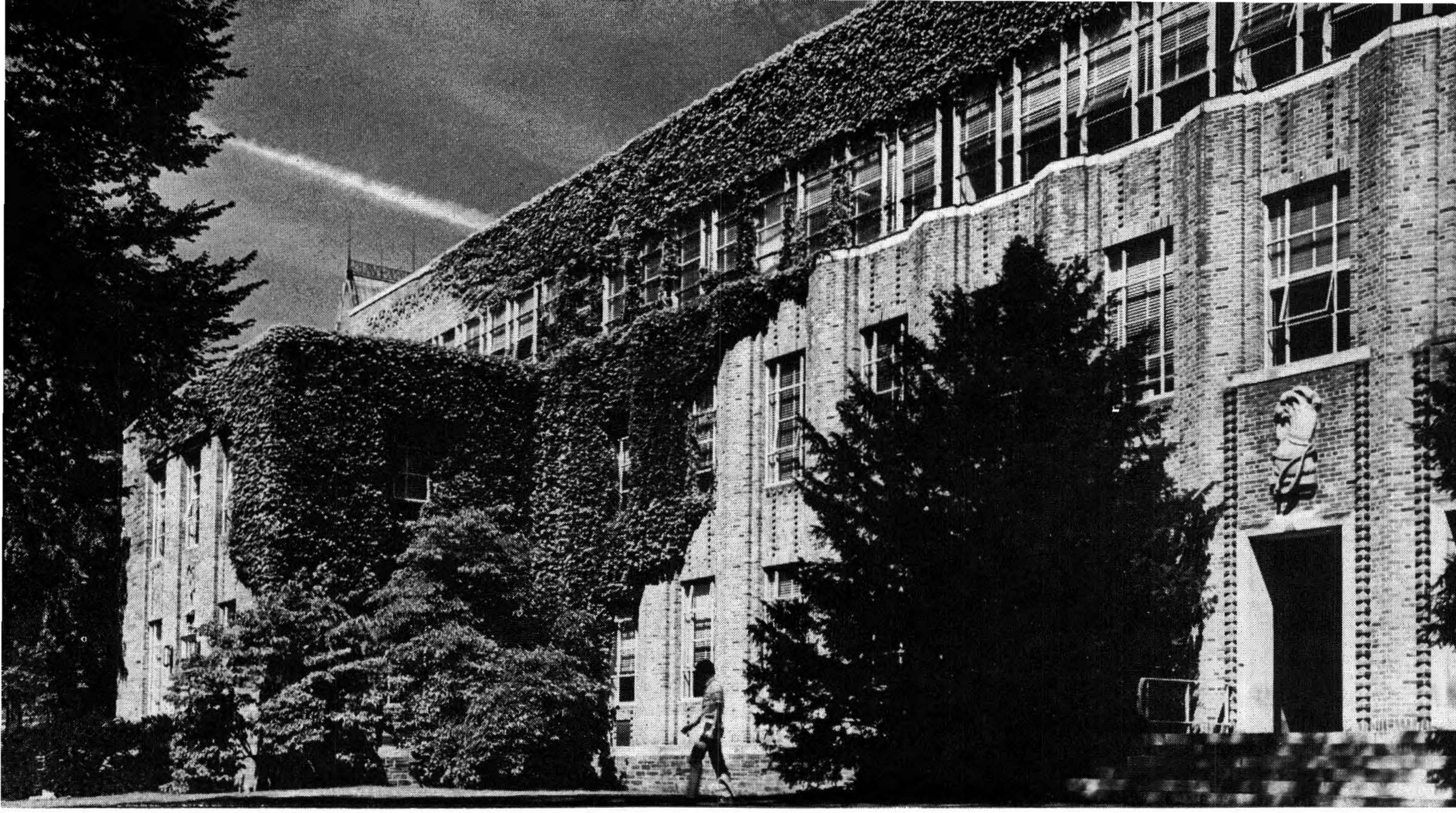

Olin Hall from the west.

ChE department

CHE AT CORNELL UNIVERSITY

JULIAN C. SMITH AND PAUL H. STEEN
Cornell University
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FOUNDED IN 1868 AND with a long tradition in engineering, Cornell is almost unique in being both private and state-supported; about half the divisions, including engineering, are privately endowed while the other half are funded by the State of New York. An awkward arrangement, it would seem, but it works surprisingly well.

Cornell, a medium sized university with a total enrollment of some 18,000 students, is set on a hill overlooking the city of Ithaca, and the waters of Cayuga Lake, the largest of the Finger Lakes. Ithaca is small but strongly cosmopolitan. The setting is semi-rural; the scenery is beautiful; the air is clean. Almost the only drawbacks are a modicum of cold gray weather on occasion, and some possible difficulties in travelling in and out. Ithaca has been called "the most centrally isolated city in the Northeast," but as a graduate student from Greece recently remarked, "If it wasn't for the weather, Ithaca would be Paradise!"

The School of Chemical Engineering has 18 faculty members, about 100 undergraduate students (3rd and 4th years only), and over 65 graduate students. During the past twelve years research activity and expenditures have greatly increased, and strong research programs have been established in fluid mechanics, polymers, surface science and catalysis, thermodynamics, and biochemical engineering. The number and quality of MS and PhD candidates (especially PhD's) have risen rapidly. The growth in research, however, has not reduced the traditional concern for undergraduate and professional graduate teaching. All faculty members are expected to teach undergraduate courses, and many participate in advanced design projects in the professional Master's program. The school occupies its own building (shared with a few other tenants) with

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a total area of some 90,000 square feet, 54,000 of which is exclusively chemical engineering.

A BRIEF HISTORY

At Cornell, as at many institutions, chemical engineering began in the Chemistry Department, but its development was somewhat unusual. Very early (before 1900) courses were offered in industrial chemistry which had a considerable practical flavor; as taught by Fred H. "Dusty" Rhodes in the 1920's they dealt with the principles and practice of chemical engineering. By 1930 Dusty had established both undergraduate and graduate programs in chemical engineering, but because of rivalries between Chemistry and the Engineering College the undergraduate program had to be a 5-year-long hybrid: four years in Arts and Sciences (leading to the degree Bachelor of Chemistry) followed by one year in engineering (for the degree Chemical Engineer).

In 1938 the department with its three faculty members became part of the Engineering College and the 5-year program led to the degree Bachelor of Chemical Engineering. In 1942 chemical engineering moved to Olin Hall, the first building on what was to become engineering's new quadrangle. It was at a considerable distance from chemistry and the old ties quickly weakened. After World War II all the undergraduate engineering programs at Cornell were lengthened to five years. This lasted until 1965, when the present 4-year BS programs, including that in chemical engineering, were established.

Dusty Rhodes was director of the school until he retired in 1957 and Charles C. "Chuck" Winding took over. Ken Bischoff, now at the University of Delaware, was director from 1970 to 1975; Julian Smith from 1975 to 1983; and Keith Gubbins from 1983 to date.

For many years chemical engineering at Cornell was known for its strong undergraduate program. Rhodes felt that good teaching was the most important thing required of a faculty member and while ability to do research should be considered in reviews for promotion or tenure, it should not be a major factor. This is not to say that there was no research or graduate work. Between 1932 and 1970 the school awarded 140 MS and 104 PhD degrees, and many of the recipients have had distinguished careers in industry and academia, including John Prausnitz (Berkeley), Ed Lightfoot (Wisconsin), and a string of past or present heads of chemical engineering departments: Bob Coughlin (UCONN); Howard Greene (Akron); Deran Hanesian (NJIT); Will Kranich (Worcester Poly); Larry McIntire (Rice); Steve Rosen (Toledo); Julian Smith (Cornell); Tom Weber (SUNY Buffalo); and Jacques Zakin (Ohio State). Bob Finn's pioneering work in biochemical engineering was begun in the 1950's.

Dusty's policies set a pattern for the school which persisted until the early 1970's. By then it was clear that the research effort had to be greatly expanded. Beginning in 1970, new faculty members were added who developed, or brought with them, strong research programs in several areas. This attracted additional research-minded faculty and increasingly stronger graduate students. During an 8-year period research expenditures increased by a factor of six. The number of graduate students has risen to 67; more significantly, a majority of them are now PhD candidates. And collaboration with Chemistry and other departments of the university is once again close and extensive.


The Fred H. Rhodes Student Lounge, redecorated through a gift from Joseph Coors, '40.

RESEARCH GROWTH

From 1976 through 1982, the annual research expenditures, in dollars per faculty member, climbed at a rate that was second highest and reached a level that was fourth highest among all chemical engineering departments in the country.* Total sponsored research costs for 1983-84 were over 1.5 million dollars, for an average of $94,000

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per full-time faculty member. This is especially striking since only about a third of the faculty was responsible for 75% of the total expenditures. As the current younger faculty develop their programs and additional research-minded faculty replace retiring senior professors, the overall research program should continue its strong expansion.

Biochemical Engineering

Biochemical engineering research has grown from **Bob Finn**'s early studies of microbes and microbial populations. The goal was, and is, to develop new and more efficient biochemical conversions. One project seeks to find economical ways of producing ethanol from pentose sugars, a second to develop better treatment methods for wastes containing pentachlorophenol (PCP), and a third to exploit an unusual bacterium which can rapidly ferment arabinose.

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Mike Shuler shares several specific interests with Bob Finn including the treatment of wastewater by specialized microorganisms. Mike's diverse interests are tied together by a view of the living cell as a "catalyst" waiting to be used in chemical reactors. His research embraces studies of plant-cell tissue culture, reactors with solid substrates (e.g. mold growth on solid surfaces), photobioreactors, biofilm formation, and the continuous protein production from bacteria with recombinant DNA. Particularly noteworthy have been his group's experimental demonstration of the feasibility of hollow-fiber membrane units for entrapment of microbial populations (necessary groundwork for the development of hollow-fiber reactors) and the construction of a mathematical model of the organism *Escherichia coli.*

Doug Clark, who joined the faculty in 1984, brings the point of view that enzymes rather than the whole cell can be the building blocks for biochemical reactors. He is studying how the immobilization, or attachment to a foreign matrix support, affects the structure and function of an enzyme. A related interest is the transport of biological macromolecules through porous media; this transport is an essential step in enzyme immobilization, gel permeation and affinity chromatography, and ultrafiltration. In collaboration with Bill Streett, Doug has initiated a study of methane-producing bacteria which live at extreme temperatures and pressures in deep-sea hydrothermal vents.

Polymers and Materials Science

For a million circuit elements to fit on a tiny silicon chip linewidths must be on the order of a tenth of a micron. In one technique for achieving such precision—electron-beam lithography—the silicon surface is covered with a polymer film (polymethyl methacrylate, for example), then irradiated by an electron beam creating a pattern of soluble polymer. The soluble polymer is washed away leaving a precision mask and the chip is ready for the final step, silicon modification. **Ferdinand (Rod) Rodriguez** is directing an interdepartmental program on polymers for advanced lithography, to improve the performance of the polymer "resist" used in the masking process. This is a good example of Rod's research on polymeric materials which has the broad goal of understanding the processes of polymerization and gelation (crosslinking) and degradation (chain scission) in order to produce better materials.

Claude Cohen uses macromolecular science to interpret the physical properties of polymer systems and to understand the structures that develop during industrial processing. On the fundamental level, predictions from models of macromolecules are used to understand rheological and light-scattering behavior, with experiments to complement the theoretical work and to test the adequacy of the models. On the applied level, the orientation of glass fibers in composite thermoplastics during the molding process is being investigated. This work is in conjunction with an interdepartmental program on injection molding.

Surface Chemistry, Catalysis and Reactor Engineering

The surface chemistry and physics of heterogeneous systems which have direct technological application is the central concern of **Bob Merrill**'s studies. Examples are CO oxidation on noble metals (automobile exhaust converters), the decomposition of hydrazine (rocket monopropellant), the oxidation of aluminum (catalyst support technology, corrosion protection, and electronic insulators in microcircuitry) and hydrodesulfurization catalysis (sulfur removal from petroleum). On the one hand, Bob's group answers practical questions; on the other they are developing and sharpening several types of analytical tools. These include the use of lasers in surface chemistry, the use of synchrotron radiation (EXAFS) to study the dynamics of gas-solid reactions, and the use of spectroscopy in real catalyst systems (high-surface-area configurations and high pressures).

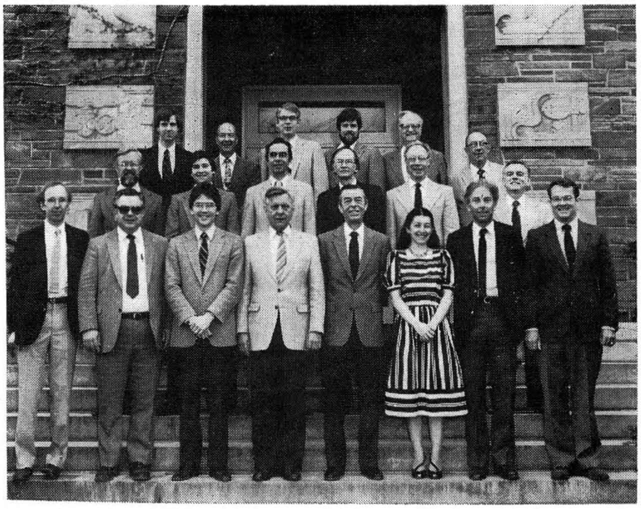
Peter Harriott studies the influence of mass transfer, heat transfer and mixing on the performance of chemical reactors as well as the kinetics of reactions in heterogeneous systems. One project concerns the regeneration of catalysts used in the pyrolysis and gasification of coal. Another examines the heat and mass transfer and the overall kinetics in lime-slurry droplets used in the "dry scrubbing" of SO_2 from flue gas; the goal is to pin down the rate-limiting step and improve the design of commercial units.

Joe Cocchetto's recent work on catalytic reaction kinetics has concentrated on the fuel cell. By controlling the structure of a porous electrode, a better understanding of the interplay between transport and reaction has been gained and techniques for improving efficiency have emerged. Joe returned to industry in early 1985.

Bob Von Berg is interested in the use of gamma radiation in various chemical processes: ammonia synthesis and the reaction of hydrocarbons and liquid nitrogen. Bob has also collaborated with Herb Wiegandt on a long-term project involving the desalination of water by freezing, as described later.

Fluid Dynamics and Stability: Rheology

Bill Olbricht concentrates on problems in fluid mechanics and rheology with applications in enhanced oil recovery, biomedical fluid mechanics, and the production of semiconductor materials. He is studying the low-Reynolds-number motion and coalescence of immiscible drops in tubes of various geometries (characteristic of porous media) for critical evaluation of methods for enhanced oil recovery. In the biomedical area, in conjunction with the University of Rochester Medical School, he is modelling the motion of red blood cells in microcapillaries to predict the distribution of these cells within tissue. A third area of research examines the momentum, heat, and mass transfer involved in silicon film growth by chemical vapor deposition with the aim of predicting rates of film growth in low-pressure deposition reactors.



Cornell's Chemical Engineering Faculty, 1984. Back row: Shuler, Finn, Scheele, Steen, Smith, Winding. Middle row: Zollweg (Research Associate), Cocchetto, Harriott, Jolls (Visiting from Iowa State), Von Berg, Rodriguez. Front row: Olbricht, Merrill, Clark, Wiegandt, Thorpe, Clancy, Gubbins, Streett.

Paul Steen, who joined the faculty in 1982, studies fluid motions and their stabilities. Buoyancy-driven convection patterns, generated in fluid-saturated porous media, are examined as prototypes of fluid motions susceptible to transitions in which strong nonlinear effects are dominant. This work involves the development of tools in applied mathematics. In another area, motions induced at fluid/fluid interfaces due to temperature gradients (thermocapillary effects) are being investigated by experiment, with relevance to the float-zone crystal-growth process and the break-up of thick films.

George Scheele's study of liquid-liquid immiscible systems focuses on the coalescence of droplets and the break-up of jets—both at relatively high Reynolds numbers. He also has interests in the computer simulation of chemical processes, particularly in computer graphics.

Molecular Thermodynamics and Computer Simulation

Keith Gubbins and **Bill Streett** have coordinated their efforts towards understanding, predicting,

Continued on page 103.

	tion; submatrices of partial derivatives in a block tridiagonal matrix
B	Bottoms product molar flow rate
f	An arbitrary function
F	Molar feed rate to a stage; mathematical function
H_F	Molar enthalpy of feed to a stage
h	The homotopy function whose arguments are x and t
H	The homotopy function whose arguments are x and λ
H_v	Molar enthalpy of vapor leaving a stage
H_L	Molar enthalpy of liquid leaving a stage
K	Vapor-liquid equilibrium ratio
L	Molar liquid flow rate leaving a stage
MP	Middle product molar flow rate
p	Path length
Q	Heat duty (R for reboiler; C for condenser)
R	Reflux ratio
s	Ratio of liquid drawoff to primary liquid (liquid not withdrawn or entrained)
S	Ratio of vapor drawoff to primary vapor (vapor not withdrawn)
t	Homotopy parameter.
T	Temperature; when used as a superscript denotes matrix transpose
V	Molar Vapor flow rate leaving stage
x	The vector of independent variables (unknowns) for the distillation equations; liquid-phase mole fraction
x^o	The starting vector for the nonlinear equation solver
x^*	The solution to the set of nonlinear equations
X	Mole fraction in liquid of a component; variable
y	Vapor-phase mole fraction
Y	Mole fraction in vapor of a component
Z	Mole fraction in feed of a component

Greek Letters

λ	Homotopy parameter

DEPARTMENT: Cornell

Continued from page 61.

and measuring the properties of liquids and liquid mixtures using theory, computer simulation, and experiment. Cornell is one of very few institutions with strength in all three areas.

Keith guides the theory and the computer simulation (with help from Senior Research Associate **Steve Thompson,**) making use of recently developed accurate theories for dense fluids of complex molecules as well as improved computer simulation methods and computer hardware. Typically, highly nonideal substances (in the thermodynamic sense) are chosen for study; substances for which traditional methods of prediction fail. Examples include mixtures occurring in coal gasification and liquefaction, hydrogen-energy technology, synthetic fuel processing and supercritical fluid extraction. Other research underway or planned includes studies of adsorption at gas-liquid, liquid-liquid and solid-fluid interfaces, nucleation and droplet phenomena, polarization in polar fluids, and surfactant effects.

Bill Streett and Senior Research Associate **John Zollweg** carry out experimental studies of dense fluids. In progress are (*i*) experiments in vapor-liquid, liquid-liquid, and gas-gas equilibria at temperatures from 70 to 500 K and pressures to 10,000 atmospheres; (*ii*) equation-of-state (PVT) measurements of pure liquids and mixtures at temperatures from 70 to 500 K and pressures to 4,000 atmospheres; and (*iii*) measurements of enthalpy of mixing in samples of liquefied gases at temperatures from 70 to 300 K and pressures to 20 atmospheres. Bill is currently developing new experiments to measure the surface and interfacial tensions and the velocity of sound in fluids under pressure.

The researches of **Paulette Clancy**, who became a member of the faculty in 1984, range from a statistical mechanical study (using perturbation theory) of multicomponent highly polar fluid mixtures to a development of phase diagrams (based on molecular thermodynamics) of semiconductor materials. In addition, she is involved in the application of computers to chemical engineering.

Herb Wiegandt's interest in desalting sea water, using a freezing process based on direct contact with butane, goes back to 1958. Recent efforts, with Bob Von Berg as a partner, have aimed at overcoming the problems associated with washing and separating the ice crystals which are typically very small.

Julian Smith, past Director of the School in a period of unprecedented growth, seasoned educator and co-author of *Unit Operations of Chemical Engineering* (now in its fourth edition, with Pete Harriott as co-author), has expertise in mixing, centrifugal separation, and handling of granular solids. He is teaching full-time and is active in the guidance of the school.

Ray Thorpe, who has advised graduate students in the areas of phase equilibria and separations processes, splits his time between teaching and university administration: he is director of the Division of Unclassified Students.

Research Interactions

Many research projects involve active collaboration with other researchers at Cornell or elsewhere. Some are directly with other departments; some are through Cornell's numerous indisciplinary programs, centers, and institutes—many industrially supported—that facilitate interaction among departments and with industry. Examples are the Biotechnology Institute; the Injection Molding Project; COMEPP (Cornell Manufacturing Engineering and Productivity Program); Applied Mathematics Center; Theory and Simulation Center (established by Ken Wilson, Cornell's 1982 Nobel laureate in physics); Materials Science Center; National Facility for Submicron Studies. Strong ties have been established with other departments and colleges of Cornell, and with workers at other universities around the world.

Paulette Clancy, Associate Director of COMEPP, is joined by Professor Scheele in a study of ways to improve the interface between the user and ASPEN software chemical process synthesis and design.

UNDERGRADUATE PROGRAM

Undergraduate chemical engineering enrollments at Cornell were almost constant during the twenty years before 1975, with about 40 bachelor's degrees awarded annually. Then, although freshman admissions to the engineering college were held constant, the number of students opting for chemical engineering roughly doubled, and for nine years the number of BS degrees awarded was between 65 and 75. After 1985, however, the number will return to 40 or so and is expected to stay at that level for the next several years.

The subject matter of the undergraduate program is much the same as at other institutions. For the first two years the students are not in chemical engineering but are enrolled in the "common curriculum" of the engineering college. Nevertheless, their curriculum has much that is different from that of other engineering students. In the freshman year chemical engineers take two semesters of chemistry, not one. Sophomores take two semesters of physical chemistry, with laboratory each term—a special course taught by Chemistry almost exclusively for chemical engineers—and the required introductory course in mass and energy balances. Organic chemistry (two semesters, one with laboratory) is given in the third year, as are chemical engineering thermodynamics, rate processes and separation processes. The fourth year includes required courses in reaction kinetics, process evaluation, process control, and unit operations laboratory, and a spring term course in process design. Overall, 132 credit hours are required for the BS degree, including two courses in computer programming and applications, four engineering distribution courses, and six courses in humanities and social sciences. Ten of the required courses (32 credit hours) are in chemical engineering subjects.

The senior laboratory course is considered the most demanding by students and faculty alike. Each student reports on only five experiments during the term, but each report is thoroughly edited for both form and content by the faculty member in charge of that experiment and nearly always must be extensively revised by the student before it is accepted. The emphasis is on technical accuracy, completeness, and clarity of expression.

Oral presentations are stressed in the senior design course, in which each team of students makes weekly oral presentations before two faculty members or industrial visitors. In recent years experienced engineers from industry have been hired for full-time assistance in this course and in the senior laboratory. Their contributions have been supplemented, during short-term visits, by those of people from Exxon, Union Carbide, and other firms. Despite this, the laboratory and design courses demand large contributions of time by senior faculty members, and pose the most difficult problems for future staffing.

A Special Cooperative Program

For the past ten years the better students in the sophomore year have been encouraged to enroll in an unusual industrial cooperative program which gives them practical experience without lengthening their time at the university. Typically 15 to 20 students are accepted into the program after company interviews exactly like those for permanent employment. Co-op students take the fall-term third-year courses during the summer following their sophomore year; they work in industry during the fall and return to Cornell in the spring; work again for the same sponsor the following summer; and complete their senior year in the regular sequence. Industrial assignments are carefully monitored to insure appropriateness, and each student is visited at the worksite by a Cornell person at least once during the course of the program.

THE PROFESSIONAL MASTER'S PROGRAM

This is a two-semester non-thesis master's program leading to the degree Master of Engineering (Chemical). It requires 30 credit hours of advanced technical work, including a substantial design project, with emphasis on practical applications. Most of the matriculants are not from Cornell or other U.S. schools; instead the program is attractive to foreign students, especially from developing countries such as the Dominican Republic, Guatemala, India, Kuwait, Taiwan and Venezuela. Over the years a chemical company in India has sent, one after another, three of its top technical employees to this program.

Required courses for the MEng (Chemical) degree include equipment design and selection, numerical methods, reactor design, the design project, and a chemical engineering elective. The remaining credit hours can be filled by elective courses in science or engineering or in the Graduate School of Management. The choice of subjects for MEng design projects is much wider than in the typical undergraduate design course, and more initiative and originality are expected of the students. Some of the projects are done in close collaboration with industrial firms.

RELATIONS WITH INDUSTRY

The school has always had close relations with industry and an unusually supportive group of alumni. Industry helps us in many ways: in the design courses; in a "Non-resident Lecture Series" (zero credit, but compulsory), given to seniors on the various kinds of professional careers; in unrestricted grants; in scholarships, fellowships, and sponsored research. Continuing fellowship support has been provided by Amoco, Chevron, Dow, DuPont, Exxon, Shell, Stauffer and Union Carbide, and recent large research projects came from IBM, Kodak and Mobil. In 1981 the Sun Company gave $250,000 over three years to support research initiation on ideas too new and ill-defined to merit submission of a proposal to NSF or other granting agencies. This unusual grant led to a number of publications and several continuing sponsored research programs.

ADVISORY COUNCIL

An advisory council, largely from industry, was formed a few years ago. It meets in Ithaca twice a year to review progress and help the director steer a course for the school. About half the members are alumni. Recently expanded to 15 members, the council now includes four academic people: Andy Acrivos (Stanford), Gus Aris (Minnesota), Gary Leal (CalTech), and Bill Schowalter (Princeton). We don't always agree with the council's suggestions, of course, but as a group it has been marvelously effective in providing an "outside" viewpoint and keeping us from being too provincial or self-satisfied.

WHAT OF THE FUTURE?

Cornell is facing many of the same problems that face other chemical engineering departments around the country—faculty retirements and future faculty development, staffing of design and laboratory courses, the optimum use of computers for teaching, expansion of research and the graduate program, and renovation of aging facilities. The five professors hired right after World War II are nearing retirement, so for the next several years an average of one new faculty member per year will have to be hired to keep the number constant. Because of the loss of professors with industrial experience one or more people with an industrial background will probably be hired on a non-tenure-track basis to teach design and to supervise the laboratory courses.

A related problem is in the use of computer software. How much emphasis should be placed on teaching the use of ASPEN, for example? More generally, as personal computers become ubiquitous, what will happen to teaching methods? Will the course in mass and energy balances, for example, become a course in the use of available canned programs?

The total number of graduate students in the school, and the fraction going for a PhD rather than an MS, should rise somewhat over the next ten years, depending on the availability of financial support. This will increase the need for equipment and laboratory and office space. Relatively speaking, the Chemical Engineering School has a lot of space, but much of it is virtually unusable for modern research. A comprehensive building renovation plan, made by a firm of architects, proposes a complete reallocation and rearrangement of available space and the conversion of the enormous unit operations laboratory into offices and small research labs. New electrical and other services will be provided, along with central air conditioning. The average faculty office will shrink from over 400 to a more modest 200 square feet and the offices will be grouped more closely, to stimulate greater interaction among the occupants. The total estimated cost is some fifteen times the original cost of the building. A fund drive for the first stage is being launched. □

AWARD LECTURE

Continued from page 77.

on the batch experience and using verified mathematical models to both design the equipment and direct the experimentation.

CHEMICAL VAPOR DEPOSITION

Laboratory Scale Research

A low pressure chemical vapor deposition (LPCVD) system for amorphous silicon is shown in Fig. 14 and the simplified process flow diagram as Fig. 15. Reactants, Si_2H_6, and material for doping the film, PH_3 and B_2H_6, in a stream of argon are controlled by valves at the inlet to the reactor. The tubular quartz reactor is temperature controlled inside an electric furnace. System pressure is controlled manually with a valve at the exit. Effluent gas can be analyzed by gas chromatography and unreacted material is decomposed in a furnace before venting. The detailed operation of this system is described by Bogaert [9].

This effort in amorphous silicon research, sponsored by the Department of Energy through the Solar Energy Research Institute, is ongoing at the present time and is far from being complete. I am discussing it here to allow the reader to contrast and compare with the physical vapor deposition reacting systems just described.

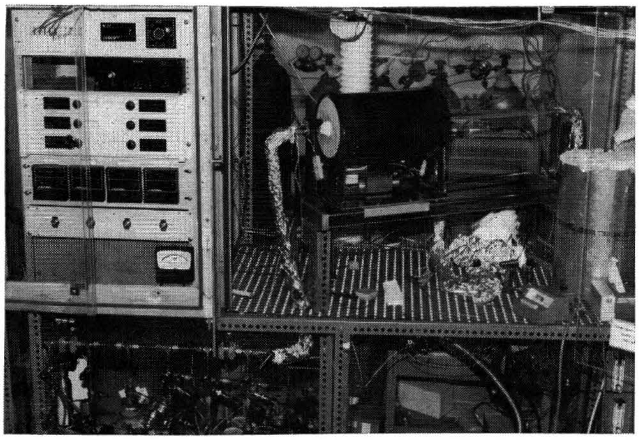


FIGURE 14. Photograph of Low Pressure Chemical Vapor Deposition unit (LPCVD).

The chemistry is much more complex for amorphous silicon than for CdS and not well understood. The present state-of-the-art is shown below:

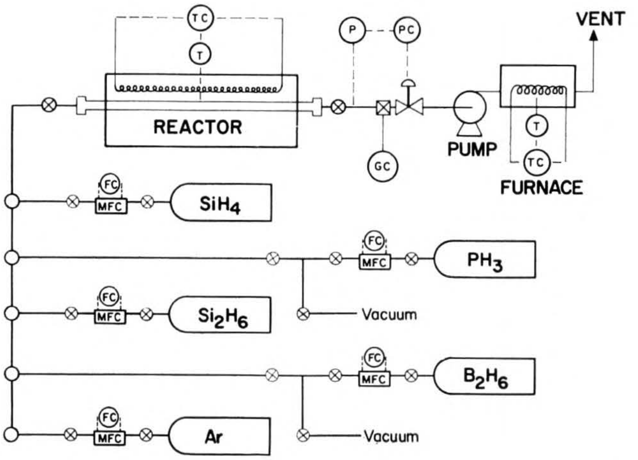


FIGURE 15. Simplified process flow diagram of LPCVD.

Gas Phase

$$Si_2H_6 \rightleftharpoons SiH_4 + SiH_2$$
$$Si_3H_8 \rightleftharpoons Si_2H_6 + SiH_2$$
$$Si_4H_{10} \rightleftharpoons Si_3H_8 + SiH_2$$
$$Si_5H_{12} \rightleftharpoons Si_4H_{10} + SiH_2$$
$$Si_6H_{14} \rightleftharpoons Si_5H_{12} + SiH_2$$
$$Si_7H_{16} \rightleftharpoons Si_6H_{14} + SiH_2$$
$$Si_8H_{18} \rightleftharpoons Si_7H_{16} + SiH_2$$

Film Formation

$$Si_5H_{12} \rightarrow 3SiH_{0.08} + 2SiH_4 + 1.88H_2$$
$$SiH_2 \rightarrow SiH_{0.08} + 0.96H_2$$

This is a preliminary set of chemical equations. The gas phase equations are based on the results of Ring [10], John and Purnell [11], and Bowery and Purnell [12]. The film formation equations are based upon our own preliminary research.

The component mass balance equations for this tubular reactor system are given below:

Gas Phase

$$\left(\frac{4q}{\pi D^2}\right)\frac{dC_i}{dZ} = \Sigma r(rxt,i) + k_g a (C_i - C_{is})$$