6, and 7, and three tests, one on each of the following chapters: 1-3, 4-6, and 7. Final examination has been dispensed with.
The 1982 ASEE Chemical Engineering Division Lecturer was Lowell B. Koppel of Purdue University. The purpose of this award lecture is to recognize and encourage outstanding achievement in an important field of fundamental chemical engineering theory or practice. The 3M Company provides the financial support for this annual lecture award.

Bestowed annually upon a distinguished engineering educator who delivers the Annual Lecture of the Chemical Engineering Division, the award consists of $1,000 and an engraved certificate. These were presented to this year's Lecturer at the Annual Chemical Engineering Division banquet, held at the University of California at Santa Barbara.

NOMINATIONS FOR 1983 AWARD SOLICITED

The award is made on an annual basis with nominations being received through February 1, 1983. The full details for the award preparation are contained in the Awards Brochure published by ASEE. Your nominations for the 1983 lecture-ship are invited. They should be sent to Robert E. Slonaker, Chairman, 3M Award Committee, ChE Department, Bucknell University, Lewisburg, PA 17837.

NEW DIVISION OFFICERS ELECTED

The newly elected ChE Division officers are: Angelo Perna, Chairman; W. D. Baasel, Past Chairman; Dee Barker, Chairman Elect; Bill Beckwith, Secretary Treasurer; John Sears and Dale Seborg, Members at Large; Hal Kemp and R. P. Stambaugh, Industrial Representatives.

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George Burnet, Iowa State University, was the recipient of ASEE's highest honor, the Lamme Award, in recognition of his excellence in teaching, contributions to research and technical literature, and achievements contributing to the advancement of the profession. William Corcoran, California Institute of Technology, received the Distinguished Service Citation for his long and continuous service in teaching, research and administration.

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Ray W. Fahien, University of Florida, was presented with an Award of Excellence. Paul V. Smith of Exxon and James Townsend of Dow were both recognized for their many contributions to the ChE Division as industrial representatives. T. W. F. Russell, Stanley I. Sandler and Sherri Barwich, all of the University of Delaware, were presented with Certificates of Appreciation for their work in coordinating the 1982 Summer School, and Dale Seborg and John Myers were both recognized for their contributions as hosts at the University of California, Santa Barbara.

ChE book reviews

OPTIMIZATION AND INDUSTRIAL EXPERIMENTATION
By W. E. Biles and J. J. Swain
John Wiley & Sons, NY

Reviewed by R. M. Bethea, H. R. Heichelheim, L. D. Clements Texas Tech University

Chapter 1. This section provides a thorough coverage and description of the properties of optimization problems with an inconsistent mixture of belaboring the mathematically obvious and "name-dropping" of methods to be developed later.

Chapter 2. The use of the chi-squared goodness-of-fit test to evaluate the Poisson distribution is unusual in most introductory statistics texts. The explanation is clear to a reader with some background in mathematical statistics but not to the novice as is the authors' stated goal. Note that in the example of the Poisson on p. 47 should be f(y) = e^{-2}y^{2}/y! and that the values of f_i and e_i in Table 2.12 have been multiplied by 100.

In the section starting on p. 89, no justification has been given for the F-tests. In this way, the student is not taught the why of analysis of vari-Continued on page 199.
A Course in

AIR POLLUTION FOR ENGINEERS

MAYIS SEAPAN
Oklahoma State University
Stillwater, OK 74078

IN THE PAST TWO DECADES the need for environmental awareness has increased the enrollment of chemical engineers in environmental courses, especially in air pollution courses. This is true both for formal university courses and for the continuing education short courses.

Traditionally, most of the air pollution courses have been developed in civil and environmental engineering departments. Only a small percentage of chemical engineering departments offer a course related to air pollution. In 1978, there were 581 air pollution courses offered in 130 American and Canadian Universities and Colleges in 189 academic departments [1]. These departments varied from traditional engineering to disciplines like geography and biology, with only 27 chemical engineering departments offering an air pollution course.

The diversity of the disciplines in which the air pollution courses have been developed and the variations in the background of students have made the air pollution courses very non-uniform. Departments with multiple air pollution courses cover different aspects of the air pollution under one or more of the following topics: fundamentals of air pollution, atmospheric sampling and analysis, atmospheric chemistry and meteorology, modeling of atmospheric dispersions, aerosol science and technology, industrial pollution processes, theory and design of air pollution control systems, and air quality management. These courses have varied from very introductory and descriptive to strongly theoretical, with intensive use of mathematics, to highly application and design oriented ones.

Many engineering students who do not intend to specialize in air pollution cannot afford to take several courses in air pollution. They would usually prefer to take one general course that would give them an overall understanding of the field. Several schools also offer a general air pollution course as an elective to students of different disciplines. Obviously, in this general air pollution course many of the above mentioned topics have to be selectively compressed or eliminated.

The air pollution course described in this article is specially designed to be a general course of one semester or two quarters duration, tailored to serve as an elective course for engineering students in their M.S. or senior level.

This course is different from other one-semester air pollution courses in several aspects. The order of presentation of the topics is completely new. The new arrangement is based on the principle of cause and effect. The theoretical basics are reviewed at the beginning of the course. Consequently, the subsequent topics are not presented as case studies, but as applications of the theoretical principles. Thus, the student studies and analyzes the applications with a creative approach and often can deduce the resultant phenomena before the empirical observations are presented. It is the main objective of this course to challenge the creative thinking of the students. This is achieved not only during the lectures, but also by the type of problems that are given during the quizzes and examinations. As a result of these efforts, the learning efficiency is improved and more material is covered in the course.

COURSE DESCRIPTION

The course consists of two major parts: fundamentals of air pollution, and control technology and equipment design. In the first part, the air pollution system is treated as a huge chemical reactor, where man is a moving boundary exposed to the pollutants. In the second part, the control technology is described and the design methods
Mayis Seapan received his Ph.D. from the University of Texas at Austin (1976) and is presently Assistant Professor of Chemical Engineering at Oklahoma State University. His current research interests are the formation of aerosol particles by chemical reactions and upgrading of coal derived liquids with specific interest in the catalyst deactivation and kinetics of hydrotreatment of coal derived liquids.

are discussed. Usually equal time is spent in teaching these two parts. However, in this article more space is devoted to the fundamentals of air pollution to show its special merits.

The most important reason for our study of air pollution is a concern both for our health and for that of future generations. The threat to our health may come from direct exposure to pollutants, or from indirect exposure through water, plants, animals, and generally from the entire environment.

The ecological effects of air pollutants depend on (a) the concentration of the pollutant, (b) the temperature, (c) the duration of exposure, and (d) the velocities of the surrounding air. In some cases other factors, such as concentrations of other constituents, may also interfere. Thus, in theory, in order to be able to evaluate the extent of the potential damage of air pollutants, one needs to know the concentration of every pollutant at any location and at any time.

The air surrounding the earth is considered as a huge non-homogeneous, non-uniform, and non-ideal chemical reactor which has the approximate shape of a spherical shell. In order to understand this non-ideal reactor, one needs to consider the following:

- Chemical and physical constituents of the reactor and their properties
- Heat transfer and temperature distributions
- Fluid dynamics and velocity distributions
- Physical boundaries of the reactor and transport phenomena through these boundaries
- Interactive and combined phenomena of all these factors

Chemical constituents of the atmosphere include not only nitrogen and oxygen but all reactive and non-reactive gases as well as the suspended particles in the atmosphere. Physical constituents are considered as atmospheric electricity, radioactivity and electromagnetic radiation; where solar radiation plays the major role. Therefore the course starts with a review of different pollutants of the atmosphere and electromagnetic radiation. This is followed by a study of the interaction of radiation with gaseous molecules, the principles of photochemistry, the formation and dynamics of aerosol particles, and the interaction of particles with electromagnetic radiation, electricity and radioactivity. It is at this stage that the students are introduced to the concept of free molecular and continuum flow behavior of particles. They learn about Brownian motion and phoretic forces and develop a general understanding of the significance of each phenomena under different conditions. The students also learn the role of wavelength in the absorption of electromagnetic radiation by chemical constituents and its significance in the initiation of different types of chemical reactions.

Before the discussion of atmospheric fluid dynamics, i.e., meteorology, the atmospheric energy balance is discussed. By introducing atmospheric layers and their role in filtering different wavelengths from solar radiation, the heat balance around the earth is introduced. The role of different chemical constituents in the atmospheric heat balance is discussed and the greenhouse effect is explained.

The fluid dynamics of the atmosphere as classified under macro-, meso- and micro-meteorology is introduced with emphasis on the concept of cause and effect, indicating the role of solar radiation and the atmospheric heat balance in the development of atmospheric motions. This discussion is further expanded to the vertical temperature distribution, lapse rate, inversion layers, and atmospheric stability.

Sources of pollution as inputs through the lower boundary of the reactor, i.e., the surface of
... it is also emphasized that "dilution is not a solution to pollution" and whatever is released into the atmosphere will eventually return to the earth in some form.

earth, are reviewed and an account is given to emission inventories. At this stage atmospheric chemistry and different types of smogs are presented. A study of air pollution sinks, both through the lower boundary to the earth and through the tropopause to the upper levels of the atmosphere illustrates how pollutants are eliminated from the air. Water bodies, open lands, plants and lungs of living creatures are considered as some of the sinks on the surface of the earth, while stratospheric ozone layer is a sink at the upper levels of the atmosphere.

To account for localized variations of pollution, dispersion of pollutants in the atmosphere from point, line, and surface sources are presented and the concept of atmospheric modeling is introduced.

Throughout the presentation of this global reactor model, the principles of global material and energy balances are repeatedly emphasized so that the students realize that whatever pollution is emitted to the atmosphere, eventually is going to be removed in the sinks in the boundaries of the reactor.

At this stage, the student, in principle, is capable of predicting the fate of and concentrations of atmospheric pollutants. The effects of air pollutants on the atmospheric environment are discussed by presenting such topics as ozone layer depletion, acid rain, and visibility reduction. Air pollution damage to vegetation and materials is followed by the effects on human and animal health.

The student at this time is quite familiar with the behavior of different gaseous and particulate pollutants and therefore the analysis of their effects is no longer a case study. For example, the dependency of particle capture rate on the particle size in the lungs is not a matter to be accepted and memorized. The student recognizes the relative significance of interception, sedimentation and diffusion, so he or she can deduce the concept of lung deposition.

Once the effects of air pollutants are studied, the safe limits of pollutants and the existing uncertainties in these limits are discussed. Air pollution regulations are presented under the two classes of receptor and emitter standards. A brief summary of air pollution measuring techniques completes the section on the fundamentals of air pollution.

In the second half of the course, control technology is taught. Again the ground is laid by reviewing the basic chemical engineering principles to show the thermodynamic and rate limitations on the formation of pollutants. Material balances are used to calculate the emission rates. An energy balance is used to calculate the combustion and outlet stream temperature. Chemical equilibria show the thermodynamic limitations on the formation of pollutants. Finally, chemical kinetics explain the rate phenomena and the time factor involved in the formation of pollutants. This review is usually repetitious to chemical engineers, but it is required for the understanding of the rest of the discussion. Therefore, it must be taught if non-chemical engineers are present in the class.

At this stage, emission inventories and emission factors are briefly reviewed. Incineration is discussed as the first control technology. As another application of the basic principles, automobile emission control is presented. Again the discussion is based on thermodynamic and kinetic principles; therefore the student can deduce the outcome of most of the control techniques.

Control of gaseous emissions by absorption and adsorption and the sizing of equipment are discussed. The students are continuously reminded of the economic limitations of gas cleaning processes so that they realize that, even with the best available control technology, the exhaust stream will contain some low levels of pollutants which need to be properly disposed into the atmosphere. The stack as a means of this dispersion of pollutants is described and its design methods are exercised. However, it is also emphasized that "dilution is not a solution to pollution" and whatever is released into the atmosphere will eventually return to the earth in some form.

A theoretical discussion of the aerodynamic capture of particles and the forces responsible for the collection and separation of particles precedes the particulate control section.

Particulate control equipment is divided into two groups; the equipment in which a specific body force results in the separation of the particles from the carrier gas, and the equipment which operates on the basis of the aerodynamic capture
of particles by an object or obstacle. In the first class, settling chambers, centrifugal separators and cyclones, and electrostatic precipitators are discussed. In the second class, filtration and wet scrubbing are described. For every type of equipment, the operating principles and the physical construction are presented first, followed by design principles and equations. Emphasis is placed on sizing of equipment, calculation of collection efficiencies, and pressure drops.

The final part of the course is based on comparing particulate control equipment. The criteria for the selection of suitable equipment is presented and the guidelines to achieve an economical design are discussed. At present, there seems to be a need for the coverage of flue gas desulfurization and other special topics, but due to time limitations these have not been incorporated in the course. Table 1 gives a more detailed course outline.

<table>
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<td>Introduction to air pollution</td>
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<td>Atmosphere, a huge chemical reactor</td>
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<td>Chemical Constituents of the Atmosphere</td>
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<td>Gaseous pollutants</td>
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<td>Particulates</td>
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<td>Physical Constituents of the Atmosphere</td>
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<td>Sulfurous smog</td>
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<td>Miscellaneous atmospheric reactions</td>
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<td>Sinks of Atmospheric Pollution</td>
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<td>Sinks at the earth’s surface: water bodies, earth, vegetation, animals</td>
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<td>Sinks at the upper layers of the atmosphere</td>
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<td>Atmospheric Dispersion</td>
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<td>Gaussian plume and ground concentrations</td>
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<td>Dispersion of particulates and their deposition from plumes</td>
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<td>Effects on human health</td>
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<td>Direct and indirect exposure</td>
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<td>Lung and its defense mechanisms</td>
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<td>Effects of gaseous and particulate pollutants on the respiratory system</td>
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<td>Sampling and Analysis of Air Pollutants</td>
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<td>Management of Air Pollution</td>
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| **II—Control Technology and Design** |
| Basic Principles |
| Material balance |
| Energy balance |
| Chemical equilibria |
| Reaction rates |
| Emission Inventories and Emission Factors |
| Incineration |
| Automobile Emissions and Control |
| Fuel tank, carburetor and crankcase emissions |
| Exhaust gas emissions and its control |
| Absorption |
| Adsorption |
| Dispersion of Pollutants From Stacks, Stack Height |
| Particle Size Distributions |
| Collection Efficiencies and Penetrations |
| Grade Efficiencies and Overall Efficiencies |
| Aerodynamic Separation and Capture of Particles |
| Gravity, centrifugal and electrostatic forces |
| Calculation of particle trajectories and stop distances |
| Capture of particles by obstacles: impaction, interception, diffusion and seiving |
| Particulate Control Equipment and Their Design |
| Settling chambers |
| Centrifugal separators, cyclones |
| Electrostatic Precipitators |
| Filtration, fabric filters |
| Wet scrubbing |
| Economics and comparative design of particulate control equipment |
TEXTBOOK

In the past two decades several textbooks have been written for air pollution courses. Unfortunately, none of them can be used for the entire course. Some of these textbooks cover primarily the fundamentals [2-6], while others cover the control aspects [7-10]. The textbooks that attempt to cover both the fundamentals and control [11, 12] do not place the desired emphasis on different topics. In addition, the sequence of topics in the textbooks is significantly different from the sequence of this course. Therefore no single textbook was found suitable for this course. For every topic, appropriate pages from different sources are recommended for reading.

ASSIGNMENTS AND EXAMINATIONS

Two types of assignments are normally given. Computational homework problems, through which the students learn to use the basic design equations, are assigned on a regular weekly basis. During the first few weeks, while the fundamentals are being covered, not many computational problems can be given. Therefore, certain reading materials are assigned which are later tested by short quizzes. In order to minimize the memorization aspect of these assignments and improve the creativity and critical thinking of the students, no direct questions are asked on the assigned reading material. The questions are indirect and require some creative thinking based on the studied material. Three one-hour exams and one final exam are given during the semester. These examinations are composed of questions similar to the ones in the short quizzes and computational problems. Since no direct questions are asked, all the examinations and short quizzes are handled on an open-book open-notes basis.

SUMMARY AND CONCLUSIONS

The described air pollution course which covers both the fundamentals and control of air pollution introduces a new sequential structure for its topic presentation. This new structure is built on the basis of theoretical principles and has minimized the traditional case study approach. The major objective throughout the course is to prepare the students to become creative thinkers capable of analyzing existing and future/new air pollution problems.

This course, developed and taught at Oklahoma State University, has attracted many superior students from different engineering disci-
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A Program in

POLYMER EDUCATION AND RESEARCH

DONALD G. BAIRD AND
GARTH L. WILKES
Virginia Polytechnic Institute
and State University
Blacksburg, VA 24061-6496

POLYMER EDUCATION AND research is gradually becoming a part of every major university in the country. At least some type of survey course in polymers is presented, and occasionally additional specific courses are offered, e.g. polymer processing, polymer synthesis, etc. Where more developed polymer programs are found, they are usually isolated in specific departments; the most common being chemistry, chemical engineering or materials engineering. A few universities have progressed to the point where separate polymer science departments now exist.

At VPI & SU a unique interdisciplinary polymer program (referred to as the Polymer Materials and Interfaces Laboratory [PMIL]) has evolved over the last five years and involves 11 faculty from five departments and some 70 graduate students and post-doctoral associates. The uniqueness of the program rests in the fact that it is truly interdisciplinary, with faculty cooperating in research and teaching activities. While other interdisciplinary groups or programs exist in the country, they often do not function smoothly due to interdepartmental or inter-college barriers. At Virginia Tech these barriers do not exist. Furthermore, the operation of this interdisciplinary effort has joint Co-Directors, with one in the College of Arts and Sciences and the other housed in the College of Engineering (see Fig. 1). This minimizes any political biases and at the same time provides smoother operation in both education and research. One example of cooperative research is a project entitled “High Performance Elastomers and Other Multiphase Organic Composites” where five faculty from the departments of chemical engineering, materials engineering, and chemistry combine their expertise in polymer synthesis, characterization, rheology and processing, and structure/property relationships to provide a complete understanding of novel elastomeric polymer systems. A second and similar example of the strong cooperative research is the newly established “Adhesion Center” where the principal aim is an understanding of the fundamentals of polymer adhesion. This center, which has acquired major outside funding from the Office of Naval Research, was established through the cooperation of four faculty members of PMIL who are housed in three different departments.

From an educational viewpoint, a chemical engineering student who is interested in pursuing polymer research is expected to obtain a basic level of proficiency in polymer synthesis and physical chemistry of high polymers while developing an expertise in either polymer processing or structure/property relationships. The remainder of this article focuses on the educational offerings in polymers within the Chemical Engineering Department at Virginia Tech.

Polymeric fluids require not only the application of a shear stress to maintain shear flow but additional normal stresses. The normal stress differences exhibited by macromolecular fluids in shear flow are more sensitive to changes in molecular structure than is viscosity.
RESEARCH ACTIVITIES

Polymer research in the department is carried out under the direction of either Professor Baird or Professor Wilkes. The general theme of Professor Baird's research is the application of rheology to polymer and biopolymer processing, while that of Professor Wilkes is directed toward the structure/property relationships in these same or related polymer systems. Although each has his own research interests, the cooperative aspects of the polymer group extends strongly into the program. (David Dwight, who is also a part of PMIL, holds a partial appointment in Chemical Engineering but contributes principally to the Department of Materials Engineering; consequently, his interests in polymer adhesion and surface analysis will not be highlighted here.)

A contrast of Virginia Tech's efforts in polymer rheology with others shows that some groups approach non-Newtonian fluid flow behavior only from a theoretical viewpoint; they are often principally concerned with developing equations of state to describe the flow behavior of viscoelastic fluids. Our efforts, however, are directed more toward the application of rheology for solving polymer processing problems, employing molecular as well as continuum viewpoints. This approach sometimes involves merely finding empirical correlations between certain rheological properties and polymer processability. On the other hand, it may also involve using an existing constitutive equation in conjunction with molecular theory to model a polymer process. Since we study many fluids which are even more complex than common polymeric melts and solutions (two examples being liquid crystals and filled polymer systems), we are also concerned with the development of rheological equations of state for these fluids. However, we tend to be motivated by a need for developing models which are useful for process calculations, as opposed to developing a model which is so mathematically complex that it is of little practical value for calculations and process design even though it may accurately describe rheological properties of polymeric fluids over a large range of conditions.

The following description of several of our ongoing research programs illustrates the type of research which is carried out and emphasizes the cooperative nature of the research. The first examples extend from the work of Professor Baird. Polymeric fluids require not only the application of a shear stress to maintain shear flow, but additional normal stresses. The normal stress differences exhibited by macromolecular fluids in shear flow are more sensitive to changes in molecular structure than is viscosity. We are presently investigating two methods (hole pressure and exit pressure) for measuring normal stresses which are related to fluid elasticity in a slit-die, using a technique called flow birefringence. These slit-die rheometers have potential for in-line monitoring and quality control of industrial polymer processes. Because flowing polymer fluids become anisotropic, they can transmit polarized light. The birefringent patterns which arise are directly related to the state of stress or momentum trans-

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Garth Wilkes received his bachelor’s and master’s degrees from the College of Forestry at Syracuse University. Further graduate study was carried out at the University of Massachusetts where another master’s degree (Polymer Science and Engineering) as well as a doctoral degree (Physical Chemistry) were obtained. He joined the chemical engineering faculty at Princeton University in 1969 and was active in the Polymer Materials Program. In 1974 he received the outstanding young engineering faculty award at Princeton. The theme of his research is the structure-property behavior of synthetic and biological polymeric systems. In 1978 he accepted a full professorship at VPI & SU within the Chemical Engineering Department. In 1981 he was awarded an endowed chair position within the same department. He participates in both teaching and research duties and serves as a frequent consultant to the polymer industry. He is also Co-Director of the Polymer Materials and Interfaces Laboratory. He has published over 100 scientific papers and contributed to numerous books. (R)
Our efforts... are directed toward the application of rheology for solving polymer processing problems, employing molecular as well as continuum viewpoints.

Our efforts... are directed toward the application of rheology for solving polymer processing problems, employing molecular as well as continuum viewpoints.

port at every point in the fluid. From the stress field various pressures related to fluid elasticity can be calculated from theory and compared to the directly measured values.

Another project involves the rheology and injection molding of filled polymers. Our first objective has been to determine what effect filler has on the non-linear rheological properties of polymer fluids. The second goal has been to determine whether the rheological properties can be described by constitutive models used for homogeneous polymer fluids. We are presently investigating the possibility of using dimensional analysis to draw correlations between rheological properties, thermodynamic properties, and the final bulk physical properties which arise as a result of process conditions. A particular processing problem of interest is weld-line formation. This study requires an additional investigation of the structure and related properties at the interface between the two polymer fronts.

To illustrate the diversity of our efforts in rheology, we are also involved with the modeling of soy flour dough extrusion cooking processes which lead to meat-like products (these systems, of course, are polymeric in nature). This project involves an initial understanding of the transport mechanism for soy dough in an extruder, determining the properties of the dough under process conditions and developing a mathematical model for predicting relationships between power, torque, temperature and output for various extruder designs. This work will eventually be extended to predicting final extrudate texture and properties which will require an understanding of the structure property behavior of the final solid and how these relationships depend on processing. These latter points are addressed more by the efforts of Professor Wilkes. This particular project involves all the concepts of momentum, heat and mass transfer plus rheology, thermodynamics, kinetics, and structure/property relationships.

A last example of rheological studies is our research on liquid crystalline polymers, which involves rheology, processing and bulk structure and properties investigations. Liquid crystals are an intermediate state of matter between the isotropic liquid and crystalline solid state. Polymeric materials in the liquid crystalline state under shear generally have extremely low viscosity and can usually be processed to give bulk specimens with physical properties approaching those of metals. Because liquid crystals are by nature anisotropic they may have unique rheological properties. We are presently studying their flow behavior in order to identify any unique flow properties which may require a different rheological equation of state than is used for isotropic fluids. Furthermore, after processing these polymers behave as if they are self-reinforcing. Our present investigation concerns the effects of injection molding conditions on the development of morphology, structure, and properties. The latter part of the research is carried out under the supervision of Professor Wilkes.

Some of the other projects that are focused more on the structure-property behavior of polymeric solids include such phenomena as crystallization of polymers, synthesis and properties of ionic elastomers as well as block and segmented copolymers, nonequilibrium behavior of network glasses and rubber modifications thereof and, finally, polymer compatibility studies. In general, these studies, directed by Professor Wilkes, utilize a molecular approach with emphasis on experimental work. Typically, a student's graduate research project often involves at least two, and sometimes three, areas in order to establish a broader educational foundation in polymer science from which to work after leaving the university level. Several of these projects, as indicated earlier, overlap with those of Professor Baird where the input of processing and rheology help to provide insight into the nature of the final bulk properties that are studied.

**EDUCATIONAL OPPORTUNITIES**

Table 1 lists the polymer courses that are taught at Virginia Tech, some of which are given within the Department of Chemical Engineering. We will now address the various polymer science educational opportunities in chemical engineering both at the undergraduate and the graduate level.

**Undergraduate Courses**

At the undergraduate level, chemical engineering students may take as many as five courses in the area of polymer science (see Table 1). Two of
these courses are taught within the Department of Chemical Engineering while three extend from the Department of Chemistry and Materials Engineering. The latter three courses (which we will not address in detail) focus on (a) polymer synthesis, (b) polymer surface chemistry, and (c) applications of polymeric materials. In our own department the two principal courses at the undergraduate level are “Introduction to Polymer Processing” and “Introduction to Polymer Materials.” In the case of the processing course, students are introduced to the concepts of non-Newtonian fluid mechanics which serves as a basis for teaching extruder design, die design, and a qualitative description of processes such as film blowing and injection molding. The importance of processing on final structure and properties is also emphasized. However the general theme in the Introduction to Polymer Materials course is to focus principally on the bulk properties of polymeric systems as found in the glassy, rubbery and semicrystalline states. The first part of this course also includes an introduction to polymer synthesis for those students who have not acquired this background through the polymer synthesis course given in chemistry. It also focuses some attention on the area of polymer characterization in order to provide an appreciation of the importance of molecular weight and molecular weight distribution effects. While undergraduate students often do not take all of the polymer courses mentioned above, many often graduate with at least two of them.

### Graduate Level

With respect to courses focusing on rheology, prior to the students taking the advanced rheology course they take non-Newtonian fluid mechanics, which prepares them for advanced polymer processing topics such as the modeling of film blowing processes, blow molding and injection molding. The latter advanced course is offered for students interested in molecular theories of rheology. Three additional courses emphasizing the structure/property behavior of polymeric solids are taught. The first, called Polymer Structure and Morphology, focuses on the area of rubbery elasticity behavior as well as the crystallization of polymers. The second course, Rheo-optics of Polymers, discusses the use of electromagnetic techniques for the purpose of characterizing polymeric materials. Examples of such techniques are light scattering, X-ray diffraction, birefringence and linear dichroism. The third course, Technology of Elastomers, is jointly taught by Professor Wilkes of Chemical Engineering and James McGrath of the Department of Chemistry. This course brings together both the chemistry of elastomers and some of their performance characteristics, but carries a stronger industrial flavor than most of the other polymer courses.

#### TABLE 1

**Polymer Science and Engineering Courses at Virginia Tech**

<table>
<thead>
<tr>
<th>DEPT.</th>
<th>INTRODUCTORY COURSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>ChE</td>
<td>Introduction to Polymer Materials</td>
</tr>
<tr>
<td>ChE</td>
<td>Introduction to Polymer Processing</td>
</tr>
<tr>
<td>ChE</td>
<td>Organic Chemistry of High Polymers</td>
</tr>
<tr>
<td>Chem</td>
<td>Polymer and Surface Chemistry</td>
</tr>
<tr>
<td>MatE</td>
<td>Applications of Polymeric Materials</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ADVANCED COURSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>ChE</td>
</tr>
<tr>
<td>ChE</td>
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<tr>
<td>ChE</td>
</tr>
<tr>
<td>ChE</td>
</tr>
<tr>
<td>ChE</td>
</tr>
<tr>
<td>Chem</td>
</tr>
<tr>
<td>Chem</td>
</tr>
<tr>
<td>ChE/ESM</td>
</tr>
</tbody>
</table>

| ESM              | Viscoelasticity |
| MatE             | Modern Composite Materials |
| MatE             | Surface and Microphase Analysis |
| MatE             | Adhesion and Bonding |
| ME               | Lubrication |
| ME               | Friction and Wear |

**SOURCES OF RESEARCH SUPPORT**

Support for our research comes from both industry and governmental agencies. Most support is for specific research projects. However, contributions of unrestricted funds are also made through PMIL (The Polymer Materials and Interfaces Laboratory) and represents many companies. This diversified funding illustrates our ability to carry out research at both the very fundamental level and the applied level in the field of polymer science. This has important ramifications as far as our students are concerned since it demonstrates that both types of research are

Continued on page 180.
A TEN WEEK SURVEY COURSE in catalysis was designed to meet the needs of both chemistry and chemical engineering graduate students in Michigan Tech's Department of Chemistry and Chemical Engineering. The aim of the course is to show how modern chemistry and chemical engineering interact in the ongoing development of industrial catalysts. As the course developed, it attracted the attention of graduate students in metallurgy who were grappling with chemical phenomena in their research in physical and extractive metallurgy.

The course outline is given in Table 1. The appearance of Gates, Katzer, and Schuit's Chemistry of Catalytic Processes, McGraw-Hill, New York (1979) provided an organizational framework. This text is incisive, mercifully slender, and contains challenging homework problems at the end of each chapter. To maintain the pace shown in Table 1, a series of sixty-five transparencies showing chemical structures and reaction mechanisms were prepared for use with an overhead projector. At the beginning of the course each student is given photocopies of all sixty-five transparencies. Constant reference is made to a wall-hung periodic table, and to a well-known organic chemistry text (Morrison and Boyd) which most students own.

At the beginning of the course the students are asked to read two articles [1] which contrast industrial processes with textbook organic chemistry and the Langmuir-Hinshelwood formalism is given for the benefit of students who have not taken the undergraduate chemical engineering kinetics course. Modern surface analysis techniques are described in a series of notes. The discussion of thermal cracking is extended to cover computer modeling of ethylene manufacture [2] and recent research on high-severity pyrolysis [3]. The catalytic effect of the tube wall is demonstrated [4]. A set of notes entitled "Physical properties of coal-derived liquids as affecting their chemical processing" summarizes the work of Ubbelohde on melts of polynuclear aromatics and of Marsh on formation of semi-cokes from aromatic liquids. A seminal paper by Virk [5] provides a framework for understanding chemical processing of aromatic liquids.

Acid-catalyzed cracking of hydrocarbons is covered next, and the textbook treatment is supplemented by a study of the Socony-Mobil methanol-to-gasoline process over shape-selective zeolites. This provides an opportunity for examination of various processes for obtaining liquid fuels from coal. The advantages of the coal - synthesis gas - methanol - gasoline route are emphasized.

An historical approach is taken to solid-catalyzed reactions, with the search for the "active site" being the main theme. For the benefit of metallurgy students the enhanced reactivity at emergent dislocations is discussed on the basis of an excellent review article [6]. Three lectures are

J. M. Skaates received his B.Sc. (1957) at Case Institute of Technology and M.S. (1958) and Ph.D. (1961) at Ohio State University in chemical engineering. He worked at California Research Corporation for three years before joining the faculty of Michigan Tech. His teaching duties have included undergraduate and graduate courses in thermodynamics and kinetics, an undergraduate course in process control, and graduate courses in catalysis and in process optimization. He has been involved in research in catalysis, biomass pyrolysis, and wet oxidation.
devoted to the work of Somorjai on clean metal surfaces, with special attention to his parallel studies on iridium, platinum, and gold [7], and the linking of the unique catalytic activity of platinum to the high density of states at the Fermi level. Surface reconstruction on platinum-rhodium screens during the oxidation of ammonia is used to illustrate that interaction of surface metal atoms with adsorbates profoundly affects the metal-metal bonds. The geometric and electronic theories of catalysis by metals are represented as reflecting primitive ideas of metal surface morphology and bonding in metals.

The synthesis and catalytic properties of metal cluster compounds is presented as a third approach (after transition metal ions in solution and clean metal surfaces) for studying bonding of metal atoms. Bonding of ligands to the metal clusters is compared with chemisorption of gases on bulk metal surfaces.

The ninth week is devoted to a discussion of proposed mechanisms for five important industrial reactions (Table 1). It is emphasized that mechanisms are never finally “proven,” but are working hypotheses reflecting present knowledge. As an illustration, the electronic theory of catalysis, as applied to semiconducting metal oxides, fails to explain the baffling Schwab-Parravano discrepancy.

Oxidation of hydrocarbons by oxygen supplied from an inorganic oxide lattice illustrates that a novel idea, tested with simple apparatus [8], can have a big economic payoff. On the other hand, millions of dollars of research failed to uncover a

<table>
<thead>
<tr>
<th>WEEK</th>
<th>TOPICS COVERED</th>
<th>7. Supported metal catalysts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Theory of active sites</td>
<td>Supported metal catalysts</td>
</tr>
<tr>
<td></td>
<td>Langmuir-Hinshelwood mechanisms and rate equations</td>
<td>Experimental techniques for characterizing supported metal catalysts</td>
</tr>
<tr>
<td></td>
<td>Survey of modern surface analysis techniques.</td>
<td>Reforming of hydrocarbons</td>
</tr>
<tr>
<td>2.</td>
<td>Thermal cracking of hydrocarbons:</td>
<td>Octane and cetane numbers</td>
</tr>
<tr>
<td></td>
<td>Free-radical mechanisms</td>
<td>Modeling catalytic reforming reactors</td>
</tr>
<tr>
<td></td>
<td>Cracking of aromatics</td>
<td>Properties of small metal crystallites</td>
</tr>
<tr>
<td></td>
<td>Recent trends in thermal cracking</td>
<td>Interaction between metal crystallites and the support</td>
</tr>
<tr>
<td>3.</td>
<td>Acid-catalyzed cracking of hydrocarbons:</td>
<td>Metal cluster compounds</td>
</tr>
<tr>
<td></td>
<td>Carbonium ion formation on solid surfaces</td>
<td>Metal-metal bonding</td>
</tr>
<tr>
<td></td>
<td>Carbonium ion mechanisms</td>
<td>Bonding of carbonyl groups</td>
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<tr>
<td></td>
<td>Silica-alumina catalysts</td>
<td>Bonding of hydrogen</td>
</tr>
<tr>
<td></td>
<td>Zeolite catalysts</td>
<td>Ammonia synthesis mechanism</td>
</tr>
<tr>
<td></td>
<td>Socony-Mobil methanol-to-gasoline process</td>
<td>Hydrocarbon synthesis by CO reduction</td>
</tr>
<tr>
<td>4.</td>
<td>Chemistry of transition metal ions</td>
<td>Proposed mechanisms for Fischer-Tropsch Synthesis</td>
</tr>
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<td></td>
<td>Zeiss’ salt</td>
<td>Proposed mechanisms for the methanation reaction</td>
</tr>
<tr>
<td></td>
<td>Wacker Process for acetaldehyde from ethylene</td>
<td>Design of methanation reactors</td>
</tr>
<tr>
<td></td>
<td>Oxo Process</td>
<td>Mechanisms involving electron transfer between adsorbate and metal oxides</td>
</tr>
<tr>
<td></td>
<td>Designing liquid-phase homogeneous catalyst reactors.</td>
<td>Catalysis on semiconductors</td>
</tr>
<tr>
<td>5.</td>
<td>Types of defects on solid surfaces</td>
<td>Electronic Theory of Catalysis as applied to semiconducting metal oxides</td>
</tr>
<tr>
<td></td>
<td>Emergent dislocations as active sites</td>
<td>Oxygen transfer from the solid oxide lattice</td>
</tr>
<tr>
<td></td>
<td>Surface morphology</td>
<td>Synthesis of acrolein and acrylonitrile from propylene</td>
</tr>
<tr>
<td></td>
<td>H-H, C-H, and C-C bond breaking on steps and kinks of metal surfaces</td>
<td>Complex oxide catalysts</td>
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<td>Surface reconstruction during catalytic reactions</td>
<td>Perovskite structures</td>
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<tr>
<td></td>
<td>Geometric theory of catalysis on metals</td>
<td>Scheelite structures</td>
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<tr>
<td>6.</td>
<td>Electronic theory of catalysis on metals</td>
<td>Automobile exhaust converter catalysts</td>
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<td>Surface compound theory of catalysis on metals</td>
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<td>Metal alloy catalysts</td>
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satisfactory metal oxide replacement for platinum in the oxidation of unburned hydrocarbons in automobile exhaust.

Student evaluation of this course has been favorable, and their comments indicate that the excitement of catalyst research is “catching.” The limitations of current chemical theories are evident in trying to understand many catalysts. Playing a “hunch,” or serendipity, often lead to valuable catalysts and also to new chemistry for the theorist to interpret.

REFERENCES


POLYMER RESEARCH

Continued from page 177.

compatible. In summary, our objective is to provide the student with an understanding of molecular and continuum approaches and an understanding of the behavior of polymeric systems. We try to emphasize the need of understanding both the chemistry of these macromolecular systems and their engineering properties.

All students receive a similar background in coursework. Along with the courses mentioned above, 11 other polymer courses (including such topics as polymer synthesis, physical chemistry of polymers and surface analysis) are available in the four other departments participating in the interdisciplinary group. Because of the large number of graduate students now in our program, even the advanced courses are offered on a routine basis.

As a final note concerning educational aspects extending from chemical engineering in the polymer science area, we might point out that there are several industrially oriented polymer short courses offered at Virginia Tech each year. These courses are taught jointly through the polymer oriented chemical engineering faculty as well as other faculty members of the PMIL group. In short, we now offer the most extensive continuing education program in polymer science through a short course format than any other university in the nation.

SUMMARY

In this article we have attempted to outline the new growth in the polymer area at Virginia Tech, with emphasis being placed on the role of the Department of Chemical Engineering. The overall polymer science effort, as indicated, extends beyond a single department, encompassing five departments across two colleges. The growth of this program has been enormous in the last three years as a result of cooperative efforts of a truly interdisciplinary nature. The overall program, part of which is focused in chemical engineering, has become a highlight of the Virginia Tech campus and one which we anticipate will become even stronger in the future. It has achieved considerable outside funding and has developed modern research facilities necessary for graduate research. Inquiries concerning information about Chemical Engineering and the Polymer Materials and Interfaces Laboratory can be directed to either of the authors of this article.
What to look for in choosing your first job.

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THE EDUCATION PROJECTS Committee of the American Institute of Chemical Engineers has carried out surveys of the undergraduate curricula in chemical engineering since 1957 [1, 2, 3, 4, 5]. The survey reported in this paper was carried out during 1981. The form, which was similar to that used in the past surveys, was sent out in the middle of June and requested its return by the first of September 1981. The questionnaire was to be based on the curricula as of September 1, 1981. The survey was sent out to all 149 schools listed in the 1980-81 Chemical Engineering Faculties [6].

Useable replies were received from 105 schools; the best response that has been given to the survey. The results of the survey were coded on IBM punch cards and analyzed using standard statistical procedures. The results of this survey are presented in the accompanying tables. For purposes of comparison, the same format has been used as in previous surveys. In this way, a comparison can be made of the changes taking place in the curriculum since 1957.

Table 1 presents the consolidated information under the categories shown in previous reports and is divided into three parts. The first set of columns shows the average number of semester hours, including all 105 schools. The second section shows the percentage of schools offering the particular category and the third section shows the average semester hours considering only those schools offering the particular category.

In the area of unit operations theory, transport theory has made an increase as well as transport labs. Unit operation theory has decreased somewhat to accommodate the transport theory increase.

The changes in the curricula, since 1957, in four categories are shown in Figs. 1 through 4. Figure 1 shows the total semester hours offered and indicates a slight increase in the net number of credit hours since 1957. However the change is

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TABLE 1


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<td>Total Items</td>
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**Mechanical Engineering Courses**

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<td>63</td>
<td>67</td>
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**Chemical Engineering Courses**

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<td>Total Items</td>
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<td>58</td>
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<td>63</td>
<td>67</td>
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**Civil Engineering Courses**

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<td>Total Items</td>
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<td>58</td>
<td>59</td>
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<td>63</td>
<td>67</td>
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**Electrical Engineering Courses**

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<tr>
<td>Total Items</td>
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<td>58</td>
<td>59</td>
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<td>63</td>
<td>67</td>
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**Computer Science Courses**

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<tr>
<td>Total Items</td>
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<td>58</td>
<td>59</td>
<td>60</td>
<td>63</td>
<td>67</td>
</tr>
</tbody>
</table>
small and probably not significant.

Figure 2 represents the changes in Humanities and Social Sciences and shows an increase of 2.6%.

Figure 3 indicates that there has been little change in the Chemistry offerings of the various departments since the last survey was undertaken. The figure represents both advanced chemistry and introduction chemistry.

In reference 5 (reporting the survey in 1976), concern was expressed for the decrease in communications offered by the various schools. This has improved greatly since 1976; today 89% of the schools present some material. The survey also indicates that communications was being covered in seminars and in lab courses and was not recorded explicitly with a given number of classes.

The earlier surveys (prior to 1976) did not include an analysis of the actual course offerings

<table>
<thead>
<tr>
<th>TABLE 2</th>
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</thead>
<tbody>
<tr>
<td><strong>B. ChE. Curriculum; Sub-Categories</strong></td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td><strong>MATH</strong></td>
</tr>
<tr>
<td>Analytical Geometry</td>
</tr>
<tr>
<td>Calculus</td>
</tr>
<tr>
<td>Differential Equation</td>
</tr>
<tr>
<td>Linear Algebra</td>
</tr>
<tr>
<td>Advanced Calculus</td>
</tr>
<tr>
<td>Complex Variables</td>
</tr>
<tr>
<td>Partial Differential Equations</td>
</tr>
<tr>
<td>Numerical Analysis</td>
</tr>
<tr>
<td>Digital Computing &amp; Programming</td>
</tr>
<tr>
<td>Analog Computations</td>
</tr>
<tr>
<td>Applied Engineering Math</td>
</tr>
<tr>
<td><strong>MECHANICS</strong></td>
</tr>
<tr>
<td>Statics</td>
</tr>
<tr>
<td>Dynamics</td>
</tr>
<tr>
<td><strong>KINETICS</strong></td>
</tr>
<tr>
<td>Chemical Kinetics</td>
</tr>
<tr>
<td>Chemical Reactor Design</td>
</tr>
<tr>
<td><strong>UNIT OPERATIONS THEORY</strong></td>
</tr>
<tr>
<td>Transport Theory</td>
</tr>
<tr>
<td>Transport Lab</td>
</tr>
<tr>
<td>Equilibrium Stage</td>
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<tr>
<td>U.O. Theory</td>
</tr>
<tr>
<td><strong>DESIGN</strong></td>
</tr>
<tr>
<td>ChE Design</td>
</tr>
<tr>
<td>Process Synthesis</td>
</tr>
<tr>
<td><strong>INSTRUMENTATION</strong></td>
</tr>
<tr>
<td>Instrumentation</td>
</tr>
<tr>
<td>Process Control</td>
</tr>
<tr>
<td>Process Dynamics</td>
</tr>
<tr>
<td><strong>OTHER</strong></td>
</tr>
<tr>
<td>Mathematical Modeling</td>
</tr>
<tr>
<td>Computer Applications in Chemical Engineering</td>
</tr>
<tr>
<td>Biomedical Engineering</td>
</tr>
<tr>
<td>Polymer Processing</td>
</tr>
<tr>
<td>Nuclear Engineering</td>
</tr>
<tr>
<td>Environmental Engineering</td>
</tr>
<tr>
<td>Other ChE required</td>
</tr>
<tr>
<td>Chemical Engineering Electives</td>
</tr>
</tbody>
</table>
under math, mechanics, kinetics, etc. This survey (and the 1976 survey) asked for information relative to the different kinds of math, etc. Table 2 presents the results of this section of the questionnaire, both for 1976 and for 1981. Introductory math is not included since none of the schools responding indicated that they were teaching introduction or review math.

In the area of unit operations theory, transport theory has made an increase as well as transport labs. Unit operation theory has decreased somewhat to accommodate the transport theory increase. In addition, a larger number of schools are offering courses in instrumentation process control and process dynamics, which previously had been listed only as instrumentation.

The distribution of course work as compared with the AIChE minimum was also calculated. This information is presented in Table 3. As can be seen, the basic science and advanced chemistry are somewhat low. Part of this could be due to the way these categories were analyzed from the survey forms since some schools counted chemistry from the chemical engineering courses. Normally it is expected that all chemistry courses will be taught in the Chemistry Department and will be the same as taught in Chemistry. The distribution of course work was determined by taking selected items from the survey forms and using them to fit into the various categories. Some problem probably arose because of this arbitrary division. For instance, there may be some chemistry in the thermodynamics courses which is not included in the chemistry shown here.

The categories of engineering design and engineering science have been lumped together in Table 3 since there was no way to determine from the survey forms which portion of the material is engineering science and engineering design. One of the problems facing educational accreditation is that of design in chemical engineering education. One of the problems facing educational accreditation is that of design in chemical engineering education.

<table>
<thead>
<tr>
<th>Curricular Area</th>
<th>AIChE Minimum (%)</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mathematics beyond Trigonometry</td>
<td>12.5</td>
<td>13.6</td>
</tr>
<tr>
<td>Basic Sciences (Show Advanced Chemistry)</td>
<td>25.0</td>
<td>24.3</td>
</tr>
<tr>
<td>Engineering Sciences</td>
<td>25.0</td>
<td>37.5</td>
</tr>
<tr>
<td>Engineering Design, Synthesis,</td>
<td>12.5</td>
<td>37.3</td>
</tr>
<tr>
<td>and Systems</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humanities/Social Sciences</td>
<td>12.5</td>
<td>16.1</td>
</tr>
<tr>
<td>Other Required Technical Courses</td>
<td></td>
<td>8.7</td>
</tr>
<tr>
<td>Other Required Courses (Non Technical)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Free Electives</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total of “Other”</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>TOTAL: Percent</td>
<td>100.00</td>
<td>100.0</td>
</tr>
<tr>
<td>TOTAL CREDIT HOURS:</td>
<td>133.4</td>
<td></td>
</tr>
</tbody>
</table>

that they had vacancies, for a total of 115 vacancies. The results of this part of the survey will be published in Chemical Engineering Progress.

In summary it appears that only minor changes have been made in the chemical engineering curricula since the last survey was undertaken. Another survey is planned in approximately four to five years. Any specific questions concerning books used and other material can be addressed to the author at Brigham Young University.

REFERENCES

The object of this column is to enhance our readers’ collection of interesting and novel problems in Chemical Engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class or in a new light or that can be assigned as a novel home problem are requested as well as those that are more traditional in nature that elucidate difficult concepts. Please submit them to Professor H. Scot Fogler, ChE Department, University of Michigan, Ann Arbor, MI 48109.

**MINE-MOUTH GEYSER PROBLEM**

NOEL DE NEVERS  
University of Utah  
Salt Lake City, UT 84102

**PROBLEM**

On November 20, 1980, an oil well drilling rig, operating in the shallow waters of Lake Peigneur, Louisiana, accidentally drilled into an underground salt mine. The hole increased rapidly in size and drained the lake, flooding the mine. Miraculously, no fatalities or serious injuries occurred, although the property damage was very large. The incident is recounted by Michael Gold in, “Who Pulled the Plug on Lake Peigneur?”, *Science* 81 2(9) (November 1981), 56-63. Figure 1 shows a sketch, roughly to scale, of the mine, lake, and drilling rig.

From the text of the article, it is clear that there were two vertical shafts from the surface to horizontal galleries: a main shaft, and a smaller ventilation shaft. Which levels of the mine were open on all levels. In addition to the two vertical shafts, one or more inclined roadways connected the various underground galleries with each other, but not with the surface. The mine itself did not consist of simple cylindrical tunnels, as the sketch might suggest, but of a series of rooms, up to 100 feet square, with roofs up to 80 feet high, connected by galleries large enough for several trucks to drive through side-by-side.

In one part of the article, the flow out of the ventilation shaft is described as follows:

For some time, a powerful jet of air had been coming from the mine’s ventilation shaft, . . . Forced out by the incoming floodwaters below, the blast had kept the emergency elevator dancing around the top of the shaft like a paper kite in a stiff wind. Suddenly the rushing air halted, and a thick stream of water rocketed out of the shaft. The geyser climbed 400 feet into the sky, surged for 10 minutes, coughed up mud, and died. (Reproduced by permission of Addison Wesley.)

The fact that the water flowing from the lake into the mine would expel the air in the mine is perfectly obvious. But, as we all know, “water seeks its own level.” This report indicates that water which flowed from the lake eventually came out of the top of the ventilation shaft (a few feet above lake level) and jetted 400 feet in the air. That means that it “sought a level” 400 feet above the level it started at. (The article does not mention any such water flow from the main shaft of the mine.)

Can the description of a 400 foot geyser possibly be correct? Were the observers, dazed by the other wild event of the day, mistaken about that? If it is correct, it must be explainable by the laws of fluid mechanics. Present an explanation, in terms of those laws, with suitable diagrams and calculations.
Noel de Nevers earned his BSChE at Stanford and his PhD at the University of Michigan, with a year out in between to be a Fulbright exchange student at the Technical Institute in Karlsruhe, Germany. He spent five years with what is now Chevron Research and Chevron Oil-field Research, before joining the faculty of the University of Utah. He spent Academic 1971-72 on leave, working for the Office of Air Programs of the Environmental Protection Agency. He is the author of a textbook on Fluid Mechanics, and editor of a book of readings and discussion on Technology and Society.

**SOLUTION**

In principle, the overall flow in the system is like that in a U-tube manometer. Inserting liquid into one leg of the U expels the less-dense air in the other leg. If the system had been a simple U-tube, we would expect the air to be expelled and the flow to stop when the liquid levels in both legs of the tube were the same. One may easily demonstrate that in the laboratory. One may also show that an oscillation can be set up, with the levels in the two tubes moving up and down 180 degrees out of phase with one another. The behavior and mathematical analysis of such an oscillating manometer are identical with that of a pendulum; if there were zero friction, they would oscillate forever, just as a frictionless pendulum would oscillate forever.

Such an oscillation represents the exchange of potential and kinetic energies between parts of the system, as does a pendulum. But, just as a pendulum can never swing higher than its initial position, so also this type of “manometer oscillation” can never take any of the fluid higher than the original position of the free surface of the fluid poured into the manometer. So, if only an orderly plugflow displacement of the air in the mine by the water from the lake had taken place, we could not have had such a fountain.

However, if one of the legs of the U-tube is a mixture of air and water, then its average density is much less than that of the water in the other leg, and it will not come to simple gravitational equilibrium at the same level as the other leg. This is the basis on which coffee percolators and gas-lift pumps work. Fig. 2 is a copy of a problem from de Nevers, *Fluid Mechanics*, Addison Wesley, 1970, which shows an analogous situation. One can easily set this up in the laboratory and show that, if one leg of the “equivalent manometer” is full of liquid while the other leg has a gas-liquid mixture, then the equilibrium level due to fluid statics alone will be higher on the gas-liquid side than the liquid side. This problem has bedevilled everyone who has ever tried to make accurate measurements with a small diameter manometer in which it is difficult to purge all the air bubbles.

Returning to the mine geyser, it seems certain that the geyser must have been caused by some of the in-rushing liquid finding a flow path which led it to the ventilation shaft before all of the air was expelled from the mine. In that case, it would temporarily block that shaft, and the pressure of the trapped air in the mine would rise enough to

**FIGURE 2.** Sketch of a fountain arrangement made of two glass jars with rubber stoppers, several lengths of glass tubing, a funnel, and a piece of rubber tubing. The level of the jet and the level of the water in the funnel are exactly the same. The space above the water in each bottle is full of air, as is the rubber tube connecting the two bottles. An inventor has come to us, telling us that with this arrangement the water will squirt high in the air, much higher than the water level in the funnel. Is he right? Explain your answer.
expel it with considerable force.

A hypothetical series of events which could have produced the jet is sketched in Fig. 3 (with only one shaft).

First Stage: The flow into the 1300-foot level reaches the shaft and begins to flow down it, trapping air in the lower, 1500-foot level. With the water flow down the shaft, the air is unable to escape. Water displaces air from the upper levels, causing air to flow out of the shaft.

Second Stage: The continued flow of water down the shaft to the lower level compresses the "bubble" of air remaining trapped in the lower level. Meanwhile, the upper galleries continue to fill, venting air through the shaft. (Fig. 4)

Third Stage: Eventually, the air bubble in the lowest level reaches the pressure at which it is at or near hydrostatic equilibrium with the inflowing water. Thus the water flow down the shaft slows and stops. This downflowing water was the seal which kept the bubble in place; now the bubble can begin to migrate up the shaft. As it does so, water flows in behind it. Once it begins to fill areas above the 1300 foot inflow level, it can again be driven up by the water. But now, the water above it in the system must be expelled to make room for it to escape. This causes that water to be expelled in the "mine-mouth geyser." (Fig. 5)

This simplified picture, with only one shaft, cannot account for the description that the geyser "surged for ten minutes, coughed up mud, and died." If there were only one entrance, the geyser would have had to end with another air jet, as the bubble escaped. But with two shafts, one of which apparently did not show any liquid flow, the air bubble could have used one of the upper galleries to move from ventilation to main shaft, and escape through it, thus ending the geyser without a final air jet. If the actual underground space had been a series of horizontal and vertical cylinders, then the surging might be hard to explain. But the actual space (as reported in the article) was a room-and-pillar mine, consisting of many more-or-less cubical rooms connected by much narrower rectangular vertical, horizontal, and inclined shafts. Thus the surging was most likely to be the result of the irregular flow of the air bubble through these various rooms and passages.

If, as reported, the jet exiting from the air shaft went 400 feet in the air, then it exited with a velocity of roughly

\[ V = \sqrt{2gh} = \sqrt{(2)(32 \text{ ft/sec}^2)(400 \text{ ft})} = 160 \text{ ft/sec} \]  

(1)

If, as shown above, the geyser flowed at 160 ft/sec, and the distance from the topmost gallery to the surface was 800 feet, then the geyser should only have lasted five seconds. However, because of the irregular rooms to be filled and emptied, the actual volume ejected is not implausible. If we assume that the ventilation shaft was ten feet in diameter, had a velocity of 160 feet a second, and flowed steadily for ten minutes, then the total volume of water ejected would have been 56 x 10^6 gallons of water. This is a high estimate, because it assumes a 400 foot high geyser for the full ten minutes; a much lower estimate is more plausible because of the reported surging, perhaps a fourth to a tenth of this number. The total flow of water from lake to mine (equal to the excavated volume of the mine) was 3.5 x 10^9 gallons. Thus this high estimate of the total liquid flow of the geyser is only 1.6% of the estimated total flow.

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of water from the lake to the mine.

If a solid column of water had been flowing up such a ten foot diameter shaft at a velocity of 160 ft/sec, the pressure gradient due to friction above the hydrostatic gradient would have been

\[ \frac{\Delta P}{\Delta x} = \frac{4f}{D} \rho \frac{V^2}{2} \]  

(2)

To determine the fraction factor, we must estimate the relative roughness of the ventilation shaft. Assuming that the individual surface roughnesses are one inch, we can estimate

\[ \frac{\epsilon}{D} = \frac{1 \text{ inch}}{120 \text{ inches}} = 0.0083 \]  

(3)

and hence \( f = 0.009, \)

\[ \frac{\Delta P}{\Delta x} = \frac{(4)(0.009)(62.4 \text{ lbm/ft}^3)(160 \text{ ft/sec})^2}{(10 \text{ ft})(2)(32.2 \text{ lbm/ft/sec})(144 \text{ in}^2)} \]

\[ = 0.62 \text{ psi/ft} \]  

(4)

This pressure gradient is 1.4 times that of a hydrostatic column of water; it is clear that a simple filling of the “U-tube” could never produce pressure gradients of this magnitude within the fluid. However, from the sketch in the problem (taken from the Science 81 article), it appears that the shallowest gallery of the mine was 800 feet below the surface, and the deepest was 1500 feet below the surface. Thus, if there were a column of air 700 feet high from this deepest gallery to the shallowest, and if the bottom were in hydrostatic equilibrium with the lake while the top were facing an 800 foot long column of liquid open to the surface, a pressure gradient of approximately 0.38 psi/ft (above the hydrostatic gradient) would have been exerted on the liquid in the ventilator shaft. Comparing that to the above estimate, I infer that either I have overestimated the relative roughness of the ventilator shaft or that the observers overestimated the height to which the geyser went.

This proposed solution is basically a hydrostatic solution. Before accepting it, we should consider alternative dynamic solutions. There are well-known devices, called hydraulic rams, which allow a liquid falling from level one to level two to pump some liquid to a level higher than level one. An illustrated description is given on page 195 of Brown and Associates’ Unit Operations, Wiley, NY, 1950. Their operation requires quick-acting valving, not likely to be approximated in the mine flooding. However, the idea on which it is based deserves examination. If a column of moving fluid is suddenly stopped, it can generate high pressures. This is the subject of waterhammer analysis. It shows, for example, that if a column of a slightly compressible fluid (e.g., water, but not air) is stopped by closing a valve very quickly, the maximum pressure which will be generated in the region of the valve will be

\[ P = u[K\rho]^{0.5} \]  

(5)

where \( P \) is the pressure, \( u \) is the original velocity before the fluid was stopped, \( K \) is the isothermal compressibility, and \( \rho \) is the density of the fluid. Inserting typical values for water, we find that, for an initial velocity of 10 ft/sec, the calculated pressure is 650 psi. This is high enough to damage equipment and rupture pipes; large hydraulic structures (e.g., hydro power plants) are designed to avoid the creation of this kind of pressure or to withstand it where it is unavoidable. But this kind of pressure can only be exerted on an unyielding structure. It cannot propel a jet of fluid for any significant time or distance. If a mass of liquid is compressed to 650 psi and then allowed to do work by expanding (\( W = \int F \, dx = \int P \, dV \)) then the compressed liquid will return to its original volume and pressure if it expands 0.2%. Thus the amount of work of accelerating some of the fluid up the ventilator shaft could not easily have been obtained by allowing some other fast-moving body of liquid to be stopped suddenly and using the high pressure thus generated to drive a fountain. It certainly could not drive one for ten minutes.

From the article in Science 81, it is clear that

Continued on page 203.
What follows is an imaginary dialogue that embodies the elements of many real conversations I have had with students. The two participants are SI SORP (Student In Search Of a Research Project) and PI NORA (Professor In Need Of a Research Assistant).

SI: I hear you might have an opening in your group for a student ready to do thesis research in chemical engineering.
PI: Right. Would you be interested?
SI: It depends. I've heard that you work with molecular beams but I really don't know what they are or what they're good for.
PI: Well, you might say that what we do is like playing billiards. We shoot individual molecules at surfaces or other molecules in a vacuum and see how they bounce.
SI: I don't understand. It doesn't sound like chemical engineering to me.
PI: Let me explain. Do you know anything about cyclotrons and other kinds of accelerators that physicists use, sometimes called atom smashers in the popular press?
SI: I've heard about them and read some articles in magazines and newspapers.
PI: Have you ever seen pictures of particle tracks in an emulsion, or a cloud chamber or a bubble chamber?
SI: Yes, but I haven't thought that much about what they mean.
PI: Look at it this way. Suppose you put a billiard ball on a table and hit it with the cue ball. What would happen?
SI: The billiard ball would go in one direction and the cue ball in another. The particular directions and speeds would depend upon how hard and how head-on the collision was.
PI: Right. Now suppose you replaced the billiard ball with an egg.

SI: I see what you mean.
PI: Well, the same thing would happen, except that the egg's trajectory might be different because it isn't spherically symmetric like a billiard ball. If the cue ball were going fast enough the egg would break and splatter. Also, the cue ball wouldn't change direction quite as much.
PI: Suppose the egg were hard boiled.
SI: Then about the same thing would happen, except that the cue ball would have to be going faster to break the egg. And the result wouldn't be as messy.
PI: In other words, you could tell the difference between a billiard ball, a fresh egg, and a hard boiled egg by observing the trajectories of the cue ball and its target before and after collision. Indeed, you could learn something about their structure and behavior.
SI: I see what you mean.
PI: Well, that's what so-called scattering or collision experiments are all about. The tracks in photographic emulsions and cloud or bubble chambers that you've seen pictures of are trajectory traces, usually of one of the collision partners and the fragments after collision. Es-
sententially, all our knowledge of nuclear structure and reactions has come from the study of such particle tracks.

SI: Very interesting... but I don't want to be a nuclear physicist.

PI: Wait a minute. Nobody said anything about your becoming a nuclear scientist or engineer. Using an egg as an example of a target didn't mean that I thought you might want to raise chickens or make omelets! I was just pointing out that what happens when objects collide can give information on their structure and properties.

SI: OK, but I still don't see any connection with chemical engineering.

PI: Let's look further. What are chemical engineers concerned with?

SI: Let me see. Well... you know, making plastics, fertilizers and pharmaceuticals, refining petroleum, processing foodstuffs... things like that.

PI: Quite a variety, right? Now what do most or all of these activities have in common?

SI: I guess you could say they all involve some sort of chemical reaction. Then, too, there is usually heating and cooling and mixing and distillation and... fluid flow... and...

PI: Good. You've just been reciting what chemical engineers once considered the basic building blocks of their discipline, the so-called unit operations. Actually, that term usually referred to physical phenomena like vaporization, crystallization, fluid flow, heat transfer, adsorption and so forth. Chemical reactions were similarly classified in such categories as oxidation, reduction, alkylation, polymerization, hydrolysis, and the like, that were known as unit processes. But we can pursue this reduction to fundamentals even further. If you stop to think, you will realize that all of these unit operations and processes are based on the transport of mass, momentum and energy and the transformation of composition by chemical reaction.

SI: I see what you're driving at. The next thing you will tell me is that all of these transport and reaction processes depend upon what happens when molecules encounter each other.

PI: Exactly. You can go to the head of the class. When we scatter a beam of molecules by another beam or a static cloud of molecules, and watch how they bounce, that is to say, what happens to their trajectories, we obtain information on their structure and the nature of the forces between them. The difference between what we do and what atom-smashing physicists do is largely a matter of energy. Physicists are concerned with forces that hold the nucleus together and that relate to energies of billions of electron volts. Chemists are concerned with extranuclear phenomena involving forces which bind electrons to the nucleus and hold molecules together. Chemical energies are always less than a few tens of electron volts. Incidentally, an electron volt per particle (atom or molecule) is equivalent to about 23 kcal/mol. Thus, we don't need and cannot use the billion volt beam energies that the nuclear physicists require and that make their accelerators so big and expensive. By the same token, we cannot see individual collision events as they can. A particle travelling with energies in the millions or billions of electron volts can go through a photographic emulsion or a bubble chamber as if it weren't there. The energy required to make its track is a negligible fraction of the total. On the other hand, an atom or molecule with only a few electron volts of energy won't even make a dent in an emulsion, let alone a track through it. Consequently, molecular beam scattering experiments of the kind we do depend upon bringing about as many collisions as possible that are as nearly identical as possible. Each collision contributes a little bit to the observed signal, usually an electric current obtained by converting the beam molecules into ions.

SI: All right. I can see how such experiments might tell us about the structure of atoms and molecules, but we already have that information about practically all species the chemical engineers are concerned with.

PI: That's quite true, but there is another difference between atom smashing and molecular beam scattering experiments. Consider reactive scattering events that change the composition or structure of at least one collision partner and are the primary interest of nuclear physicists. The energy which seems to count in bringing about nuclear reactions is translational kinetic energy. At least that is the only kind of energy that physicists have a handle on. Chemists, on the other hand, have long recognized that molecules can have several kinds of energy: translational, vibrational, and rotational energy, as well as electronic excitation energy. Most classical gas phase reactions experiments measure composition change with time in a container of reactants at a uniform temperature that can be varied from experiment to experiment. Unfortunately, rotational,
vibrational, and translational energies all change with temperature. Consequently, it is generally impossible to isolate the effects of these different forms of energy on the rate or mechanism of the reaction. Indeed, a molecular beam experiment 20 years ago was one of the first bits of tangible evidence that translational energy was not a very important component of activation energy in some reactions. Since then, of course, hindsight and laser experiments have everybody convinced that vibrational energy is much more important in many, if not most, reactions involving reactants with more than one atom.

**SI:** Are you saying that excited state intermediates are not important in nuclear reactions?

**PI:** I guess that's what I am implying, but I should retreat a bit because I am not expert in nuclear affairs. It does seem that physicists can't control internal (nuclear) energy states of colliding partners as readily as chemists can control vibrational and electronic excitation. Consequently, the role of excited internal states in nuclear reactions is not as clear as it is becoming in chemical reactions. But there is still another difference in kind between atom smashing and molecular beam scattering experiments.

**SI:** What is that?

**PI:** We have been talking so far about reactive scattering. There are two other kinds of collisions that are more important to chemists and chemical engineers than to nuclear physicists. **Elastic** collisions are those in which both momentum and translational kinetic energy are conserved but there is no change in the structure or internal energy state of either collision partner. Then there are **inelastic** collisions in which there is no change in structure but there is a change in the vibrational, rotational or electronic energy of one or both partners. The trajectories of the participants in these kinds of collisions generally respond less to intra- than to inter-molecular forces that are generally repulsive when molecules are close together, attractive when they are further apart. It is convenient to characterize these forces in terms of the work required to pull the molecules apart to an infinite separation, i.e., where the forces are zero. A plot of this work as a function of intermolecular separation is called an inter-molecular potential because the work required for separation is equivalent to a potential energy.

**SI:** Oh, I'm beginning to remember. Didn't we discuss something in our transport course called a Lennard-Jones potential which governs the interaction between two molecules?

**PI:** That's right. The Lennard-Jones or 12-6 potential model assumes the actual potential is a simple sum of repulsive and attractive potential energies that are inversely proportional respectively to the 12th and 6th powers of the distance between the molecules. The difference between these two powers leads to net repulsion when the molecules are close together and net attraction when they are far apart. Real potentials are more complicated and cannot be accurately described in terms of only two parameters. For many engineering approximations, a Lennard-Jones model is sufficiently accurate to be useful. Which leads me to a question. Why did the subject of potentials come up in your transport class?

**SI:** We were learning about the dependence of viscosity, thermal conductivity and diffusion in gases upon the forces between molecules! In fact, don't I remember that it is possible to determine the parameters of a potential from measured values of the transport properties and the equation of state?

**PI:** Correct. But there is a problem. These macroscopic properties represent the integrated or average result of collisions taking place over a wide range of energies, orientations and impact parameters (a measure of the head-on-ness of a collision). For any particular property and set of conditions, there are many combinations of potential parameters that will match a computation with a given experiment. Consequently, it is hard to choose the best one. Moreover, one cannot be sure that a particular potential which matches computation and experiment over a particular range of conditions will give reliable results outside of that range. In addition, it frequently turns out that a potential that works for one transport property, e.g., thermal conductivity, gives unreal results when used to calculate another transport property, e.g., diffusion coefficients.

**SI:** So what's different about potentials obtained from scattering experiments?

**PI:** Such experiments probe the intermolecular potential much more directly and with greater sensitivity than macroscopic property measurements. The net result is that potentials based on scattering experiments are more accurate, particularly at separation distances where attractive forces are important. Note that if one does the arithmetic correctly a calculation based on a particular potential can lead to only one possible value of a transport property for a particular
temperature and pressure. The converse is not true. There are many possible potential parameter combinations which can lead to a given value of transport property.

SI: I'll take your word for that but it sounds more like science than engineering. Why should engineers do molecular beam scattering experiments?

PI: To answer that question I guess I need to know what you think engineers should do.

SI: I believe engineers should be concerned with practical problems. At least they should try to solve problems in a practical and efficient way. More than that, I guess I believe that they should work on problems that have some commercial impact or significance. If an engineer needs to know the viscosity and thermal conductivity of a gas to design a heat exchanger he can look them up in a handbook or measure them directly. All this business about molecular beams, scattering experiments and intermolecular potentials sounds like pretty esoteric science to me. Maybe it's all right for chemists, but chemical engineers? . . . . I dunno.

PI: I understand your reaction. You say engineers should be practical and efficient. If you need the value for a property like viscosity, "you could look it up" as Casey Stengel used to say. If a value isn't available then you could measure just what you need, but you wouldn't bother measuring what you don't see an immediate need for.

SI: Right on.

PI: Let's look at the heat exchanger problem a little further. Suppose an engineer is trying to design one as a preheater for a cracker but that the client isn't exactly sure what feedstock he will be using. Depending on the time of year and the market it may vary from a mixture of ethane and propane to a melange of several alkanes. In fact, suppose the client's specification calls for a design which can accommodate any arbitrary mixture of 30 hydrocarbons from C\textsubscript{1} to C\textsubscript{8}. To simplify the problem for our purpose let's suppose that the mixtures would be binary. There are 450 possible combinations if we include like pairs, i.e., the case of a single species feedstock. Now let's assume that temperatures range from 300 K to 700 K and that the concentration of one component in the other can be anywhere from 0 to 100 per cent. If we further assume that it would take measurements at 10 concentrations to cover any unlike pair and at 10 temperatures to cover the range we're talking about, something like 42,000 data points would be needed to map the entire temperature composition surface for any one property. If it took an average of only one hour for each point, two solid years would be required for the measurements. Of course, by judicious choices and by taking advantage of behavior similarities one could cut down substantially on the actual number of measurements required, but to obtain enough data would still be a formidable undertaking.

SI: I agree, but how would scattering measurements be any better?

PI: As you might guess my choice of problem here was not entirely whimsical. A few years ago a student in my lab determined total cross-sections for the scattering of an argon beam by those 30 hydrocarbons. From these cross-sections she was able to obtain the so-called C\textsubscript{6} values, the coefficients of the r\textsuperscript{-6} attractive term in the Lennard-Jones potential. She found that the coefficient of the r\textsuperscript{-12} repulsive term could be estimated from condensed phase densities, values for which are available. Then she made enough scattering cross-section measurements of one hydrocarbon on another to satisfy herself (and me) that the so-called geometric mean mixing rule was effective enough to give reliable C\textsubscript{6} values for any hydrocarbon pair from the argon-hydrocarbon result. We haven't checked it out yet but we are reasonably confident that similar estimates can be made for the C\textsubscript{12} coefficients of the r\textsuperscript{-12} term. In sum, from 30 measurements which took about two weeks after the machine was set up, we were able to get 450 C\textsubscript{6} values. Let's allow another six weeks to get estimates for C\textsubscript{12} and to do a little cross-checking. We would then have a Lennard-Jones potential for all possible hydrocarbon pairs. A computer could be programmed to handle this information and presto!—we can in principle get a printout of all transport properties at any temperature for any binary or multicomponent mixture of these hydrocarbons. I submit that this "esoteric science" is engineering at its best—practical and efficient!

SI: I'm impressed! But still, somehow that kind of research seems more like science than engineering. I'm not quite comfortable with the prospect of a thesis on molecular beams.

PI: OK. We'll come back to that problem in a minute. But first let me make another point about molecular beam research. Did you know that there are a number of articles and processes of commerce based on molecular beam technology?

SI: Is that a fact? Tell me more.
To begin with there is the atomic clock. Until 1967 the standard unit of time, the second, was defined as \((31,556,925.9747)\) - 1 of the tropical year 1900! Since then it has been officially defined as the “duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the fundamental state of the atom of cesium 133.” The device that provides a signal of the corresponding frequency to an accuracy of one part in \(10^{11}\) or \(10^{12}\) is a molecular beam apparatus that one can buy off the shelf. Thus any laboratory can have a primary time standard for not a whole lot more than a very fine Swiss watch! Much less than an astronomical telescope and computer. Then there are lasers, the direct descendants of the maser that was first embodied in a molecular beam experiment.

One of the hottest high technologies in thin film-solid state electronics is called “molecular beam epitaxy” which permits the growth of single-crystal-like films of very precisely controlled semiconductor compositions on appropriate substrates. The method allows in situ synthesis of complex compounds in layers whose thickness is measured in Angstroms. At last count there were fifty or more companies and institutional laboratories developing this art and five companies engaged in manufacturing the equipment for it.

Golly! Molecular beams are getting to be big business, aren’t they?

Yes, but that is neither the only nor the best reason for chemical engineering students to engage in molecular beam research. Let’s go back to what you said a few minutes ago, that molecular beam research was more like science than engineering. You’ve mentioned some of the things engineers do. Let me hear how you define “engineering.” What do you think are its essential features?

I guess I would say that engineering is the design, construction and operation of structures, plants and processes that produce useful goods or perform useful services.

Not bad. But what do you mean by “useful?”

Hmm. I guess to be considered useful in the sense I am thinking about something would have to have commercial or market value. Of course, an activity can be useful because it is informative or constitutes an exercise for somebody’s talents, but I think it would have to result in actual or forseeable market value to qualify as engineering. If the result were only interesting but non-marketable then I guess I would call the activity science.

Well, that is a conventional point of view, and very thoughtfully put, by the way, but it troubles me. Suppose somebody designed and built a microwave antenna dish as part of a relay station in a long distance communication network. That would qualify as engineering by your definition, wouldn’t it?

Of course.

Now suppose that same person designed and built a similar antenna for use in radio astronomy simply to listen in on the stars. Would he be an engineer? Not according to your definition, I think. You would say he was a scientist.

That’s a tough call.

A former classmate of mine designed and built a reactor which comprises a 100,000 gallon tank. The reaction medium is perchlorethylene, dry cleaning fluid. The product is volatile and at very low concentration in the medium. To recover it, a recycling stream of inert gas is bubbled through the tank and passed through an adsorbent that captures the product selectively. Would the design, construction, and operation of this system qualify as chemical engineering?

I would certainly say so.

OK. Now let me tell you that the product is a radioactive isotope of argon which is formed in extremely low yield when a neutrino flux passes through chlorine-containing material. The rate of formation in the tank is of the order of 5 to 10 atoms of argon per day! The whole purpose of the enterprise is to measure the neutrino flux from the sun. Is it still chemical engineering by your definition?

I think I’ve painted myself into a corner. My instinct tells me that in view of its objective that project should be called science. Logically, I must admit that it sure looks like engineering.

Why can’t it be both?

What do you mean?

I think that a lot of semantic confusion arises when we try to classify activities in terms...
of why people do things rather than in terms of what they do. To me, engineering is the art of applying quantitative knowledge to the solution of various kinds of problems. It is really irrelevant whether the objective is to make a salable product or to obtain a publishable bit of information.

SI: You mean it's what a person does rather than why he does it that counts?

PI: Exactly. Especially from the standpoint of what kind of education and training he gets. Take farming for example. A poor man farms for money. He tries to make a living. A rich man often farms with money. He wants to lose money. That is, at least on paper so that he can claim a tax deduction. They both practice agriculture. My wife loves flower gardening and does it for purely aesthetic and recreational returns. She also is practicing agriculture. Three people with entirely different motivations all practicing the same kind of art.

SI: You mean that there is no difference between science and engineering?

PI: What I mean is that they are not mutually exclusive categories. An activity should not be considered as either science or engineering. In fact, engineering is an art that scientists practice. It is an art that people other than scientists also practice. In other words, all scientists are engineers but not all engineers are scientists. Such an assertion would offend many scientists and more engineers but I think it is true.

SI: I'll have to think about that one.

PI: The important point is that engineering is an art; "the systematic application of knowledge and skill to achieve a desired result." In addition, an engineer must make educated guesses or hypotheses about what he doesn't know and put everything together in the design of a gadget, an experiment or a computer program aimed at achieving his objective. He then makes tests, modifies his design in light of test results, makes further tests and continues this iteration until his objective is realized within his limits of tolerance.

SI: That sounds reasonable.

PI: There's another point to be made. As in the case of any other art, engineering must be learned by practice. Like playing tennis, composing music, or painting pictures, it can't be taught in the classroom or learned from a book. The needed knowledge and the rules can be learned from books or in classrooms, but not the art of using them. That must be practiced, preferably under the guidance and supervision of a master practitioner. Medical schools are well aware of this truth and acquaint their students with the "factory", i.e., the hospital and clinic, early in their professional education experience. Later they serve an apprenticeship as interns and residents during which they practice the art of applying what they have learned, in association with and under the guidance of accomplished experts.

SI: I'd never thought of physicians and surgeons as engineers, but I see your analogy.

PI: In a sense medical schools do a better job of engineering education than most engineering schools. Unfortunately, to provide the same kind of practical experience for its professional students a chemical engineering department would have to operate, or participate in the operation of, a chemical plant or an oil refinery. That just isn't feasible in a university. What a university can do, is expected to do and be in the forefront of, is research. Research consists in learning all that is already known about some aspect of a subject, making guesses about what isn't known, designing an experiment or program based on this knowledge and the guesses, performing the experiment and then evaluating the result from the perspective of previous knowledge and the judgment of peers and experts. In my view that process of scientific research embodies the very essence of engineering and is the most valuable part of an engineering graduate educational experience. It doesn't really make much difference what is chosen as the particular topic or objective. The important point is that the student, on his own but with expert guidance, undertakes and completes a project which involves these important components: 1) learning what is already known; 2) making guesses or approximations about what isn't known but is necessary for: 3) the design of an approach or program or experiment; 4) execution of the program or experiment; 5) exercise of judgment in the evaluation of the result. In sum: Research is Engineering.

SI: That's a provocative statement!

PI: Yes, I guess it is and I know there are a lot of my industrial brothers who would take issue with it. They say that universities are ivory towers where researchers are out of touch with reality, that they don't have to face up to real world constraints like budgets, materials limitations, personnel problems, and competition. I have Continued on page 199.
EDITOR'S NOTE: A historical view of chemical engineering education in Mexico appeared in the Summer 1982 issue of CEE (Vol. XVI, No. 3). In that paper the authors described the needs, deficiencies, and possible solutions for the education of chemical engineers in the undergraduate programs of that country. In this paper the authors extend their comments to the status of graduate education in Mexico.

THE MASTER OF SCIENCE program in chemical engineering was introduced about ten years ago, both at the National University (UNAM) and the National Polytechnic Institute (IPN), in an effort to improve the basic education of engineers who were not being fully trained in the undergraduate programs. It was also an initial attempt to prepare teachers with a high academic standard to staff Mexican universities.

It should be mentioned that this initiative was not casual. We will examine how the proper conditions came about as a natural development of the growth of Mexican universities and technological institutes, and as a result of the need for highly qualified engineers in industry.

It was in the late sixties when the first foreign-educated postgraduates joined both UNAM and IPN. It was during that same period of time that industry also realized that the quality of the engineers they were recruiting did not meet their requirements. Thus, both professors and engineers from industry (who also staffed the chemical engineering schools) pressed enthusiastically for the creation of graduate programs. As a result, UNAM introduced its Master in Science program in 1967, and IPN followed suit to establish its own program in 1968.

It cannot be overemphasized that the main objective of these early programs was to alleviate the deficiencies of the undergraduate studies. This can be seen from noting the contents of those early programs. Most of the courses were, to a great extent, a review of undergraduate topics. Fundamental material such as transport phenomena, numerical methods, etc., which is undergraduate material elsewhere, was introduced in the graduate program. This left no time for an in-depth treatment due to time restrictions. Research activities were very limited, both in quality and quantity, since there was neither equipment nor enough qualified personnel for instruction.

The graduate programs at the mentioned institutions have slowly evolved towards programs where research has become an ever-important activity. This was a result of hiring a significant number of teachers with higher degrees (mostly obtained abroad) and of the improvement of conditions within the universities themselves.

In order to fully understand this development
it is interesting at this point to briefly examine, in general, the role of research in recent history.

Research in Mexican universities and technology institutes had very limited importance until, say, 25 years ago. Prior to that, research as we understand it today was almost nonexistent. Both universities and industry suffered from the lack of this activity and it left the country without any real possibility of participating in the generation of scientific knowledge or technology. To mention only one case, a famous Mexican physicist, Sandoval Vallarta, worked at MIT for over 20 years, only returning to Mexico in the early fifties when conditions seemed adequate.

It was, in fact, in that decade that research became a desirable activity and the National University moved towards institutionalizing it by creating a number of research centers, called "Institutes" (mainly in scientific and social disciplines), devoted to research. Unfortunately, these were separated from the teaching activities which belonged to the "Schools." In the early sixties, research in engineering fields began with the establishment of the Instituto de Ingeniería which initiated studies in soil mechanics. This was important due to the soil characteristics of the capital city which is situated in a highly seismic-prone zone.

In the early sixties, the Polytechnic Institute founded its Center for Research and Advanced Studies, which again was totally devoted to research activities (although it also offered some graduate programs in pure science and later in engineering). But again, it separated research activities from teaching at the undergraduate level. However, both institutions left out chemical engineering, which was traditionally more related to the chemistry schools than to the engineering ones. Thus, research in chemical engineering did not materialize until the graduate programs matured in the pioneer institutions (UNAM and IPN).

The economic reality of the country, and therefore that of its educational system, should not be forgotten. It was very difficult to divert large amounts of funds to universities for research when other social programs, such as elementary schooling, communications and health centers, were more pressing. It is only fair to mention that, because of the limited resources, research at the universities was not feasible until the country was able to afford it.

We have heretofore examined how the proper conditions for doing research came about within the university realm. We will now discuss the industrial aspect and its influence and contributions, if any, in this direction.

Industry developed in an isolated and protected medium where most of the required technology was acquired abroad and where there was little incentive, economic or political, for innovation or development of local technology. Due credit must be given to the engineers who in the span of a few years developed a well organized, profitable and expanding industry; in particular the petroleum industry, which has reached a prominent position worldwide.

It was as a direct result of this expansion, which has recently outgrown the national frontiers, that Mexican industry realized that in order to keep its level of competence both in the local and international markets, it would have to modernize and optimize its resources both economically and technically.

Thus, the necessary gradient towards innovation, adaptation and development of technology was established and the need for highly qualified engineers became apparent. The recent practices of hiring specialists who work at universities as consultants and sponsoring research projects carried out at the universities, are indicative of this mood.

This analysis serves several purposes: first, it shows that research (or the lack of it) in chemical engineering has been intimately related to the development of the Mexican chemical industry on one hand, and to the development of the higher education system on the other. Secondly, it provides some guidelines for designing a graduate program which can contribute to alleviate the difficulties previously mentioned, as well as to respond actively to the challenges that the country as a whole, and chemical engineering in particular, face.

GRADUATE PROGRAM DESIGN

It has been established that in order to meet the demand for highly qualified engineers, both
the undergraduate and the graduate programs in Mexico have to be strengthened. It is clear that the strengthening of the undergraduate program depends to a great extent on the availability of qualified personnel to staff the educational institutions; also, industry is demanding more engineers with higher degrees. Graduate programs must meet this dual purpose and be designed accordingly.

It is therefore not fortuitous that the basic philosophy which molded the undergraduate program at UAM-I (as described in our previous paper) should again be applied to the design of the masters program. A solid formation at the graduate level, in the fundamentals of chemical engineering disciplines, is sought. This would allow the students to perform equally well either in industry or in research and teaching activities.

The masters program should also be a step towards establishing a doctorate program, which is now nonexistent. Hence, it should prove itself capable of fulfilling, in accordance to its scope, the requirements of both industry and the educational system.

The benefits that the country as a whole should expect from such a program are

- Formation of human resources with high academic standards to staff the educational system.
- Development of technology at an intermediate level of sophistication.
- Improvement of plant operation and productivity.
- Generation of applied scientific and technical knowledge.
- Generation of research programs, both in industry and in research institutes, in applied chemical engineering science.

THE MASTERS PROGRAM AT UAM-I

The masters program at UAM-I, took advantage of the experience gained at UNAM and of the new attitudes with regard to graduate studies. It is therefore not a program intended to alleviate former deficiencies in the education of the engineer, but is rather directed toward strengthening the knowledge of the chemical engineering fundamentals and introducing the student to the research field. The objectives of the program are

- A sound formation in the chemical engineering fundamentals, i.e., applied mathematics, thermodynamics, transport phenomena and reactor engineering.
- An adequate capacity and ability to perform research through a basic understanding of the relationship between theory and practice.
- The skill to exercise creativity in order to implement new technologies and to adapt or optimize the
type of chemical engineer; one capable of assimilating the imported technologies and of developing new processes more suitable to the efficient utilization of our resources. This requirement provides one of the fundamentals for curriculum development; the other is a sound knowledge of what chemical engineering is.

With these two points in mind, we propose the formation of an "Academic Commission" on a national level, composed of highly qualified professors from all parts of the country who would coordinate the design of a curriculum which could then be implemented at all government sponsored schools. This curriculum should contain a fundamental core of basic science (chemistry, physics and mathematics), with strong interaction through practice in lab sessions. The second stage of the curriculum should emphasize the fundamentals of chemical engineering (thermodynamics, transport phenomena and reaction engineering). Finally, the third stage should be flexible and concentrate on several aspects, depending on the region of the country or the strength of the faculty at hand. As examples, important areas to cover are process design and development, project engineering, energy resources, and equipment design.

It is obvious that the implementation of the proposed curriculum requires highly trained teachers and researchers. These people should be educated through the graduate programs now existing in Mexico; therefore, those programs should be strengthened and strongly supported at the main government sponsored institutions. Furthermore, since all these programs offer only a M.S. degree thus far, emphasis should be placed on the development of one or two doctorate programs at the schools with the capabilities to implement them. Clearly, UNAM is one of them.

Strengthening the graduate programs should also develop research in chemical engineering, which so far has been meager and is greatly needed for the development of our industry. The few people that are presently capable of doing this have been schooled abroad. We feel that we have reached the stage where it is possible, and in fact imperative, to do it in Mexico.

BOOK REVIEW: Optimization
Continued from page 167.

ance, just the how for a few cases. The why is needed so the student can develop, understand and use other designs. It is surprising that the Newton-Bairstow method for curve fitting is not given.

Chapter 3. This chapter, though well-written, desperately needs more worked examples. On p. 102, the concepts of consistency and efficiency should be included with unbiasedness as properties of an estimator.

Chapter 4. This chapter appears to be a literature search from a thesis. The notation will be confusing to older readers whose formal mathematical background predates 1955 but who apply mathematics daily. A glossary of symbols would help. The coverage is excellent in scope. The section on interval reduction is very good. It is unfortunate that the Kuhn-Tucker conditions for constrained optimization are not mentioned. The basis for several algorithms are described but no executable algorithm is actually given. Completed examples are rare; no student exercises are provided. There is no warning against sectioning.

Chapter 5. This is an improvement over Chapter 4 in that stepwise algorithms are given but not worked.

Chapter 6 contains only four complete examples to illustrate applications to physical processes.

Chapter 7 is descriptive in nature. For the two "examples" of simulation models, only the results were given.

RESEARCH IS ENGINEERING
Continued from page 195.

spent about half as much time in industry as in academic institutions and I can tell you that the neurial, competitive and cost conscious as anything in the "real" world. Our budgets are even more inflexible than those of our industrial brothers. We can't pass cost overruns on to our clients, customers, or stockholders, for example. I suggest that when you hear someone say that research in academe is not the real world, you are listening to a person who doesn't know what he's talking about, who is so unaware of the actualities of university research that his own perspective is unreal.

SI: Well, you have certainly given me some food for thought. Let me digest it for awhile and come back to see you again.

PI: Fine. When you come I'll take you through the lab. It may make you feel better. It has 500-gallon tanks, 32-inch vacuum pumps, 6-inch valves and piping, and 10-horsepower motors. You'll think you're in a factory!
MASS TRANSFER
Continued from page 162.

examining chemically reactive mass transfer in
trayed equipment. Measurements of film co­
efficients and active interfacial areas are being
made in the three-tray column shown in Figure 2.
Glitsch valve trays with four square feet of active
area are being used; the center tray has adjust­
able downcomer and weir heights and is the test
tray. The column will be used eventually to pro­
vide tests of models based on treating the separa­
tion as a rate process. Real industrial solvent
solutions will be used in an evaluation of the effect
of corrosion inhibitors and antifoam agents on
mass transfer performance.

Again, as for multicomponent mass transfer,
these models are necessarily computer based and
treat the process on a mechanistic level. Once
more the final aim is to develop reliable methods
for the design and analysis of industrial equip­
ment, an objective that pervades all of our work.

FIGURE 2. Three-valve-tray column for mass transfer
rate measurements in gas absorption.

MULTICOMPONENT SEPARATIONS WITH CHEMICAL
REACTION AND OVERALL PHASE CHANGE

Condensation is another operation of such
broad importance that a wealth of books and
papers have been devoted to its analysis. The com­
plexity of condensation processes varies from
simple systems of pure vapors with no mass
transfer resistances to systems involving non­
condensibles in the vapor phase and those which
condense in the form of two immiscible fluids. The
condensation of multicomponent mixtures is diffi­
cult to analyze because of diffusional interaction
effects, particularly in the vapor phase. Design
methods depend on filmwise condensation with
either a completely unmixed or completely mixed
liquid phase [39]. Vapor condensation to im­
miscible liquid mixtures does not fall even between
the limits of a mixed or unmixed liquid film, but
progress has been made in developing design
methods.

Another example of condensation that can­
not be described by known methods is that of a
multicomponent vapor in which two or more
species undergo chemical reaction in the liquid
phase. This part of our research addresses these
types of processes by bringing together work
from the areas of condensation and chemically re­
active mass transfer. Until now, these have always
been considered as quite separate, yet they are
intimately linked in a number of systems of com­
mercial significance. Design methods are totally
lacking for such systems and this forms one of
the objectives of the present work.

In order to simplify the rate calculations, the
mass transfer resistance offered by the liquid
phase is traditionally ignored. One of two types of
approximation is commonly made: (i) the liquid
phase is always in the totally unmixed state (zero
liquid-side mass transfer coefficients) and the
surface composition of the liquid is decided by the
relative rates of condensation, or (ii) the liquid
phase is completely mixed as far as compositions
are concerned (but normal temperature gradients
still operate) and the liquid composition is calcu­
lated from a material balance along the flow path.
It is clear that the truth lies between these ex­
tremes, at least for miscible systems. There is
also some evidence that the final results are in­
sensitive to whichever extreme is taken [44].

The mixture to be condensed is usually multi­
component and the last decade has seen increased
interest in the development of advanced models
for such systems, along with the necessary experimental verification. For example, the classical Ackermann-Colburn-Drew [40, 41] analyses have been extended by Schrodt [42] to multicomponent mixtures; however, his approach is somewhat naive because it neglects the effects of diffusional interaction in the vapor. Recently Webb et al. [43] have examined the significance of coupling effects in ternary condensation and concluded that an effective diffusivity type of model (as used by Schrodt [42]) may safely be employed provided the condensing species are not too dissimilar and condensation rates are modest. The safe use of an effective diffusivity type of model for this process is partly a result of the unidirectional nature of the transfer process.

The method of Schrodt [42] and the modification by Webb et al. [43] are based on a film model of the transport process. More exact multicomponent generalizations of the Ackermann-Colburn-Drew analyses have also been developed [44, 45]. There are a number of other methods available; some have been supported experimentally and some have not. The important point in the present context, however, is that all of these methods are strictly limited to vapors that condense filmwise and form a condensate characterizable as being either perfectly mixed or entirely unmixed.

There are a number of situations that do not fall into these categories, and one that we are studying is the condensation of a multicomponent vapor in which two or more of the species undergo chemical reaction in the liquid phase. A striking example of such a system is the ternary mixture carbon dioxide-ammonia-water vapor which must be condensed in a number of commercial processes for the manufacture of the fertilizer and monomer, urea. It is well known that CO₂ and NH₃ react in aqueous solution to form ammonium carbamate and it must be expected that this will have a profound effect not only on condensation rates, but also on the compositions of both the condensate and the gas mixture being vented from the condenser.

Since the reaction product, ammonium carbamate, is nonvolatile, a first impression might be that reaction would lower the concentrations of both CO₂ and NH₃ in the liquid film, thereby lowering the corresponding concentrations in the gas phase at the interface. Thus, an increase in the driving forces in the vapor phase would favor heat and mass transfer and lead to a condenser of lower area. However, such an argument would be quite specious. It is crucial to recognize that although ammonia is highly soluble in water, carbon dioxide is sparingly soluble and that its physical solubility is of paramount importance in deciding its transfer rate even in the presence of a rapid chemical reaction. Chemical equilibrium, of course, is tied to the reactions involved, whereas, the physical process of dissolving (which must proceed reaction) is relatively unaffected by reaction, except insofar as the concentration of dissolved gas is kept low and the liquid film thickness is reduced. Our intuitive arguments are of little consequence and it is clear that such systems do not fall between the two extremes regarding condensate mixing described above. Indeed, it must be said that the hydrodynamics of the liquid film are decisive in determining rates of mass transfer, including condensation, because the resistance offered by the liquid film is dominant for the transfer of CO₂ even though the vapor phase resistance is probably more important for the transfer of ammonia. Thus, arguments about whether the liquid phase is well mixed or not beg the issue and will undoubtedly lead to calculations totally in error.

Gas absorption has been the main focus of most previous studies of chemically-reactive mass transfer. However, it is important to recognize a number of essential differences between absorption and condensation. In the former, the absorbing medium (water) does not undergo a significant degree of phase change; whereas, in the CO₂ — NH₃ — H₂O system for example, condensation results in an extremely large flux of water vapor that exerts a dominant influence on the total transfer rate of all the species. The larger part of the condensate would be expected to be water which could absorb a considerable amount of ammonia, since this gas is highly soluble. Although CO₂ is a very sparingly soluble gas, the presence of dissolved ammonia greatly increases the total capacity of the liquid for CO₂ because it essentially removes it in the form of ammonium carbamate which is nonvolatile. In the present context, CO₂ does not act as an inert gas since it can be dissolved in large amounts.

ERRATA

The Summer 1982 issue of CEE contained an article written by Leise, Jenkins, and Tarbel, entitled "The Oscillating Sink." The diagrams in Figs. 3 and 6 (pgs. 112, 113) in that article should be interchanged.
governed by the chemical reaction equilibrium and the composition of the condensate. The latter is of course determined by transfer rates of water vapor and ammonia which are themselves influenced by the transport of carbon dioxide, so we have here a process very much complicated by the chemical reaction.

In summary, the process being examined here involves a very large flux of water from the vapor towards the condensate film which simultaneously drives the other two species toward the film, greatly increasing their vapor-phase concentrations at the interface. Ammonia transfer, being largely gas-phase controlled, will be much affected by the presence of CO₂; whereas, CO₂ transfer is liquid-phase controlled and will be influenced by dissolving ammonia. In addition, because the diffusion film in the liquid at the interface will be at a relatively high temperature, the reactions will likely have to be considered reversible; however, temperatures may not be so high that a chemical reaction equilibrium assumption will apply. Conditions in the condensate film, particularly near the vapor boundary are crucial to the transport rates so that assumptions about complete mixing or nonmixing would be meaningless. The work being done here will provide a rather severe test of not only condensation theory but also of absorption with reversible reaction and the ability of the present state-of-the-art to combine these theories in an effective way for such novel but important situations.

ACKNOWLEDGMENTS

Some of the studies reported here have been supported in the past by the Research Grants Committee (Australia) and the Science Research Council (United Kingdom) for which the authors are grateful. Present studies are being supported by individual grants to the authors by the National Science Foundation and by substantial funding from Dow Chemical U.S.A. Donations of equipment by Goulds Pumps, Inc. and Glitsch, Inc. are gratefully acknowledged.

REFERENCES


GEYSER PROBLEM
Continued from page 189.

this jet of liquid occurred at the very end of the filling process, 9.5 hours after the first penetration of the mine by the drill. At that point, most of the mine must have been full of water, and the only forces likely to generate such a spectacular effect are gravitational ones, of which the bubble mechanism proposed above is the most plausible.

An alternative gravitational explanation would be that the first fluid to flow into the mine was relatively clean water, while the later fluid, flowing in after the hole had enlarged, would be quite muddy. In oil well drilling practice it is possible to produce drilling muds (mud-water slurries), with densities up to twice that of water. If the first half of the path from wellbore to ventilator shaft were filled with ordinary water, and the second half filled with a mud whose density were 1.5 times that of water then the hydrostatic pressure difference from lake level to ventilator shaft would have been

\[ P = gh\Delta \rho = 32 \text{ ft/sec}^2 \times 1300 \text{ ft} \times (0.5 \times 62.4 \text{ lbm/ft}^2) \times \text{ lbf sec}^2/32 \text{ lbm ft} \times \text{ ft}^2/144 \text{ in}^2 = 281 \text{ psi} \]

This would likely have been adequate to produce the geyser. I consider this a less-likely explanation than the air bubble, because it requires a much more organized process, with strong segregation of the earlier clean inflowing fluid from the later mud-laden fluid. But I cannot rule it out for certain without more data on the accident than has been published.
OXIDATIVE DEHYDROGENATION
Continued from page 151.

Solid state changes may be occurring deep within the bulk phase that affect the catalytic activity.

Several techniques were used to test this possibility. First of all, X-ray diffraction patterns were taken on the fresh catalyst and on samples that were progressively deactivated. The fresh catalyst was about 90% MgFe₂O₄, but 5% of the material was iron oxide, α-Fe₂O₃. Deactivated catalysts showed only MgFe₂O₄. This suggested that the true "catalyst" was not the ferrite but was in fact the Fe₂O₃ which was possibly present as a surface coating on the MgFe₂O₄ base. Auger spectroscopic measurements confirmed the absence of Mg in the surface layers of the catalyst. Both magnetic susceptibility and Mössbauer spectroscopy confirmed the conclusions derived from the X-ray data, namely that the iron oxide was present in the fresh active samples but was absent in the used inactive catalysts.

Upon inquiring about how the catalyst was synthesized [11], we were informed that it was made by the high temperature fusion reaction

\[ \text{MgO} + \text{Fe}_2\text{O}_3 \xrightarrow{\Delta} \text{MgFe}_2\text{O}_4 \]  \hspace{1cm} (13)

The reaction was carried out to only 90% completion during synthesis ... and this is one of the secrets of preparing this active catalyst! As heat was released by the exothermic OXD reaction, the iron oxide reacted with the MgO dissolved in solid solution to carry the reaction (13) to completion.

TRANSPORT EFFECTS

The catalyst has a low surface area (about 7 m²/g) and large pores. Furthermore, the reaction was carried out in an all-Pyrex batch recirculation reactor at low temperature to keep the rate slow. These factors resulted in a very small Thiele modulus and no mass transport limitations. On the other hand, it was very difficult to keep the reactor isothermal due to the large exothermicity of the reaction. Dilution of the catalyst bed with inert particles helped, but still the reaction was difficult to control. Only data obtained under conditions where the temperature remained essentially constant were used in the kinetics analysis.

As mentioned in the previous section, it is likely that the slow dissipation of the heat of reaction away from the active sites could have caused localized hot spots in the vicinity of the active site pairs that led to the progression of the solid state reaction (13) [12].

CONCLUSIONS

It is rare that one can find a catalytic system of commercial interest that can be studied in detail by such a variety of techniques. The small molecules are easily handled in the laboratory and can be labeled with both radioactive and stable isotopic tracers. Being well crystallized and containing iron, the catalyst itself is amenable to study by a wide range of solid state techniques.

The results can be summarized by the following points.

- A redox mechanism (Fe²⁺/Fe³⁺ interconversion) occurs.
- C-H cleavage is rate limiting.
- Two sites are involved (anion and cation vacancies).
- Non-competitive Langmuir-Hinshelwood kinetics are obeyed.
- Surface oxygen is added and removed; the surface is fully covered so long as there is even a small amount of O₂ in the gas phase.
- The catalyst is easily reduced by hydrocarbons in absence of O₂.
- Activity correlates with the presence of α-Fe₂O₃, which is probably present as a thin coating on the MgFe₂O₄ spinel support.
- Deactivation occurs when MgO reacts with Fe₂O₃ to form MgFe₂O₄.

RELATED WORK AT RICE UNIVERSITY

In related work we have studied the oxidative dehydrodimerization (OXDD) of propylene over Bi₂O₃ to form 1,5-hexadiene and benzene [13-14]. We have also looked at the OXD of butane to form n-butenes and butadiene over a commercial Ni-Sn-P oxide catalyst [15]. Finally, the ferrite work has been expanded to other catalysts such as CoFe₂O₄ [10] and manganese ferrite [16]. While some of the questions about the nature of catalytic activity of these materials have been answered, many more questions remain in this exciting area of heterogeneous catalysis.

ACKNOWLEDGMENTS

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**ChE book reviews**

**PLANT DESIGN AND ECONOMICS FOR CHEMICAL ENGINEERS, 3RD EDITION**  
*By Max S. Peters, Klaus D. Timmerhaus*  
*McGraw-Hill Book Company, NY*

Reviewed by Oran L. Culberson  
University of Tennessee

This book in its third edition continues to be among those classics which should be in the personal library of every chemical engineer. It is, however, basically unchanged from the second edition and may not merit acquisition by those who own the second edition.


The erstwhile appendices on Linear Programming and Dynamic Programming have been moved into Chapter 10, Optimum Design and Design Strategy. This was perhaps a mistake. These two optimization algorithms have little application in design. Geometric programming would have been a more appropriate offering. It is also unfortunate that the material on linear programming does not note that modern computer programs do not use the Simplex algorithm described; this omission will be confusing and aggravating to the reader who wants to use library programs on computers. A better use of the space would have resulted from exposition on the Critical Path Method and for the Project Evaluation and Review Technique which are valuable for the scheduling and control of projects. Chapter 10 has been expanded also to explain the concept of cash flow and to show how the effects of inflation might be covered in economic analysis.

Chapter 3 on General Design Considerations has been more than doubled to include information on design requirements to protect against thermal, air, liquid and solid waste pollution. Chapter 15, formerly devoted exclusively to Mass Transfer Equipment, now treats Reactor Equipment also. This material is from an appendix of the second edition, with some augmentation.

A great strength of this book has always been the voluminous bibliography at the end of each chapter. These literature references have been updated and are very valuable to anyone wanting to delve into a topic beyond the limited treatment which can be made in the book. The new edition is still replete with equipment costs, now updated to January 1, 1979. A table of the costs of chemicals appears in the new edition which unfortunately contains neither a date nor a warning to the neophyte that these costs can change rapidly.

Another quite useful feature of this book is the extensive sets of problems for each chapter, but the problems have not been changed in the two editions. This reviewer overheard a professor bemoaning this fact at the AICHE meeting in Chicago.
GRADUATE PROGRAMS
FOR M.S. AND PH.D. DEGREES
IN CHEMICAL ENGINEERING

The University of Alabama, enrolling approximately 14,000 undergraduate and
3,000 graduate students per year, is located in Tuscaloosa, a town of some 70,000
population in West Central Alabama. Since the climate is warm, outdoor activities
are possible most of the year.

The Department of Chemical and Metallurgical Engineering has an annual
enrollment of approximately 200 undergraduate and 25 graduate students. For
information concerning available graduate fellowships and assistantships, con-
tact: Director of Graduate Studies, Department of Chemical and Metallurgical
Engineering, P.O. Box G, University, AL 35486.

Faculty and Research Interests

G.C. APRIL, Ph.D. (Louisiana State): Biomass Con-
version, Modeling, Transport Processes

D.W. ARNOLD, Ph.D. (Purdue): Thermodyna-
mics, Physical Properties, Phase Equilibrium

J.H. BLACK, Ph.D. (Pittsburgh): Process Design,
Cost Engineering, Economics

W.C. CLEMENTS, JR., Ph.D. (Vanderbilt): Process
Dynamics and Control, Micro-computer Hard-
ware

W.J. HATCHER, JR., Ph.D. (Louisiana State): Cata-
lysis, Chemical Reactor Design, Reaction Kinetics

E.K. LANDIS, Ph.D. (Carnegie Institute of Tech-
nology): Metallurgical Processes, Solid-liquid
Separations, Thermodynamics

M.D. MCKINLEY, Ph.D. (Florida): Coal and Oil
Shale, Mass Transfer, Separation Processes

L.Y. SADLER, III, Ph.D. (Alabama): Energy Conver-
sion Processes, Rheology, Lignite Technology
Faculty and Research Interests

I. G. Dalla Lana, Ph.D. (Minnesota):  
Kinetics, Heterogeneous Catalysis.

D. G. Fisher, Ph.D. (Michigan):  
Process Dynamics and Control, Real-Time 
Computer Applications, Process 
Design.

C. Kiparisides, Ph.D. (McMaster):  
Polymer Reactor Engineering, Opti-

misation, Modelling, Stochastic 
Control.

D. Lynch, Ph.D. (Alberta):  
Kinetic Modelling, Numerical Methods, 
Computer Aided Design.

J. H. Masliyah, Ph.D. (British Colum-
bia): Transport Phenomena, 
Numerical Analysis, In-Situ Recovery 
of Oil Sands.

A. E. Mather, Ph.D. (Michigan):  
Phase Equilibria, Fluid Properties at High 
Pressures, Thermodynamics.

W. Nader, Dr. Phil, (Vienna): Heat 
Transfer, Air Pollution, Transport 
Phenomena in Porous Media, Applied 
Mathematics.

F. D. Otto (Chairman), Ph.D. (Michi-
gan): Mass Transfer, Gas-Liquid Re-
actions, Separation Processes, Envi-
nronmental Engineering.

D. Quon, Sc.D. (MIT), Professor Emeri-
tus: Energy Modelling and Economics, 
Linear Programming, Network 
Theory.

D. B. Robinson, Ph.D. (Michigan):  
Thermal and Volumetric Properties of 
Fluids, Phase Equilibria, Thermo-
dynamics.

J. T. Ryan, Ph.D. (Missouri):  
Process Economics, Energy Economics and 
Supply.

S. L. Shah, Ph.D. (Alberta):  
Linear Systems Theory, Adaptive Control, 
Stability Theory, Stochastic Control.

S. E. Wanke, Ph.D. (California-Davis):  
Catalysis, Kinetics.

R. K. Wood, Ph.D. (Northwestern):  
Process Dynamics and Identification, 
Control of Distillation Columns, 
Modelling of Crushing and Grinding 
Circuits.

Graduate Study

U of A's Chemical Engineering graduate 
program offers exciting research 
opportunities to graduate students moti-
vated towards advanced training and 
research. Graduate programs leading to 
the degrees of Master of Science, Master 
of Engineering and Doctor of Philosophy 
are offered. There are currently 13 full-
time faculty members, a few visiting 
faculty, several post-doctoral research 
associates and 35 graduate students.

Financial Aid

Financial support is available to full-
time graduate students in the form of 
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research assistantships.

The University of Alberta

U of A is one of Canada’s largest 
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renowned resident professional theatre, 
symphony orchestra and professional 
football, hockey and soccer leagues. 
The famous Banff and Jasper National 
Parks in the Canadian Rocky Mountains 
are within easy driving distance.

For application forms or 
more information, write to

CHAIRMAN, 
Department of Chemical 
Engineering 
University of Alberta 
Edmonton, Canada T6G 2G6

FALL 1982
The Chemical Engineering Department at the University of Arizona is young and dynamic with a fully accredited undergraduate degree program and M.S. and Ph.D. graduate programs. Financial support is available through government grants and contracts, teaching, and research assistantships, traineeships and industrial grants. The faculty assures full opportunity to study in all major areas of chemical engineering.

THE FACULTY AND THEIR RESEARCH INTERESTS ARE:

JOSEPH F. GROSS, Professor
Ph.D., Purdue University, 1956
Boundary Layer Theory, Pharmacokinetics, Fluid Mechanics and Mass Transfer in The Microcirculation, Biomechanology

ALAN D. RANDOLPH, Professor
Ph.D., Iowa State University, 1962
Simulation and Design of Crystallization Processes, Nucleation Phenomena, Particulate Processes, Explosives Initiation Mechanisms

THOMAS R. REHM, Professor and Acting Head
Ph.D., University of Washington, 1960
Mass Transfer, Process Instrumentation, Packed Column Distillation, Applied Design

JOST O.L. WENDT, Professor
Ph.D., Johns Hopkins University, 1968
Combustion Generated Air Pollution, Nitrogen and Sulfur Oxide Abatement, Chemical Kinetics, Thermodynamics, Interfacial Phenomena

DON H. WHITE, Professor
Ph.D., Iowa State University, 1949
Polymers Fundamentals and Processes, Solar Energy, Microbial and Enzymatic Processes

WILLIAM P. COSART, Assoc. Professor
Ph.D. Oregon State University, 1973
Transpiration Cooling, Heat Transfer in Biological Systems, Blood Processing

THOMAS W. PETERSON, Assoc. Professor
Ph.D., California Institute of Technology, 1977

FARHANG SHADMAN, Asst. Professor
Ph.D., University of California-Berkeley, 1972
Reaction Engineering, Kinetics, Catalysis

Tucson has an excellent climate and many recreational opportunities. It is a growing, modern city of 450,000 that retains much of the old Southwestern atmosphere.

For further information, write to:
Dr. T. W. Peterson
Graduate Study Committee
Department of Chemical Engineering
University of Arizona
Tucson, Arizona 85721

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CATALYSIS • ENVIRONMENTAL CONTROL •
ENGINEERING DESIGN • PROCESS CONTROL •

Our excellent facilities for research and teaching are complemented by a highly-respected faculty:

James R. Beckman, University of Arizona, 1976
Lynn Bellamy, Tulane University, 1966
Neil S. Berman, University of Texas, 1962
Timothy S. Cale, University of Houston, 1980
William J. Crowe, University of Florida, 1969 (Adjunct)
William J. Dorson, Jr., University of Cincinnati, 1967
Eric J. Guilbeau, Louisiana Tech University, 1971
James T. Kuester, Texas A&M University, 1970
Kim L. Nelson, University of Delaware, 1981
Castle O. Reiser, University of Wisconsin, 1945 (Emeritus)
Vernon E. Sater, Illinois Institute of Technology, 1963
Robert S. Torrest, University of Minnesota, 1967
Bruce C. Towe, Pennsylvania State University, 1978
James M. Trebilcock, Michigan State University, 1950
Imre Zwiebel, Yale University, 1961

Fellowships and teaching and research assistantships are available to qualified applicants.

ASU is in Tempe, a city of 120,000, part of the greater Phoenix metropolitan area. More than 38,000 students are enrolled in ASU's ten colleges; 10,000 of whom are in graduate study. Arizona's year-round climate and scenic attractions add to ASU's own cultural and recreational facilities.

FOR INFORMATION, CONTACT:
Imre Zwiebel, Chairman,
Department of Chemical and Bio Engineering
Arizona State University, Tempe, AZ 85287
CHEMICAL ENGINEERING

GRADUATE

STUDIES

THE PROGRAM
The Department is one of the fastest growing in the Southeast and offers degrees at the M.S. and Ph.D. levels. Research emphasizes both experimental and theoretical work in areas of national interest, with modern research equipment available for most all types of studies. Generous financial assistance is available to qualified students.

THE LOCALE
Auburn University has 19,000 students and is located midway between Atlanta, GA, and Montgomery, AL. Situated in a beautiful wooded setting, the local population numbers about 75,000 and supports good shopping and entertainment facilities. The University also sponsors many types of artistic, dramatic, cultural and sporting events. The combination of good weather and pleasant surroundings make outdoor activities such as hiking, boating, fishing and camping particularly enjoyable.

THE FACULTY
Robert P. Chambers (University of California, 1965) Enzymatic and Biomedical Engineering, Biomass Conversion, Adsorption and Ion Exchange.
Christine W. Curtis (Florida State University, 1976) Analytical Methods, Coal Chemistry and liquefaction, Catalysis of Hydrocarbon Residuals.
Y. Y. Lee (Iowa State University, 1972) Biochemical Engineering, Reaction Engineering of Bio-Systems, Biomass Conversion
Timothy D. Placek (University of Kentucky, 1978) Environmental Pollution, Process Simulation, Multi-phase Transport Phenomena.
A. R. Tarrer (Purdue University, 1973) Coal Liquefaction, Oil Reprocessing, Solid-Liquid Separations.
Donald L. Vives (Columbia University, 1949) Oil Reprocessing, Vapor-Liquid Equilibria, Heat Transfer.
Dennis C. Williams (Princeton University, 1980) Process Dynamics and Control, Reactor Engineering.

RESEARCH AREAS
Biomedical/Biochemical Engineering
Biomass Conversion
Coal Conversion
Environmental Pollution
Heterogeneous Catalysis
Oil Reprocessing
Process Design and Control
Process Simulation
Reaction Engineering
Reaction Kinetics
Separations
Surface Science
Transport Phenomena
Thermodynamics

For financial aid and admission application forms write:
Dr. R.P. Chambers, Head
Chemical Engineering
Auburn University, AL 36849

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- Research
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  Catalysis  Electrochemical Engineering
  Coal Gasification  Fluid Mechanics
  Fossil Fuels Recovery  High Pressure Chemistry
  Thermochemistry & Calorimetry

- Faculty
  D. H. Barker, (Ph.D., Utah, 1951)
  C. H. Bartholomew, (Ph.D., Stanford, 1972)
  M. W. Beckstead, (Ph.D., Utah, 1965)
  D. N. Bennon, (Ph.D., Berkeley, 1964)
  B. S. Brewster, (Ph.D., Utah, 1979)
  J. J. Christensen, (Ph.D., Carnegie Inst. Tech, 1958)
  J. M. Glassett, (M.S., MIT, 1948)
  R. W. Hanks, (Ph.D., Utah, 1961)
  W. C. Hecker, (Ph.D., U.C. Berkeley, 1982)
  P. O. Hedman, (Ph.D., BYU, 1973)
  J. L. Oscarson, (Ph.D., Michigan, 1982)
  P. J. Smith, (Ph.D., BYU, 1979)
  L. D. Smoot, (Ph.D., Washington, 1960)
  K. A. Solen, (Ph.D., Wisconsin, 1974)

- Beautiful campus located in the rugged Rocky Mountains
- Financial aid available

Address Inquiries to: Brigham Young University, Dr. Richard W. Hanks, Chairman
Chemical Engineering Dept. 350 CB Provo, Utah 84602

FALL 1982
CHEMICAL AND PETROLEUM ENGINEERING

Program of Study

Degrees Offered
- Master of Science
- Master of Engineering
- Doctor of Philosophy

Both the M.Sc. and Ph.D. programs are on the full-time basis and have residency requirements. Course work and a research thesis based on an original investigation are required of each student enrolled in either degree program. The M.Eng. involves part-time study. It is designed for those individuals working in the industry who would like to enhance their technical education. The M.Eng. thesis is usually on a design oriented project related to current or anticipated industrial trends. All the programs are designed to meet the specific interests and individual needs of the student. The research and computing facilities within the department and the faculty of engineering are excellent and continuously being upgraded.

Generous fellowships and assistantships are available throughout the calendar year to qualified applicants. The four month summer months are usually devoted to active research. Supplementary financial support may also be available from the research grants of the individual faculty members.

Research Areas

- Thermodynamics—Phase Equilibria
- Mass Transfer and Fluid Mechanics
- Heat Transfer and Cryogenics
- Kinetics and Combustion
- Reaction Engineering and Process Control
- Flow in Porous Media
- Multi-phase Flows in Pipelines
- Computer Aided Design of Pipe Networks
- Fluidization
- Environmental Engineering
- In-situ Recovery of Bitumen and Heavy Oils
- Natural Gas Processing and Gas Hydrates
- Bioremediation and Biochemical Engineering
- Reverse Osmosis and Ultra Filtration

The Community

The university is located in Calgary, Alberta, home of the world famous Calgary Stampede. This city of half a million combines the traditions of the Old West with the sophistication of a modern, dynamic urban centre. Beautiful Banff National Park is 60 miles from the city and the ski resorts of the Banff and Lake Louise areas are readily accessible. Jasper National Park is only five hours away by car via one of the most scenic highways in the Canadian Rockies. A wide variety of cultural and recreational facilities are available both on campus and in the community at large. Calgary is the business centre of the petroleum industry in Canada and as such has one of the highest concentrations of engineering activity in the country.

Applications

For further information and application material write to:

The Chairman, Graduate Studies Committee
Department of Chemical and Petroleum Engineering
The University of Calgary,
Calgary, Alberta, T2N 1N4 Canada

Faculty

R. A. HEIDEMANN, Professor and Head D.Sc. (Wash. U.)
A. BADAKHSHAN, Professor Ph.D. (Birm.)
L. A. BEHR, Assoc. Professor Ph.D. (W. Ont.)
D. W. BENNION, Professor Ph.D. (Penn. St.)
P. R. BISHNOI, Professor Ph.D. (Alta.)
M. FOGARASI, Sr. Instructor B.Sc. (Alta.)
G. A. GREGORY, Professor Ph.D. (Waterloo)
M. A. HASTADOLU, Asst. Professor Ph.D. (SUNY)
J. J. HAVLEN, Sr. Instructor B. Sc. (Czech.)
A. A. JRJE, Assoc. Professor Ph.D. (MIT)
N. G. McDEPPHIE, Assoc. Professor Ph.D. (Texas)
A. E. MEHROTRA, Asst. Professor Ph.D. (Calgary)
M. F. MOHTADI, Professor Ph.D. (Birm.)
B. G. MOORE, Professor Ph.D. (Alta.)
P. M. SIMNSD, Assoc. Professor Ph.D. (Texas)
P. M. STANISLAV, Professor Ph.D. (Prague)
W. Y. SVRCEK, Professor Ph.D. (Alta.)
E. L. TOLLEFSON, Professor Ph.D. (Tor.)

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CHEMICAL ENGINEERING EDUCATION
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RESEARCH INTERESTS
ENERGY UTILIZATION
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KINETICS AND CATALYSIS
THERMODYNAMICS
POLYMER TECHNOLOGY
ELECTROCHEMICAL ENGINEERING
PROCESS DESIGN AND DEVELOPMENT
SURFACE AND COLLOID SCIENCE
BIOCHEMICAL ENGINEERING
SEPARATION PROCESSES
FLUID MECHANICS AND RHEOLOGY
ELECTRONIC MATERIALS PROCESSING

FACULTY
Alexis T. Bell (Chairman)
Harvey W. Blanch
Elton J. Cairns
Morton M. Denn
Alan S. Foss
Simon L. Goren
Edward A. Grens
Donald N. Hanson
Dennis W. Hess
C. Judson King
Scott Lynn
James N. Michaels
John S. Newman
Eugene E. Petersen
John M. Prausnitz
Clayton J. Radke
Jeffrey A. Reimer
David S. Soong
Charles W. Tobias
Theodore Vermeulen
Charles R. Wilke
Michael C. Williams

PLEASE WRITE: Department of Chemical Engineering
UNIVERSITY OF CALIFORNIA
Berkeley, California 94720

FALL 1982
Degrees Offered
Master of Science
Doctor of Philosophy

Faculty
RICHARD L. BELL, University of Washington
Mass Transfer, Biomedical Applications
RUBEN G. CARBONELL, Princeton University
Enzyme Kinetics, Applied Kinetics, Quantum Statistical Mechanics, Transport Processes in Porous Media
ALAN P. JACKMAN, University of Minnesota
Environmental Engineering, Transport Phenomena
BEN J. McCOY, University of Minnesota
Separation and Transport Processes
DAVID F. OLLIS, Stanford University
Catalysis, Biochemical Engineering
DEWEY D. Y. RYU, Massachusetts Inst. of Technology
Biochemical Engineering, Fermentation
JOE M. SMITH, Massachusetts Institute of Technology
Applied Kinetics and Reactor Design
PIETER STROEVE, Massachusetts Institute of Technology
Mass Transfer, Colloids
STEPHEN WHITAKER, University of Delaware
Fluid Mechanics, Interfacial Phenomena, Transport Processes in Porous Media

Davis and Vicinity
The campus is a 20-minute drive from Sacramento and just over an hour away from the San Francisco Bay area. Outdoor sports enthusiasts can enjoy water sports at nearby Lake Berryessa, skiing and other alpine activities in the Sierra (2 hours from Davis). These recreational opportunities combine with the friendly informal spirit of the Davis campus to make it a pleasant place in which to live and study.
Married student housing, at reasonable cost, is located on campus. Both furnished and unfurnished one- and two-bedroom apartments are available. The town of Davis (population 36,000) is adjacent to the campus, and within easy walking or cycling distance.

For further details on graduate study at Davis, please write to:

Graduate Advisor
Chemical Engineering Department
University of California
Davis, California 95616
or call (916) 752-0400

CHEMICAL ENGINEERING EDUCATION
CHEMICAL ENGINEERING

PROGRAMS

UCLA's Chemical Engineering Department maintains academic excellence in its graduate programs by offering diversity in both curriculum and research opportunities. The department's continual growth is demonstrated by the newly established Institute for Medical Engineering and the National Center for Intermedia Transport Research, adding to the already wide spectrum of research activities.

Fellowships are available for outstanding applicants. A fellowship includes a waiver of tuition and fees plus a stipend.

Located five miles from the Pacific Coast, UCLA's expansive 417 acre campus extends from Bel Air to Westwood Village. Students have access to the highly-regarded sciences programs and to a variety of experiences in theatre, music, art and sports on campus.

CONTACT
Admissions Officer
Chemical Engineering
5405 Boelter Hall
UCLA
Los Angeles, CA 90024

FACULTY
D. N. Bennion
Yoram Cohen
S. M. Dinh
S. Fathi-Afshar
T. H. K. Frederking
S. K. Friedlander
E. L. Knuth
J. W. McCutchan
Ken Nobe
L. B. Robinson
O. I. Smith
W. D. Van Vorst
V. L. Vilker
F. E. Yates
M. M. Baizer

RESEARCH AREAS
Thermodynamics and Cryogenics
Reverse Osmosis and Membrane Transport
Process Design and Systems Analysis
Polymer Processing and Rheology
Mass Transfer and Fluid Mechanics
Kinetics, Combustion and Catalysis
Electrochemistry and Corrosion
Biochemical and Biomedical Engineering
Aerosol and Environmental Engineering
FACULTY AND RESEARCH INTERESTS

SANJOY BANERJEE
Ph.D. (Waterloo)
(Vice Chairman, Nuclear Engineering)
Two Phase Flow, Reactor Safety,
Nuclear Fuel Cycle Analysis
and Wastes

H. CHIA CHANG
Ph.D. (Princeton)
Chemical Reactor Modeling,
Applied Mathematics

HENRI FENECH
Ph.D. (M.I.T.)
Nuclear Systems Design and Safety,
Nuclear Fuel Cycles, Two-Phase Flow,
Heat Transfer.

OWEN T. HANNA
Ph.D. (Purdue)
(Chairman)
Theoretical Methods, Chemical
Reactor Analysis, Transport
Phenomena.

G. ROBERT ODETTE
Ph.D. (M.I.T.)
Radiation Effects in Solids, Energy
Related Materials Development.

A. EDWARD PROFIO
Ph.D. (M.I.T.)
Bionuclear Engineering, Fusion
Reactors, Radiation Transport
Analyses.

ROBERT G. RINKER
Ph.D. (Caltech)
Chemical Reactor Design, Catalysis,
Energy Conversion, Air Pollution.

ORVILLE C. SANDALL
Ph.D. (Berkeley)
Transport Phenomena, Separation
Processes.

DALE E. SEBORG
Ph.D. (Princeton)
Process Control, Computer Control,
Process Identification.

PROGRAMS AND FINANCIAL SUPPORT

The Department offers M.S. and Ph.D. degree programs. Financial aid, including fellowships, teaching assistantships, and research assistantships, is available. Some awards provide limited moving expenses.

THE UNIVERSITY

One of the world's few seashore campuses, UCSB is located on the Pacific Coast 100 miles northwest of Los Angeles and 330 miles south of San Francisco. The student enrollment is over 14,000. The metropolitan Santa Barbara area has over 150,000 residents and is famous for its mild, even climate.

For additional information and applications, write to:

Professor Owen T. Hanna, Chairman
Department of Chemical & Nuclear Engineering
University of California,
Santa Barbara, CA 93106
PROGRAM OF STUDY  Distinctive features of study in chemical engineering at the California Institute of Technology are the creative research atmosphere and the strong emphasis on basic chemical, physical, and mathematical disciplines in the program of study. In this way a student can properly prepare for a productive career of research, development, or teaching in a rapidly changing and expanding technological society.

A course of study is selected in consultation with one or more of the faculty listed below. Required courses are minimal. The Master of Science degree is normally completed in one academic year and a thesis is not required. A special M.S. option, involving either research or an integrated design project, is a feature to the overall program of graduate study. The Ph.D. degree requires a minimum of three years subsequent to the B.S. degree, consisting of thesis research and further advanced study.

FINANCIAL ASSISTANCE  Graduate students are supported by fellowship, research assistantship, or teaching assistantship appointments during both the academic year and the summer months. A student may carry a full load of graduate study and research in addition to any assigned assistantship duties. The Institute gives consideration for admission and financial assistance to all qualified applicants regardless of race, religion, or sex.

APPLICATIONS Further information and an application form may be obtained by writing

Professor L. G. Leal
Chemical Engineering
California Institute of Technology
Pasadena, California 91125

It is advisable to submit applications before February 15, 1983.

FACULTY IN CHEMICAL ENGINEERING

JAMES E. BAILEY, Professor
Ph.D. (1969), Rice University
Biochemical engineering; chemical reaction engineering.

GEORGE R. GAVALAS, Professor
Ph.D. (1964), University of Minnesota
Applied kinetics and catalysis; process control and optimization; coal gasification.

ERIC HERBOLZHEIMER, Assistant Professor
Ph.D. (1979), Stanford University
Fluid mechanics and transport phenomena

L. GARY LEAL, Professor
Ph.D. (1969), Stanford University
Theoretical and experimental fluid mechanics; heat and mass transfer; suspension rheology; mechanics of non-Newtonian fluids.

C. DWIGHT PRATER, Visiting Associate
Ph.D. (1951), University of Pennsylvania
Catalysis; chemical reaction engineering; process design and development.

JOHN H. SEINFELD, Louis E. Nohl Professor, Executive Officer
Ph.D. (1967), Princeton University
Air pollution; control and estimation theory.

FRED H. SHAIR, Professor
Ph.D. (1963), University of California, Berkeley
Plasma chemistry and physics; tracer studies of various environmental and safety related problems.

GREGORY N. STEPHANOPoulos, Assistant Professor
Ph.D. (1978), University of Minnesota
Biochemical engineering; chemical reaction engineering.

NICHOLAS W. TSCHOEGI, Professor
Ph.D. (1958), University of New South Wales
Mechanical properties of polymeric materials; theory of viscoelastic behavior; structure-property relations in polymers.

W. HENRY WEINBERG, Chevron Professor
Ph.D. (1970), University of California, Berkeley
Surface chemistry and catalysis.
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PITTSBURGH, PENNSYLVANIA 15213
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Chemical Engineering Department
Case Western Reserve University
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FACULTY
Stanley Cosgrove
Robert Delcamp
Joel Fried
Rakesh Govind
David Greenberg
Daniel Hershey
Sun-Tak Hwang
Yuen-Koh Kao
Soon-Jai Khang
Robert Lemlich
William Licht
Joel Weisman

CHEMICAL REACTION ENGINEERING AND HETEROGENEOUS CATALYSIS
Modeling and design of chemical reactors. Deactivating catalysts. Flow pattern and mixing in chemical equipment. Laser induced effects.

PROCESS SYNTHESIS

POLYMERS
Viscoelastic properties of concentrated polymer solutions. Thermodynamics, thermal analysis and morphology of polymer blends.

AIR POLLUTION
Modeling and design of gas cleaning devices and systems.

TWO-PHASE FLOW
Boiling. Stability and transport properties of foam.

THERMODYNAMIC ANALYSIS OF LIVING HUMAN AND CORPORATE SYSTEMS
Longevity, basal metabolic rate, and Prigogine's and Shannon's entropy formulae.

FOR ADMISSION INFORMATION
Chairman, Graduate Studies Committee
Chemical & Nuclear Engineering, 171
University of Cincinnati
Cincinnati, OH 45221
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Faculty
S. V. Babu                    D. H. Rasmussen
Der-Tau Chin                 Herman L. Shulman
Robert Cole                  R. Shankar Subramanian
Sandra Harris                Peter C. Sukanek
Angelo Lucia                  Ross Taylor
Richard J. McCluskey         Thomas J. Ward
John B. McLaughlin           Ralph H. Weiland
Richard J. Nunge             William R. Wilcox
Nsima Tom Obot               Gordon R. Youngquist

Research Projects are available in:
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- Heat Transfer
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- Particle Separations
- Phase Transformations and Equilibria
- Reaction Engineering
- Optimization and Control
- Crystallization
- And More . . .

Financial aid in the form of fellowships, research assistantships and teaching assistantships is available. For more details, please write to:
Dean of the Graduate School
Clarkson College of Technology
Potsdam, New York 13676
THE FACULTY AND THEIR RESEARCH

P. F. Dickson, Professor and Head; Ph.D., University of Minnesota. Oil-shale, shale oil processing, petrochemical production from shale oil, heat transfer, heat exchanger design.

J. H. Gary, Professor; Ph.D., University of Florida. Upgrading of shale oil and coal liquids, petroleum refinery processing operations, heavy oil processing.


R. M. Baldwin, Associate Professor, Ph.D., Colorado School of Mines. Coal liquefaction by direct hydrogenation, mechanisms of coal liquefaction, kinetics of coal hydrogenation, relation of coal geochemistry to liquefaction kinetics, upgrading of coal-derived asphaltenes.

M. S. Graboski, Associate Professor; Ph.D., Pennsylvania State University. Coal and biomass gasification processes, gasification kinetics, thermal conductivity of coal liquids, kinetics of SNG upgrading.

M. C. Jones, Associate Professor; Ph.D., University of California at Berkeley. Heat transfer and fluid mechanics in oil shale retorting, radiative heat transfer in porous media, free convection in porous media.

E. D. Sloan, Jr., Associate Professor; Ph.D., Clemson University. Phase equilibrium thermodynamics, phase equilibrium thermodynamics measurements of natural gas fluids and natural gas hydrates, thermal conductivity measurements for coal derived fluids, adsorption equilibria measurements, stage-wise processes, education methods research.

V. F. Yesavage, Professor; Ph.D., University of Michigan. Kinetic studies of shale oil, phase behavior and enthalpy of synthetic fuels.

A. L. Bunge, Assistant Professor; Ph.D., University of California at Berkeley. Enhanced oil recovery.

M. S. Selim, Associate Professor; Ph.D., Iowa State University. Flow of concentrated fine particulate suspensions in complex geometries; Sedimentation of multizized, mixed density particle suspensions.

For Applications and Further Information On M.S., and Ph.D. Programs, Write Chemical and Petroleum Refining Engineering Colorado School of Mines Golden, CO 80401

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- reactor design
- molecular thermodynamics/statistical mechanics

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- mechanical engineering
- business administration
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Graduate programs lead to the degrees of Doctor of Philosophy, Master of Science, and Master of Engineering (the M.Eng. is a professional, design-oriented program). Financial aid, including attractive fellowships, is available.

The faculty members are:

FOR FURTHER INFORMATION: Write to
Professor Keith E. Gubbins
Cornell University
Olin Hall of Chemical Engineering
Ithaca, New York 14853
The University of Delaware awards three graduate degrees for studies and practice in the art and science of chemical engineering.

An M.Ch.E. degree based upon course work and a thesis problem.
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THE REGULAR FACULTY ARE:

Gianni Astarita (½ time)
M. A. Barteau
C. E. Birchennall
K. B. Bischoff
C. D. Denson
P. Dhorjati
B. C. Gates
M. T. Klein
R. L. McCullough
A. B. Metzner
J. H. Olson
M. E. Paulaitis
R. L. Pigford
T. W. F. Russell
S. I. Sandler (Chairman)
G. C. A. Schuit (½ time)
J. M. Schultz
A. R. Stiles (½ time)
M. A. Streicher (½ time)
R. S. Weber

CURRENT AREAS OF RESEARCH INCLUDE:

Thermodynamics and Separation Process
Rheology, Polymer Science and Engineering
Materials Science and Metallurgy
Fluid Mechanics, Heat and Mass Transfer
Economics and Management in the Chemical Process Industries
Chemical Reaction Engineering, Kinetics and Simulation
Catalytic Science and Technology
Biomedical Engineering—Pharmacokinetics and Toxicology
Biochemical Engineering—Fermentation and Computer Control

FOR MORE INFORMATION AND ADMISSIONS MATERIALS, WRITE:
Graduate Advisor
Department of Chemical Engineering
University of Delaware
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Ph.D., University of Wisconsin, 1980
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Catalytic Hydrocracking of
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<td>Boiling Heat Transfer, Two-Phase Flow</td>
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<td>G. M. Brown</td>
<td>Thermodynamics, Process Simulation</td>
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</tr>
<tr>
<td>R. S. H. Mah</td>
<td>Computer-Aided Process Planning, Design and Analysis</td>
</tr>
<tr>
<td>G. Ryskin</td>
<td>Fluid Mechanics</td>
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<tr>
<td>W. Sachtler</td>
<td>Heterogeneous Catalysis</td>
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<tr>
<td>J. C. Slattery</td>
<td>Transport and Interfacial Phenomena</td>
</tr>
<tr>
<td>W. F. Stevens</td>
<td>Process Optimization and Control, Computer Applications</td>
</tr>
<tr>
<td>G. Thodos</td>
<td>Properties of Fluids, Coal Processing, Solar Energy</td>
</tr>
</tbody>
</table>

For information and application materials, write

Professor J. C. Slattery, Chairman
Department of Chemical Engineering
Northwestern University
Evanston, IL 60201
The Ohio State University
Chemical Engineering

THE OHIO STATE UNIVERSITY has offered graduate degrees in Chemical Engineering since just after the turn of the century and has a proud tradition of distinguished alumni in industry, government and academic positions.

The requirements for both the M.S. and the Ph.D. degree include a core of basic chemical engineering courses and other courses appropriate to the student's research and professional goals. Because research is such a vital part of graduate education, close relationships between research advisors and students are fostered. The Department has fourteen faculty members and the range of research topics and/or course option areas cover a wide cross section of chemical engineering theory and practice:

- Biochemical Engineering
- Coal Conversion and Treatment
- Digital Process Control
- Fluidized Bed
- Heat Transfer
- Mass Transfer
- Polymer Processing
- Process Simulation
- Separation Processes
- Turbulence
- Bioengineering
- Combustion of Materials
- Environmental
- Fluid Mechanics
- Kinetics
- Petroleum Reservoir
- Process Design
- Rheology
- Thermodynamics

The Chemical Engineering Building has more than 80,000 square feet and includes 45 research and teaching laboratories and classrooms. The Department has a DEC VAX 11/780 computer for data acquisition, computation, and process control services. More than fifteen interactive graphics terminals are available for research and teaching. Many kinds of specialized research equipment are available along with a University computer and an extensive library with fine search capabilities.

COLUMBUS is a center for technical activity with Battelle Memorial Institute and Chemical Abstracts adjacent to the campus and many corporate research centers and technically-based industries nearby. Cultural offerings in music, art and drama are also widely available in Columbus. For those interested in recreational activities, the University offers opportunities for virtually every sport from archery to water skiing.

For further information, write to Prof. Jacques L. Zakin, Dept. of Chemical Engineering, 140 W. 19th Street, The Ohio State University, Columbus, Ohio 43210.
M.S. in Chemical Engineering
for chemical engineering and
non-chemical engineering students

Dr. John R. Collier
Chemical Engineering Department
OHIO UNIVERSITY
Athens, Ohio 45701

DRAWING BY DR. JAMES E. THRONE, AMOCO RESEARCH, NAPERVILLE, ILL.
THE UNIVERSITY OF OKLAHOMA

- Catalysis
- Corrosion
- Membrane Separations
- Design
- Polymers
- Metallurgy
- Thermodynamics
- Rate Processes
- Enzyme Technology
- Biomass Conversion
- Statistical Mechanics

WRITE TO:

THE SCHOOL OF CHEMICAL ENGINEERING
AND MATERIALS SCIENCE

THE UNIVERSITY OF OKLAHOMA
ENGINEERING CENTER
202 W. BOYD ROOM 23
NORMAN, OKLAHOMA 73019
OKLAHOMA STATE UNIVERSITY

... School of Chemical Engineering welcomes you

for further information write to:
Billy L. Crynes, Head
School of Chemical Engineering
Oklahoma State University
Stillwater, Oklahoma 74078

The Oklahoma State University Chemical Engineering faculty:

Dr. B. L. Crynes
Dr. Kenneth J. Bell
Dr. R. Robinson, Jr.
Dr. Mayis Seapan
Dr. Gary L. Foutch

Dr. Robert Maddox
Dr. John H. Erbar
Dr. Jan Wagner
Dr. Arch G. Hill
Dr. Robert A. Wills

Dr. Robert H. Heidersbach
Pennsylvania's chemical engineering program is designed to be flexible while emphasizing the fundamental nature of chemical and physical processes. Students may focus their studies in any of the research areas of the department. The full resources of this Ivy League university, including the Wharton School of Business and one of this country's foremost medical centers, are available to students in the program.

For additional information, write:

Director of Graduate Admissions
Department of Chemical Engineering
School of Engineering and Applied Science
311A Towne Building/D3
University of Pennsylvania
Philadelphia, Pennsylvania 19104
LOOKING FOR A GRADUATE EDUCATION IN CHEMICAL ENGINEERING?
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R. NAGARAJAN (SUNY Buffalo)
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JONATHAN PHILLIPS (Wisconsin)
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JAMES S. ULMAN (Delaware)
M. ALBERT VANNICE (Stanford)
JAMES S. VRENTAS (Delaware)
DANIEL WHITE (Florida)

Financial aid is available to qualified applicants in the form of graduate teaching and research assistantships and fellowships.
For application forms and further information, write to:

Dr. Lee C. Eagleton, Head
Department of Chemical Engineering
158 Fenske Laboratory
Pennsylvania State University
University Park, PA 16802

Individually holding the B.S. in Chemistry or other related areas are encouraged to apply.

BIOMEDICAL ENGINEERING
Physiological Transport Processes
Newborn Monitoring

ENVIRONMENTAL RESEARCH
Gaseous and Particulate Control
Atmospheric Modeling

UNSTEADY STATE OPERATIONS
Cyclic Distillation
Cyclic Reactor Operations

HETEROGENEOUS CATALYSIS
Metal-Support Interactions
Adsorption and Desorption Processes
Catalyst Characterization
Sulfur Poisoning Studies

TRANSPORT PHENOMENA
Analytical and Numerical Solutions
Polymer Rheology and Transport
Convective Heating and Mass Transfer
Mass Transfer in Co-current Flow

PROPERTY PREDICTION
Thermodynamic, Physical, and Transport

APPLIED MATHEMATICS
Stability and Bifurcation Theory
Perturbation Theory

APPLIED CHEMISTRY AND KINETICS
Industrial Chemical Processes
Complex Reaction Systems

PETROLEUM REFINING
Process Development
Product Conversion

TRIBOLOGY
Properties of Liquid Lubricants
Boundary Lubrication Fundamentals

INTERFACIAL PHENOMENA
Adsorption Thermodynamics and Kinetics
Monolayer and Membrane Processes
Applications of Surfactants

ENERGY RESEARCH
Tertiary Oil Recovery
Nuclear Technology
Coal Conversion Processes
HOW WOULD YOU LIKE TO DO YOUR GRADUATE WORK IN THE CULTURAL CENTER OF THE WORLD?

CHEMICAL ENGINEERING POLYMER SCIENCE & ENGINEERING

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C. D. Han
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J. S. Mijovic
E. M. Pearce
E. Sadle
P. F. Schubert
L. I. Stiel
E. N. Ziegler

RESEARCH AREAS
Biochemical Engineering
Catalysis, Kinetics and Reactors
Computer Aided Process Design
Energy Conversion
Engineering Properties of Polymers
Fluidization
Fluid Mechanics
Heat and Mass Transfer
Polymer Processing
Polymer Morphology
Polymer Synthesis and Modification
Polymerization Reaction Engineering
Rheology
Separation Sciences
Thermodynamic Properties of Fluids

Polytechnic Institute of New York
Formed by the merger of Polytechnic Institute of Brooklyn and New York University School of Engineering and Science.

Department of Chemical Engineering
Programs leading to Master's and Doctor's degrees. Areas of study and research: chemical engineering, polymer science and engineering.

Fellowships and Research Assistantships are available.

For further information contact
Professor R. F. Benenati
Acting Head, Department of Chemical Engineering
Polytechnic Institute of New York
333 Jay Street
Brooklyn, New York 11201
University of Queensland

POSTGRADUATE STUDY
IN
CHEMICAL ENGINEERING

- Scholarships Available -

STAFF

L. S. LEUNG (Cambridge)
P. R. BELL (N.S.W.)
P. C. BROOKS (M.I.T.)
D. D. DO (Queensland)
P. F. GREENFIELD (N.S.W.)
G. J. KELLY (Tasmania)
R. B. NEWELL (Alberta)
D. J. NICKLIN (Cambridge)
E. T. WHITE (Imperial College)
R. J. WILES (Queensland)

RESEARCH AREAS

Two Phase Flow • Fluidization • Systems Analysis • Computer Control • Applied Mathematics • Transport Phenomena •
Crystallization • Rheology • Chemical Reactor Analysis • Energy Resource Studies •
Oil Shale Processing • Water and Wastewater Treatment • Electrochemistry •
Corrosion • Fermentation • Enzyme Engineering • Environmental Control • Process Economics •

THE DEPARTMENT

The Department occupies its own building, is well supported by research grants, and maintains an extensive range of research equipment. It has an active postgraduate programme, which involves course work and research work leading to M.Eng. Studies, M.Eng.Science and Ph.D.degrees.

THE UNIVERSITY AND THE CITY

The University is one of the largest in Australia with more than 18,000 students. Brisbane, with a population of about one million, enjoys a pleasant climate and attractive coasts which extend northward into the Great Barrier Reef.

For further information write to: Co-ordinator of Graduate Studies, Department of Chemical Engineering, University of Queensland, Brisbane, Qld. 4067 AUSTRALIA.

254 CHEMICAL ENGINEERING EDUCATION
Department Faculty and Areas of Research

Michael M. Abbott Ph.D. (Rensselaer)—classical thermodynamics; vapor/liquid equilibria; analytic equations of state; expressions for excess thermodynamic functions.

Elmar R. Aitwicker Ph.D. (Ohio State)—air pollution control; atmospheric chemistry; combustion additives; mass transfer with chemical reactions.

Yaman Arkun Ph.D. (Minnesota)—process design, dynamics, and control; control strategies for highly integrated chemical plants.

Donald B. Aulenbach P.E., Ph.D. (Rutgers)—heavy metals removal; chemical interactions in fresh-water lakes and streams; disposal of radioactive wastes.

Georges Belfort Ph.D. (California-Irvine)—separations engineering (membrane processes and adsorption); biochemical concentration and reactors; particle dynamics; adsorption thermodynamics.

Henry R. Bungay III P.E., Ph.D. (Syracuse)—oxygen transfer in various microbial systems; high flow rate continuous cultures; biomass refining.

Chan I. Chung Ph.D. (Rutgers)—engineering aspects of polymer processing; physics of the structure-property relationships of polymer melts.

Nicholas L. Clesceri Ph.D. (Wisconsin)—intermedia transport research; acid precipitation; toxic heavy metals removal; water supply taste/odor problems; lake eutrophication.

Dady B. Dadyburjor Ph.D. (Delaware)—heterogeneous catalysis: deactivation, regeneration, and effects of catalyst microstructure; aggregation of surface active agents.

Arthur Fontijn D.Sc. (Amsterdam)—kinetic measurements on high temperature reactions for combustion applications; air pollutant luminescence monitoring methods development.

Cynthia S. Hirtzel Ph.D. (Northwestern)—probabilistic and statistical analysis of extreme value phenomena; stochastic analysis of random processes in engineering science.

Arland H. Johannes Ph.D. (Kentucky)—acid precipitation; wet and dry deposition; atmospheric chemistry; surface studies of coal mineral matter.

Clement Kleinstreuer Ph.D. (Vanderbilt)—non-isothermal fluid-particle systems; higher-order boundary layer theory; membrane separation systems, biochemical reactor design.

Peter K. Lashmet P.E. Ph.D. (Delaware)—process engineering; application of several numerical techniques such as probabilistics and collocation to improve design procedures.

Howard Littman Ph.D. (Yale)—Fluid-particle systems with emphasis on the mechanics of spouted beds.

Charles Muckenfuss Ph.D. (Wisconsin)—theoretical studies of transport phenomena; applications of kinetic theory and irreversible thermodynamics to multicomponent reacting systems.

E. Bruce Nauman Ph.D. (Leeds)—polymer reaction engineering; study of motionless mixers in tubular polymerizers; residence time theory—extensions to nonisothermal nonhomogeneous reactors.

Michael H. Peters Ph.D. (Ohio State)—aerosol dynamics; theoretical and experimental investigations on fluidization and fluid-particle systems.

Raj Rajagopalan Ph.D. (Syracuse)—colloidal and interfacial phenomena; statistical physics and thermodynamics of macromolecular systems; transport phenomena.

William W. Shuster P.E., D.Ch.E. (Rensselaer)—treatment and disposal of hazardous wastes; evaporation of toxic organics; methane production from anaerobic decomposition.

Sanford S. Sternstein Ph.D. (Rensselaer)—engineering and mechanical properties of polymers and polymeric materials; inhomogeneous swelling theory; high performance composites.

Hendrick C. VanNess Ph.D., D.Eng. (Yale)—solution thermodynamics of ternary mixtures; development of efficient data reduction procedures and appropriate correlating expressions.


Financial Support:

Full time graduate students are eligible for financial support including tuition remission and tax-free fellowships.

Applications and Information:

For full details, write:
Dr. PK. Lashmet, Executive Officer Department of Chemical Engineering and Environmental Engineering, Rensselaer Polytechnic Institute, Troy, New York 12181
Graduate Study in Chemical Engineering at Rice University

Graduate study in Chemical Engineering at Rice University is offered to qualified students with suitable backgrounds in the fundamental principles of Chemical Engineering, Chemistry, Mathematics, and Physics. The curriculum is aimed at strengthening the student's understanding of these principles and provides a basis for developing in certain areas the necessary proficiency for conducting independent research. Research programs are pursued in various areas of Chemical Engineering and related fields, such as Biomedical Engineering and Polymer Science. A joint program with the Baylor College of Medicine, leading to M.D.-Ph.D. and M.D.-M.S. degrees is also available.

The Department has approximately 60 graduate students, predominantly Ph.D. candidates. There are also several post-doctoral fellows and research engineers associated with the various laboratories. Permanent faculty numbers 12, all active in undergraduate and graduate teaching, as well as in research. The high faculty-to-student ratio, outstanding laboratory facilities, and stimulating research projects provide a graduate education environment in keeping with Rice's reputation for academic excellence. The Department is one of the leading Chemical Engineering Departments in the U.S., ranked by graduate faculty quality and program effectiveness, according to recent evaluations.

MAJOR RESEARCH AREAS
Thermodynamics and Phase Equilibria
Chemical Kinetics and Catalysis
Chromatography
Optimization, Stability, and Process Control
Biochemical Reaction Engineering
Rheology and Fluid Mechanics
Polymer Science
Chemical Reactor Modeling
Coal Liquefaction
Tertiary Oil Recovery
Interfacial Phenomena

BIOMEDICAL ENGINEERING
Blood Flow and Blood Trauma
Biorheology
Biomaterials

Rice University
Rice is a privately endowed, nonsectarian, coeducational university. It occupies an architecturally attractive, tree-shaded campus of 300 acres, located in a fine residential area, 3 miles from the center of Houston. There are approximately 2600 undergraduate and 1000 graduate students. The school offers the benefits of a complete university with programs in the various fields of science and the humanities, as well as in engineering. It has an excellent library with extensive holdings. The academic year is from August to May. As there are no summer classes, graduate students have nearly four months for research. The school offers excellent recreational and athletic facilities with a completely equipped gymnasium, and the southern climate makes outdoor sports, such as tennis, golf, and sailing year-round activities.

FINANCIAL SUPPORT
Full-time graduate students receive financial support with tuition remission and a tax-free fellowship of $650-800 per month. A few special fellowships with higher stipends are given to particularly outstanding students.

APPLICATIONS AND INFORMATION
Address letters of inquiry to:
Chairman, Graduate Committee
Department of Chemical Engineering
Rice University
Houston, Texas 77251

Houston
With a population of nearly two million, Houston is the largest metropolitan, financial, and commercial center in the South and Southwest. It has achieved world-wide recognition through its vast and growing petrochemical complex, the pioneering medical and surgical activities at the Texas Medical Center, and the NASA Manned Spacecraft Center. Houston is a cosmopolitan city with many cultural and recreational attractions. It has a well-known resident symphony orchestra, an opera, and a ballet company, which perform regularly in the newly constructed Jesse H. Jones Hall. Just east of the Rice campus is Hermann Park with its free zoo, golf course, Planetarium, and Museum of Natural Science. The air-conditioned Astrodome is the home of the Houston Astros and Oilers and the site of many other events.
RUTGERS  THE STATE UNIVERSITY  OF NEW JERSEY

M.S. and Ph.D. PROGRAMS  IN THE DEPARTMENT OF  CHEMICAL  AND  BIOCHEMICAL  ENGINEERING

AREAS OF TEACHING AND RESEARCH

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BIOCHEMICAL ENGINEERING FUNDAMENTALS
- MICROBIAL REACTIONS AND PRODUCTS  •  SOLUBLE AND IMMOBILIZED ENZYMES  •  BIOMATERIALS  •  ENZYME AND FERMENTATION REACTORS

ENGINEERING APPLICATIONS
- BIOCHEMICAL TECHNOLOGY  •  INDUSTRIAL FERMENTATIONS  •  FUELS FROM BIOMASS  •  CONTROL OF FERMENTATION  •  FOOD PROCESSING
- CHEMICAL TECHNOLOGY  •  COAL DESULFURIZATION  •  ELECTROCHEMICAL ENGINEERING  •  POLYMER PROCESSING  •  PLANT DESIGN AND ECONOMICS
- WATER RESOURCES ANALYSES  •  OCEANS AND ESTUARIES  •  QUALITY MANAGEMENT  •  WASTES RECOVERY

FELLOWSHIPS AND ASSISTANTSHIPS ARE AVAILABLE

For Application Forms and Further Information Write To:
Graduate Admissions Office
Van Nest Hall
Rutgers, The State University
New Brunswick, N.J. 08903

FALL 1982
The College of Engineering offers M.S., M.E. and Ph.D. degrees in Chemical Engineering. Graduate students have the opportunity to work closely with the faculty on research projects. Research and teaching stipends are available.

The University of South Carolina, with an enrollment of 23,800 on the Columbia campus, offers a variety of cultural and recreational activities. Columbia is part of one of the fastest growing areas in the country.

The Chemical Engineering Faculty

B.L. Baker, Distinguished Professor Emeritus, Ph.D., North Carolina State University, 1955 (Process design, environment problems, ion transport).

M.W. Davis, Jr., Weisiger Chair Professor, Ph.D., University of California (Berkeley), 1951 (Kinetics and catalysis, chemical process analysis, solvent extraction, waste treatment).

F.A. Gadala-Maria, Assistant Professor, Ph.D., Stanford University, 1979 (Fluid mechanics, rheology).

J.H. Gibbons, Professor, Ph.D., University of Pittsburgh, 1961 (Heat transfer, fluid mechanics).


T.G. Stanford, Assistant Professor, Ph.D., The University of Michigan, 1977 (Chemical reactor engineering, mathematical modeling of chemical systems, process design, thermodynamics).

V. Van Brunt, Associate Professor, Ph.D., University of Tennessee, 1974 (Mass transfer, computer modeling, fluidization).

For further information contact:
Prof. J.H. Gibbons
Chairman, Chemical Engineering
College of Engineering
University of South Carolina
Columbia, South Carolina 29208
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Graduate Programs in Chemical Engineering
Leading to the Degrees of
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Process Simulation and Control
Separation Processes

FACULTY
J. A. Biesenberger (Ph.D., Princeton)
G. B. Delancey (Ph.D., Pittsburgh)
C. G. Gogos (Ph.D., Princeton)
S. Kovenklioglu (Ph.D., Stevens)
P. Hold (D.Eng., Vienna)
D. H. Sebastian (Ph.D., Stevens)
H. Silla (Ph.D., Stevens)
K. K. Sirkar (Ph.D., Illinois)
A. P. Zioudas (Ph.D., Illinois)

For additional information, contact:
Department of Chemistry and Chemical Engineering
Stevens Institute of Technology
Hoboken, N.J. 07030
(201) 420-5546

For application, contact:
Office of Graduate Studies
Stevens Institute of Technology
Hoboken, N.J. 07030
(201) 420-5234

Financial aid available to qualified students.

Overlooking the Hudson River and midtown Manhattan, the 55-acre Stevens campus encompasses more than 30 buildings, including classroom and research facilities. The location of the campus is unique, just 15 minutes from the heart of New York and within a 50-mile radius of the country's largest research laboratories and chemical, petroleum and pharmaceutical companies.

Stevens Institute of Technology does not discriminate against any person because of race, creed, color, national origin, sex, age, marital status, handicap, liability for service in the armed forces or status as a disabled or Vietnam era veteran.
**THE UNIVERSITY OF TENNESSEE, KNOXVILLE**

Graduate Studies in
Chemical, Metallurgical, and Polymer Engineering

<table>
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<tr>
<th>Programs</th>
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<tr>
<td>Programs for the degrees of Master of Science and Doctor of Philosophy are offered in chemical engineering, metallurgical engineering and polymer engineering. The Master’s program may be tailored as a terminal one with emphasis on professional development, or it may serve as preparation for more advanced work leading to the Doctorate.</td>
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<tr>
<th>Faculty</th>
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<tr>
<td>William T. Becker</td>
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<tr>
<td>Donald C. Bogue</td>
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<td>Charlie R. Brooks</td>
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<td>Duane D. Bruns</td>
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<td>Edward S. Clark</td>
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<td>Robert M. Counce</td>
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<td>John F. Fellers</td>
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<td>George C. Frazier</td>
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<tr>
<td>John M. Holmes</td>
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<tr>
<td>Hsien-Wen Hsu</td>
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<tr>
<td>Homer F. Johnson, Department Head</td>
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<tr>
<td>Carl D. Lundin</td>
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<tr>
<td>Charles F. Moore</td>
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<tr>
<td>Ben F. Oliver</td>
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<tr>
<td>Joseph J. Perona, Associate Department Head for Chemical Engineering</td>
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<tr>
<td>Joseph E. Spruill, Associate Department Head for Materials Engineering</td>
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<tr>
<td>E. Eugene Stansbury</td>
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<td>Carl O. Thomas</td>
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<tr>
<td>Roy A. Vandermeer</td>
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<tr>
<td>Fred Weber</td>
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<tr>
<td>James L. White, Professor-in-Charge of Polymer Engineering</td>
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<th>Research</th>
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<td>Process Dynamics and Control</td>
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<td>Coal Processing</td>
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<td>Chromatographic and Ultracentrifuge</td>
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<td>Studies of Macromolecules</td>
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<td>Development and Synthesis of New Engineering Polymers</td>
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<td>Fiber and Plastics Processing</td>
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<td>Chemical Bioengineering</td>
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<tr>
<td>X-Ray Diffraction, Transmission and Scanning Electron Microscopy</td>
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<tr>
<td>Solidification, Zone Refining</td>
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<td>Welding</td>
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<tr>
<td>Cryogenic and High Temperature Calorimetry</td>
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<tr>
<td>Flow and Fracture in Metallic and Polymetric Systems</td>
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<tr>
<td>Corrosion</td>
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<td>Solid State Kinetics</td>
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</table>

**Financial Assistance**
Sources available include graduate teaching assistantships, research assistantships, and industrial fellowships.

**Send Inquiry**
with listing of degree(s), date(s), and grade point average(s) to
Department of Chemical, Metallurgical, and Polymer Engineering
The University of Tennessee
Knoxville, Tennessee 37996-2200
CHEMICAL ENGINEERING FACULTY

J. W. BARLOW (University of Wisconsin)
J. R. BROCK (University of Wisconsin)
T. F. EDGAR (Princeton University)
J. G. EKERDT (University of California)
J. R. FAIR (University of Texas)
D. M. HIMME (University of Washington)
K. P. JOHNSTON (University of Illinois)
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E. H. WISSLER (University of Minnesota)

RESEARCH INTERESTS

Aerosol Physics & Chemistry
Air Pollution Science
Artificial Internal Organs
Aqueous Mass Transfer
Biomass Liquefaction
Biomedical Engineering
Catalysis
Chemical Engineering Education
Coal Beneficiation
Coal Desulfurization
Coal Gasification & Combustion
Computer Applications
Computer-Based Education
Colloid Science
Crystal Structure & Properties
Energy Applications
Enhanced Oil Recovery
Heat Transfer
Material Science
Membrane Science
Multi-phase Systems
Optimization
Polymer Applications
Polymer Processing
Polymer Properties
Polymer Thermodynamics
Process Control
Process Design & Development
Process Simulation
Reaction Kinetics & Mechanisms
Separation Processes
Stack Gas Desulfurization
Surface Science
Thermodynamics
Transition Metal Studies

Inquiries should be sent to
Graduate Advisor
Department of Chemical Engineering
The University of Texas
Austin, TX 78712

FALL 1982
TEXAS A&M UNIVERSITY

Texas A&M is a land-grant and sea-grant university, and the oldest public institution of higher learning in Texas. The current enrollment is about 35,000. The university location is Bryan/College Station, Texas—twin cities with a combined population of 122,000 (including students). The surrounding country is deciduous forest—Houston is 95 miles Southeast and Dallas is 160 miles North.

CHEMICAL ENGINEERING DEPARTMENT

The ChE department has an enrollment of about 1000 undergraduates and 70 graduates. ChE has excellent facilities in the Zachry Engineering Center. All graduate students have desk space. Graduate stipends are currently $1050/month for teaching assistantships and $870/month for research assistants.

FACULTY AND RESEARCH INTERESTS

C. D. Holland (department head)—distillation
A. Akgerman—kinetics
R. G. Anthony—catalysis
D. B. Bukur—simulation
J. A. Bullin—gas sweetening, air pollution
R. Darby—rheology
R. R. Davison—solar energy
L. D. Durbin—process control
P. T. Eubank—thermodynamics
T. W. Fogwell—applied mathematics
A. M. Gadalla—catalysts
C. J. Glover—polymer solutions
K. R. Hall—thermodynamics
D. T. S. Hanson—biochemical
W. B. Harris—methanol fuel
J. C. Holste—thermodynamics
G. B. Tatterson—turbulence and mixing
A. T. Watson—porous media
R. E. White—electrochemical applications

Admission to The Texas A&M University System and any of its sponsored programs is open to qualified individuals regardless of race, color, age, religion, sex, national origin or educationally unrelated handicaps.

FOR INFORMATION CONTACT:

Graduate Advisor
Chemical Engineering Dept.
Texas A&M University
College Station, TX 77843
713/845-3361
Chemical Engineering
at Virginia Polytechnic Institute and State University . . .
applying chemistry to the needs of man.

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Renewable Resources
chemical and microbiological processing, chemicals from renewable resources

Coal Science and Process Chemistry
chemistry of prompt intermediates, reaction paths in coal liquefaction, fate of trace elements

Coal Combustion Workshop
small-scale systems, fate of trace elements, environmental controls, fluidized beds

Microcomputers, Digital Electronics, and Control
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Graduate applicants should write:

Graduate Coordinator, Chemical and Petroleum Engineering
School of Engineering
University of Pittsburgh
Pittsburgh, PA 15261

Princeton University
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FACULTY


WRITE TO

Director of Graduate Studies
Chemical Engineering
Princeton University
Princeton, New Jersey 08544
Graduate Studies in Chemical Engineering
MSc and PhD Degree Programs

- Resource Recovery
  solid-waste treatment
  biotechnology
  biochemical engineering

- Chemical Reaction Engineering
  catalysis
  statistical design
  polymerization

- Transport Processes
  combustion
  turbulence and mixing
  drying
  rheology

- Fuels and Energy
  coal conversion
  fluidized-bed combustion
  wood gasification
  alcohol production

Write:
Dr. Henry A. Becker
Department of Chemical Engineering
Queen's University
Kingston, Ontario
Canada K7L 3N6

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M.S. and Ph.D. Degrees

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Food Engineering  Separation Processes
Materials Engineering  Energy Engineering
Phase Change Kinetics  Heat Transfer

APPLICATIONS
APPLY TO: Chairman, Graduate Committee
Department of Chemical Engineering
University of Rhode Island
Kingston, RI 02881

Applications for financial aid should be received not later than Feb. 16
UNIVERSITY OF ROCHESTER
ROCHESTER, NEW YORK 14627
MS & PhD Programs

The Faculty
S. H. Chen, Ph.D., 1981, Minnesota
E. H. Chimowitz, Ph.D., 1982, Connecticut
G. R. Cokelet, Sc. D., 1963, MIT
R. F. Eisenberg, M.S., 1948, Rochester
M. R. Feinberg, Ph.D., 1968, Princeton
J. R. Ferron, Ph.D., 1958, Wisconsin
J. C. Friedly, Ph.D., 1965, California (Berkeley)
R. H. Heist, Ph.D., 1972, Purdue
J. Jorne, Ph.D., 1972, California (Berkeley)
R. H. Notter, Ph.D., 1969, Washington (Seattle)
M.D., 1980, Rochester
H. J. Palmer, Ph.D., 1971, Washington (Seattle)
H. Saltsburg, Ph.D., 1955, Boston
S. V. Sotirchos, Ph.D., 1982, Houston
G. J. Su, Sc. D., 1937, MIT

Mass Transfer, Interfacial Phenomena
Computer-Aided Design
Blood & Suspension Rheology, Biotechnology
Corrosion, Physical Metallurgy
Complex Reaction Systems, Continuum Mechanics
Molecular Transport Processes, Applied Mathematics
Process Dynamics, Control, Heat Transfer
Nucleation, Solid State, Atmospheric Chemistry
Electrochemistry
Interfacial Phenomena, Bioengineering
Interfacial Phenomena, Mass Transfer
Surface Phenomena, Catalysis, Molecular Scattering
Reaction Engineering, Combustion and Gasification
Colloidal & Amphorous States, Glass Science

For information write: J. C. Friedly, Chairman

ROSE-HULMAN
INSTITUTE OF TECHNOLOGY

RESEARCH AREAS
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• Energy Resources and Conversion
• Process Control
• Polymers
• Thermodynamics
• Transport Phenomena
• Biochemical Processing
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FACULTY
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T. R. Hanley, Ph.D., VPISU
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P. F. Hogan, Ph.D., Rice
N. E. Moore, Ph.D., Purdue

For Information Write:
Dr. Thomas R. Hanley
Dept. Graduate Advisor
Rose-Hulman Institute of Technology
Terre Haute, IN 47803

DEPARTMENT OF CHEMICAL ENGINEERING
**FACULTY AND RESEARCH INTEREST**

<table>
<thead>
<tr>
<th>Name</th>
<th>Research Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>N. N. Bakhshi</td>
<td>Fischer-Tropsch synthesis, Reaction Engineering</td>
</tr>
<tr>
<td>W. J. Decoursey</td>
<td>Absorption with chemical reaction, Mass transfer</td>
</tr>
<tr>
<td>M. N. Esmail</td>
<td>Fluid mechanics, Applied Mathematics</td>
</tr>
<tr>
<td>G. Hill</td>
<td>Petroleum Recovery, Numerical Modelling</td>
</tr>
<tr>
<td>D. Macdonald</td>
<td>Biochemical Engineering</td>
</tr>
<tr>
<td>J. F. Mathews</td>
<td>Heterogeneous Catalysis, Conversion of Natural Resources</td>
</tr>
<tr>
<td>S. Rohani</td>
<td>Mixing with fast chemical reactions, Mathematical Modelling</td>
</tr>
<tr>
<td>J. Postlethwaite</td>
<td>Corrosion Engineering</td>
</tr>
<tr>
<td>C. A. Shook</td>
<td>Transport Phenomena, Slurry Pipelines</td>
</tr>
</tbody>
</table>

For Information, Write

M. N. Esmail, Head
Department of Chemical Engineering
University of Saskatchewan
Saskatoon, Saskatchewan, Canada S7N 0W0

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**UNIVERSITY OF SOUTHERN CALIFORNIA**
Los Angeles

Graduate Study in Chemical Engineering

**FACULTY**

<table>
<thead>
<tr>
<th>Name</th>
<th>Research Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>WENJI VICTOR CHANG</td>
<td>Rheological properties of polymers and composites, adhesion, polymer processing</td>
</tr>
<tr>
<td>JOE D. GODDARD</td>
<td>Rheology and mechanics of non-Newtonian fluids and composite materials, transport</td>
</tr>
<tr>
<td>LYMAN L. HANDY</td>
<td>Fluid flow through porous media and petroleum reservoir engineering</td>
</tr>
<tr>
<td>FRANK J. LOCKHART</td>
<td>Distillation, air pollution, design of chemical plants</td>
</tr>
<tr>
<td>CORNELIUS J. PINGS</td>
<td>Thermodynamics, statistical mechanics and liquid state physics</td>
</tr>
<tr>
<td>RONALD SALOVEY</td>
<td>Physical chemistry and irradiation of polymers, characterization of elastomers and polyurethanes</td>
</tr>
<tr>
<td>KATHERINE S. SHING</td>
<td>Thermodynamics and statistical mechanics; computer simulation and applied mathematics</td>
</tr>
<tr>
<td>THEODORE T. TSOTIS</td>
<td>Chemical reaction engineering, process dynamics and control</td>
</tr>
<tr>
<td>JAMES M. WHELAN</td>
<td>Thin Films III-V, heterogenous catalysis, sintering processes</td>
</tr>
<tr>
<td>YANIS C. YORTSOS</td>
<td>Mathematical modelling and transport processes, flow in porous media and thermal oil recovery methods</td>
</tr>
</tbody>
</table>

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Graduate Admissions
Department of Chemical Engineering
University of Southern California
University Park,
Los Angeles, CA 90089-1211

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FALL 1982
Chemical Engineering at Stanford

Stanford University offers programs of study and research leading to master of science and doctor of philosophy degrees in chemical engineering, with a number of financially attractive fellowships and assistantships available to outstanding students pursuing either program. For further information and application blanks, write to:

Admissions Chairman
Department of Chemical Engineering
Stanford University
Stanford, California 94305

Closing date for applications is January 15, 1983.

FACULTY:
Andreas Acrivos (Ph.D., 1954, Minnesota)
Fluid Mechanics
Michel Boudart (Ph.D., 1950, Princeton)
Kinetics and Catalysis
Curtis W. Frank (Ph.D., 1972, Illinois)
Polymer Science
Gerald G. Fuller (Ph.D., 1980, Cal Tech)
Microchemistry
George M. Homsy (Ph.D., 1969, Illinois)
Fluid Mechanics and Stability
Robert J. Madix (Ph.D., 1964, U. Cal-Berkeley)
Surface Reactivity
David M. Mason (Ph.D., 1949, Cal Tech)
Applied Thermodynamics and Chemical Kinetics
Channing R. Robertson (Ph.D., 1969, Stanford)
Bioengineering

LECTURERS AND CONSULTING FACULTY:
A. John Appleby, Electric Power Research Institute
Palo Alto, California
Electrochemistry
C. Richard Brundle, IBM Research Laboratory
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Surface Science
Robert M. Kendall, Acurex Corporation
Mountain View, California
Combustion
Robert H. Schwarcz, S.R.I. International
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Technological Development and Process Design
Manesh Shah, IBM Corporation
Menlo Park, California
Process Analysis and Control

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at Buffalo

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Chairman, Graduate Committee
Department of Chemical Engineering
State University of New York at Buffalo
Buffalo, New York 14260
CHEMICAL ENGINEERING
GRADUATE STUDY IN
SYRACUSE UNIVERSITY

RESEARCH AREAS
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Biomedical Engineering
Membrane Processes
Desalination
Liquid-Liquid Extraction

Catalysis
Polymer Characterization
Process Simulation
Fluid-Particle Separation

FACULTY
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John C. Heydweiller
Vasilios Karagounis
George C. Martin
Philip A. Rice
Ashok S. Sangani
James A. Schwarz
S. Alexander Stern
Lawrence L. Tavlarides
Chi Tien

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FOR THE ACADEMIC YEAR 1982-1983

For Information: Chairman
Department of Chemical Engineering and Materials Science
Syracuse University
Syracuse, New York 13210

Stipends: Stipends range from $6,000 to $7,800 with most students receiving at least $6,000 per annum in addition to remitted tuition privileges.

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Chemical Engineering
M.S. and M.E.

Natural Gas Engineering
M.S. and M.E.

FACULTY

F. Al-Saadoon
Petroleum and Natural Gas Engineering

J. B. Finley
Mass Transfer and Corrosion

W. A. Heenan
Process Control and Computer Applications

Obed Paracha
Petroleum and Natural Gas Engineering

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GRADUATE ADVISOR
Department of Chemical & Natural Gas Engineering

Texas A&I University
Kingsville, Texas 78363

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Department of Chemical Engineering
The University of Toledo
Toledo, Ohio 43606
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*If you would like to learn more about this and other burning questions in Chemical Engineering, contact*

Noel de Nevers
Director of Graduate Studies
Department of Chemical Engineering
University of Utah
Salt Lake City, Utah 84112
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- Transport processes and operations—heat and mass transfer, low Reynolds number and surface tension driven flow, mixing, fluidization, crystallization, fixed bed adsorption, polymer rheology.
- Chemical reactor analysis and engineering.
- Chemical process development, design, and economics.
- Chemical and energy technology—electrochemical processes, pollution control, catalysis, solar and alternative energy utilization.
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Graduate Coordinator
Department of Chemical Engineering
UNIVERSITY OF VIRGINIA
Charlottesville, Virginia 22901

WASHINGTON STATE UNIVERSITY

DEPARTMENT OF CHEMICAL ENGINEERING

RESEARCH INTERESTS:
- Air Pollution
- Biochemical Engineering
- Computer Applications
- Energy
- Nuclear Engineering
- Polymer Engineering
- Transport Phenomena

FOR INFORMATION CONTACT:
Graduate Student Advisor
Department of Chemical Engineering
Pullman, WA 99164
509-335-4332
GRADUATE STUDY in
CHEMICAL ENGINEERING

D. A. Crowl, PhD
H. G. Donnelly, PhD
E. R. Fisher, PhD
E. Gulari, PhD
J. Jorne, PhD
R. H. Kummler, PhD
C. B. Leffert, PhD
R. Marriott, PhD
J. H. McMicking, PhD
R. Mickelson, PhD
P. K. Rol, PhD
E. W. Rothe, PhD
S. Salley, PhD
S. K. Stynes, PhD

Combustion-process control
Thermodynamics-process design
Kinetics-molecular lasers
Transport-laser light scattering
Electrochemical engr.-fuel cells
Environmental engr.-kinetics
Energy conversion-heat transfer
Computer applications-nuclear engr.
Process dynamics-mass transfer
Polymer science-combustion processes
Molecular beams-vacuum science
Molecular beams-analysis of experiments
Biosystems modelling-kinetics
Multi-phase flows-environmental engr.

Contact: Dr. Ralph H. Kummler
Chairman, Department of Chemical Engineering
Wayne State University
Detroit, Michigan 48202

BREADTH and DEPTH
CHEMICAL ENGINEERING
UNIVERSITY OF WISCONSIN-MADISON

FOR FURTHER INFORMATION WRITE:

Graduate Committee
Chemical Engineering Department
University of Wisconsin-Madison
1415 Johnson Drive
Madison, Wisconsin 53706

FALL 1982
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CHEMICAL ENGINEERING DEPARTMENT

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- Biopolymers
- Catalytic properties of surfaces
- Chemical reactor modelling
- Coal and syngas technology
- Complex reaction kinetics
- Fermentation engineering and control
- Homogeneous catalysis
- Zeolite synthesis and catalysis

Faculty
- D. DiBiase (Purdue)
- A. G. Dixon (Edinburgh)
- W. L. Kranich (Cornell)
- Y. H. Ma (M.I.T.)
- J. W. Meader (M.I.T.)
- W. R. Moser (M.I.T.)
- J. E. Rollings (Purdue)
- A. Sacco (M.I.T.)
- L. B. Sand (Penn State)
- R. W. Thompson (Iowa State)
- R. E. Wagner (Princeton)
- A. H. Weiss (U. Penn.)

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Chemical Engineering Department
Worcester Polytechnic Institute
Worcester, Massachusetts 01609
(617) 793-5250

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For more information contact:
Dr. A. L. Hines
Dept. of Chemical Engineering
University of Wyoming
P.O. Box 3295
University Station
Laramie, Wyoming 82071

Admission, employment, and programs of the University of Wyoming are offered to all eligible people without regard to race, color, national origin, sex, religion, or political belief.
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- Biomedical Engineering
- Coal Gasification, Liquefaction, and Combustion
- Electrochemical Engineering
- Electrokinetic Phenomena
- Fluid Dynamics
- Fluidization
- Heat Transfer
- Kinetics
- Liquid Extraction
- Magnetic Effects
- Mass Transfer
- Modelling and Optimization
- Particle Dynamics
- Process Dynamics
- Pulp & Paper
- Rheology
- Rotary Kilns
- Separation Processes
- Spouted Beds
- Sulphur
- Thermodynamics
- Water Pollution

Inquiries should be addressed to:

Graduate Advisor
Department of Chemical Engineering
THE UNIVERSITY OF BRITISH COLUMBIA
Vancouver, B.C. V6T 1W5

THE UNIVERSITY OF IOWA

Iowa City

M.S. Ph.D.

Research in

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- Membrane Separations
- Mass transfer operations
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- Materials science
- Materials processing
- Air pollution
- Computer Modeling
- Reaction kinetics
- Catalysis

Write: Chairman
Chemical and Materials Engineering
University of Iowa
Iowa City, Iowa 52242
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CLAYTON, VICTORIA
Department of Chemical Engineering
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- Chemical Reactor Engineering
- Extractive Metallurgy and Mineral Engineering
- Process Dynamics, Control and Optimization
- Polymer Processing and Rheology
- Transport Phenomena
- Waste Treatment and Water Purification
- Hydrogenation and Drying of Brown Coal

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Postal Address: Monash University
Wellington Road
Clayton, 3168
Victoria, Australia

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NEWARK COLLEGE OF ENGINEERING

GRADUATE STUDY
FOR M.S., ENGINEER AND Sc.D. DEGREES IN CHEMICAL ENGINEERING

- Biomedical Engineering
- Biochemical Engineering
- Environmental Engineering
- Polymer Science and Engineering
- Basic Studies-Chemical Engineering
- Basic Studies-Applied Chemistry
- Process and Design Studies

For details on applications and financial aid, write:
Mr. Dino Sethi
Director of Graduate Studies
New Jersey Institute of Technology
323 High Street
Newark, New Jersey 07102

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Graduate Studies in Chemical Engineering
M.S. and Ph.D. Degree Programs
FRANCIS J. BONNER: Polymer Engineering, Characterization of polymers, Thermal Diffusion and Membrane Transport of macromolecules.
KENNETH A. DEBELAK: Gasification and Liquefaction of coal, Energy-Environmental Systems, Mathematical Modeling of Chemical Processes
THOMAS M. GOLDBOLD: Process Dynamics and Control, Mass Transfer, Coal Conversion Technology
KNOWLES A. OVERHOLSER: Biological Transport Processes, Bioremediation
ROBERT J. ROSELLI: Biomedical Engineering, Biological Transport Processes
JOHN A. ROTH: Industrial Waste Treatment, Physical-Chemical Waste Treatment, Reaction Kinetics and Chemical Reaction Design
KARL B. SCHNELLE, JR.: Chairman of the Department; Air Pollution Control, Solution Thermodynamics, Environmental Transport Processes
ROBERT D. TANNER: Enzyme Kinetics, Fermentation Processes and Kinetics, Pharmacokinetics, Microbial Assays
W. DENNIS THREADGILL: Unit Operations, Food and Dairy Industry Waste Treatment

Further Information: Knowles A. Overholser
Director of Graduate Studies
Chemical Engineering Department
Box 6173, Station B
Vanderbilt University
Nashville, Tennessee 37235

UNIVERSITY OF NORTH DAKOTA
Graduate Studies
MS and MEngr. in Chemical Engineering
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RESEARCH PROJECTS: Most funded research projects are energy related although other basic and applied projects are available. Students may participate in project-related thesis problems or may be employed as project workers in the Department, the Engineering Experiment Station or the Grand Forks Energy Technology Center.

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FOR INFORMATION WRITE TO:
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Chemical Engineering Department
University of North Dakota
Grand Forks, North Dakota 58202
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Chemical Engineering Department
West Virginia Inst. of Technology
Montgomery, WV 25136

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For Further Information, Write to

Dr. D. De Kee
Department of Chemical Engineering
University of Windsor
Windsor, Ontario, Canada N9B 3P4

ACKNOWLEDGEMENT

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