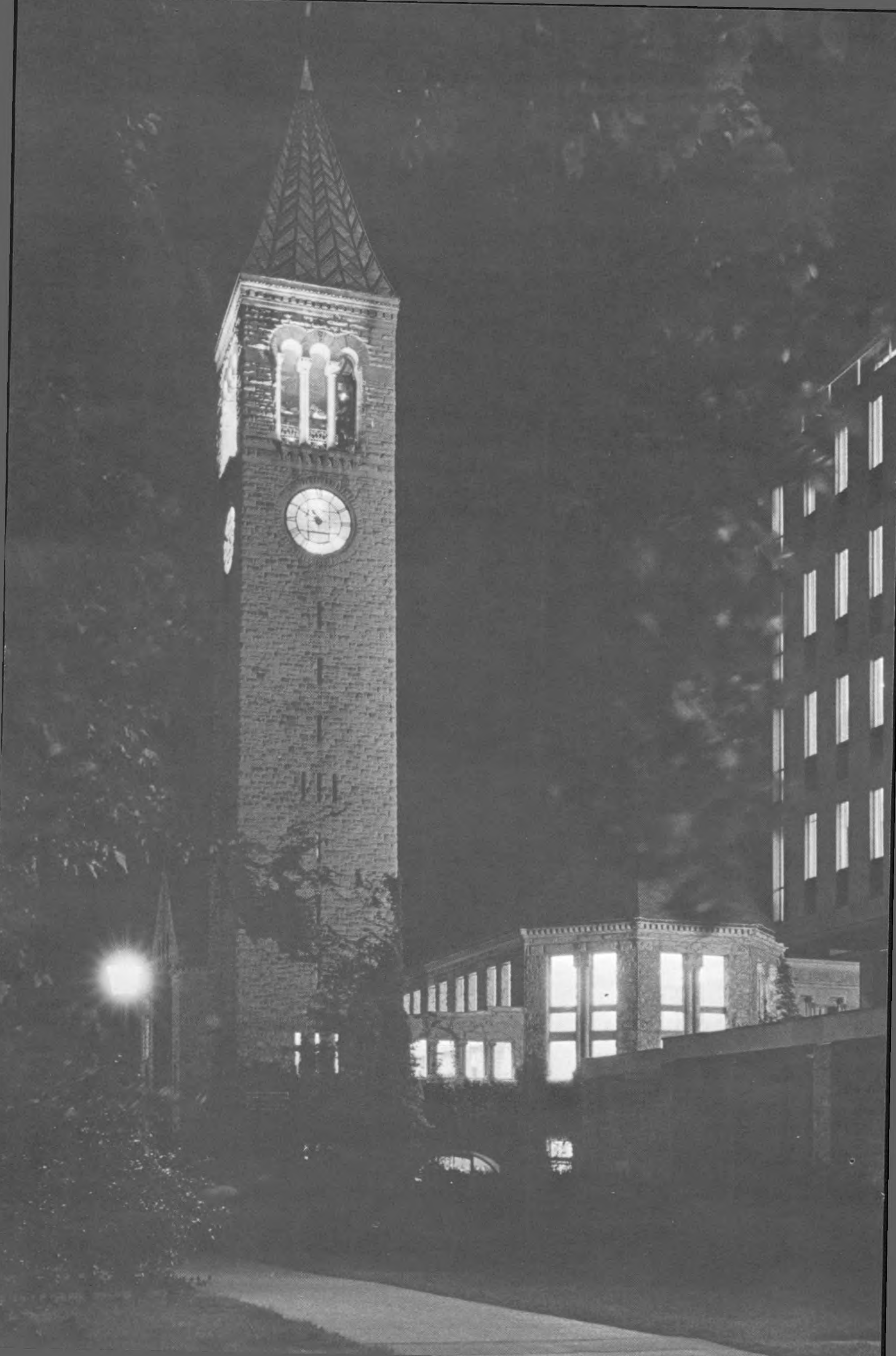
Graduate Study in Engineering and Applied Science

Cornell University Announcements

Aerospace Engineering Agricultural Engineering Applied Physics Chemical Engineering Civil and Environmental Engineering Computer Science Electrical Engineering Geological Sciences Materials Science and Engineering Mechanical Engineering Nuclear Science and Engineering Operations Research Theoretical and Applied Mechanics Aerospace Engineering Agri-

Graduate Study in Engineering and Applied Science

Cornell University
Ithaca, New York



Contents

Graduate Study in Engineering and Applied Science 5
The Graduate Fields 9
Aerospace Engineering 9
Agricultural Engineering 13
Applied Physics 21
Chemical Engineering 31
Civil and Environmental Engineering 37
Computer Science 45
Electrical Engineering 49
Geological Sciences 57
Materials Science and Engineering 61
Mechanical Engineering 67
Nuclear Science and Engineering 73
Operations Research 79
Theoretical and Applied Mechanics 85
Interdisciplinary Centers at Cornell 89
General Information 93

Cornell University Announcements

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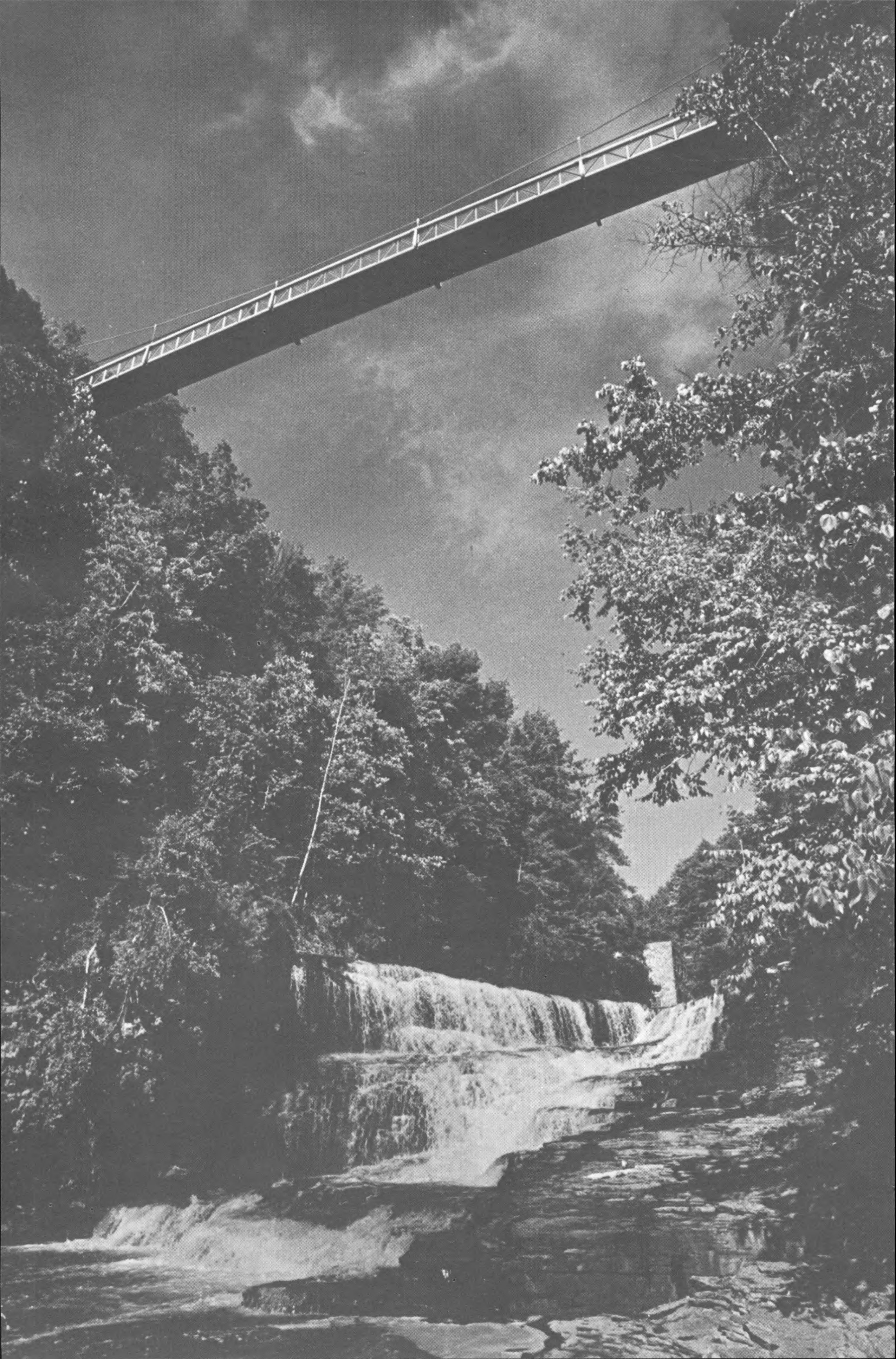


Graduate Study in Engineering and Applied Science

At Cornell, graduate study in engineering and applied sciences is conducted through the College of Engineering, but it is truly a University experience. The faculty and resources of the entire University are available to each graduate student in accordance with his special needs and interests.

About 650 students are working toward advanced degrees in the various fields of engineering and applied science at Cornell. Some of these students are working in the research-oriented Master of Science and Doctor of Philosophy degree programs administered by the Graduate School, and some are enrolled in the professional Master of Engineering degree programs offered by the College of Engineering.

The prospective student who wishes to specialize in an engineering or related subject in an M.S. or Ph.D. program should perhaps first settle on the graduate Field of instruction that offers the course work and research opportunities best suited to his plans and interests. The student may also wish to work under the supervision of a particular faculty member whose research activities are especially appealing. The descriptions, in this *Announcement,* of the graduate Fields and of some of the research projects under way may be helpful in the student's choice of Field and faculty supervisor. It may be noted that the separation of graduate study into Fields is necessarily somewhat arbitrary. Some areas of research are interdisciplinary in nature, and some of the Fields described draw on faculty members in other departments or areas. Actual selection of the supervising professor is made by the student toward the beginning of his residency when he chooses his Special Committee, a faculty group which is wholly responsible for the direction of his degree program.

Candidates for the M.S. or Ph.D. degree are required to submit a thesis based on supervised research. Detailed information on Graduate School procedures, requirements, costs, financial aid, etc., is given in the *Announcement of the Graduate School.*

The suspension bridge across Fall Creek Gorge is a pleasant route for pedestrians entering the Cornell campus.

Course descriptions are given in the *Announcement of the Graduate School: Course Descriptions.*

The professional Master of Engineering programs offer another option for advanced study. These are intended for graduate students who wish to prepare for professional engineering careers. The M.Eng. programs are often pursued by Cornell students who begin an integrated three-year curriculum in their junior year of undergraduate study, but they are open to graduates of other four-year engineering schools. Degrees are awarded in eleven areas: aerospace engineering (administered by the Graduate School of Aerospace Engineering), engineering physics, engineering mechanics, and agricultural, chemical, civil, electrical, industrial, materials, mechanical, and nuclear engineering. These programs and specific courses are described in more detail in the *Announcement of the College of Engineering.*

Cornell University and the College of Engineering

Cornell is an internationally known university consisting of fourteen colleges and schools which enroll about 15,000 students, including 3,500 in the Graduate School. A unique feature of the University is the combination of privately financed and state-supported units, a circumstance that fosters Cornell's century-old concept of education in all subjects for all qualified students. The individual student is afforded an unusually rich and diverse background of academic life.

The College of Engineering has a total enrollment of about 2,750 and a faculty of about 200. Graduate instruction is augmented by the faculties of other University units, especially science and mathematics departments. The College is organized into schools, departments, and graduate Fields. In general, the faculty of a school or department is responsible for undergraduate education and for the professional M.Eng. degree programs, and the faculty members associated with the various graduate Fields supervise the M.S. and Ph.D. degree pro-

grams. The Fields associated with the College of Engineering are described in some detail in this *Announcement.*

Facilities

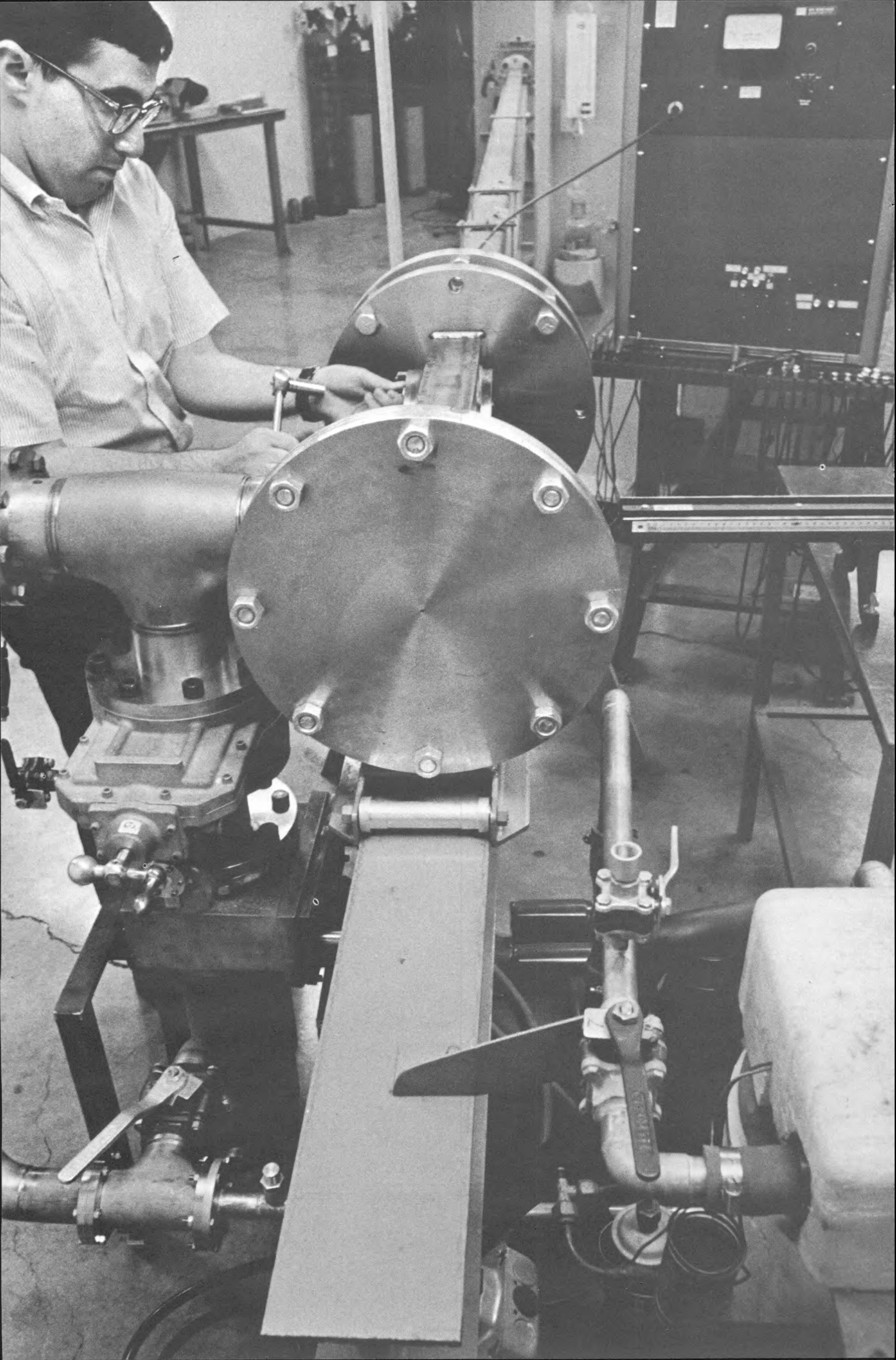
Cornell University maintains more than ninety major buildings on its 740-acre Ithaca campus. The College of Engineering is centered in ten modern buildings in the area known as the Engineering Quadrangle, although some of its activities are carried out at other campus locations, in buildings such as Clark Hall, which is the University's center for solid state and applied physics, and the Space Sciences Building.

Cornell's outstanding library system is comprised of two large central facilities supplemented by a number of specialized libraries in buildings throughout the campus. The entire collection, including more than 3.6 million volumes, is available to all students. The College of Engineering library, which has approximately 125,000 books and periodicals, and the physical sciences and mathematics libraries are especially useful to engineering and applied sciences graduate students.

Of special importance to many graduate students is the University's computing facility, which is a multiprocessor complex of IBM 360 systems. The central machine, a 360/65 system, is directly linked to satellite computers at three different campus locations. The College of Engineering is served through one of these satellite stations, as well as by a number of teletypewriter terminals in different locations.

Special facilities that may be of importance or interest to prospective students in the various areas of graduate study are described in the sections on each graduate Field.

The ten modern buildings on the Engineering Quadrangle are located at the south side of the Cornell campus, bordering the scenic Cascadilla Gorge.



The Graduate Fields

Aerospace Engineering

Aerospace engineering is the Field of engineering concerned with the flight of aircraft, guided missiles, and space vehicles. The objective of the Graduate School of Aerospace Engineering is to educate selected engineering and science graduates for research and advanced development in this field.

Emphasis is placed on the aerospace and associated sciences as well as on current design practice; consequently, students are encouraged to take courses in physics, mathematics, chemistry, astronomy, and allied engineering fields in order to strengthen their understanding of fundamentals. The School offers courses in fluid mechanics, gasdynamics, advanced thermal physics, plasma dynamics, dynamics of rarefied gases, aircraft structures, space mechanics, theory of viscous flows, hypersonic flow theory, acoustics and aerodynamic noise, and atmospheric motions.

A weekly colloquium and a weekly advanced seminar help students in the graduate Field of Aerospace Engineering keep informed on research and developments in this general area. Another feature is the weekly research conference at which students present regular summaries of their research progress and students and staff members are encouraged to make comments and suggestions. The conference is particularly helpful in the early phases of research.

The School emphasizes direct contact between faculty and students, who at the present time number about twenty-five. Students are also encouraged to help each other solve their research problems. The entire School operates as a research group, and a friendly, informal atmosphere is encouraged.

Facilities

Superior experimental facilities are available for laboratory studies in such areas as basic fluid mechanics, aerodynamics, gasdynamics and gas chemistry, hypersonics, rarefied gasdynamics, magnetohydrodynamics, plasma dynamics, laser chemistry, sonic boom, aerodynamic noise, geophysical fluid dynamics, radiation gasdynamics, ferro-fluidics, and general acoustics.

The School pioneered in the development of the shock tube as a research tool for studying chemical kinetics and electrically conducting gases and for supporting studies in fusion plasmadynamics and laser chemistry.

A shock tube is used in aerospace engineering research to measure rates of chemical reactions important in gas lasers.

Areas of Research

The School has emphasized research on shock tubes, magnetohydrodynamics, sonic boom, geophysical flow problems, and related areas in pollution control and atmospheric dynamics.

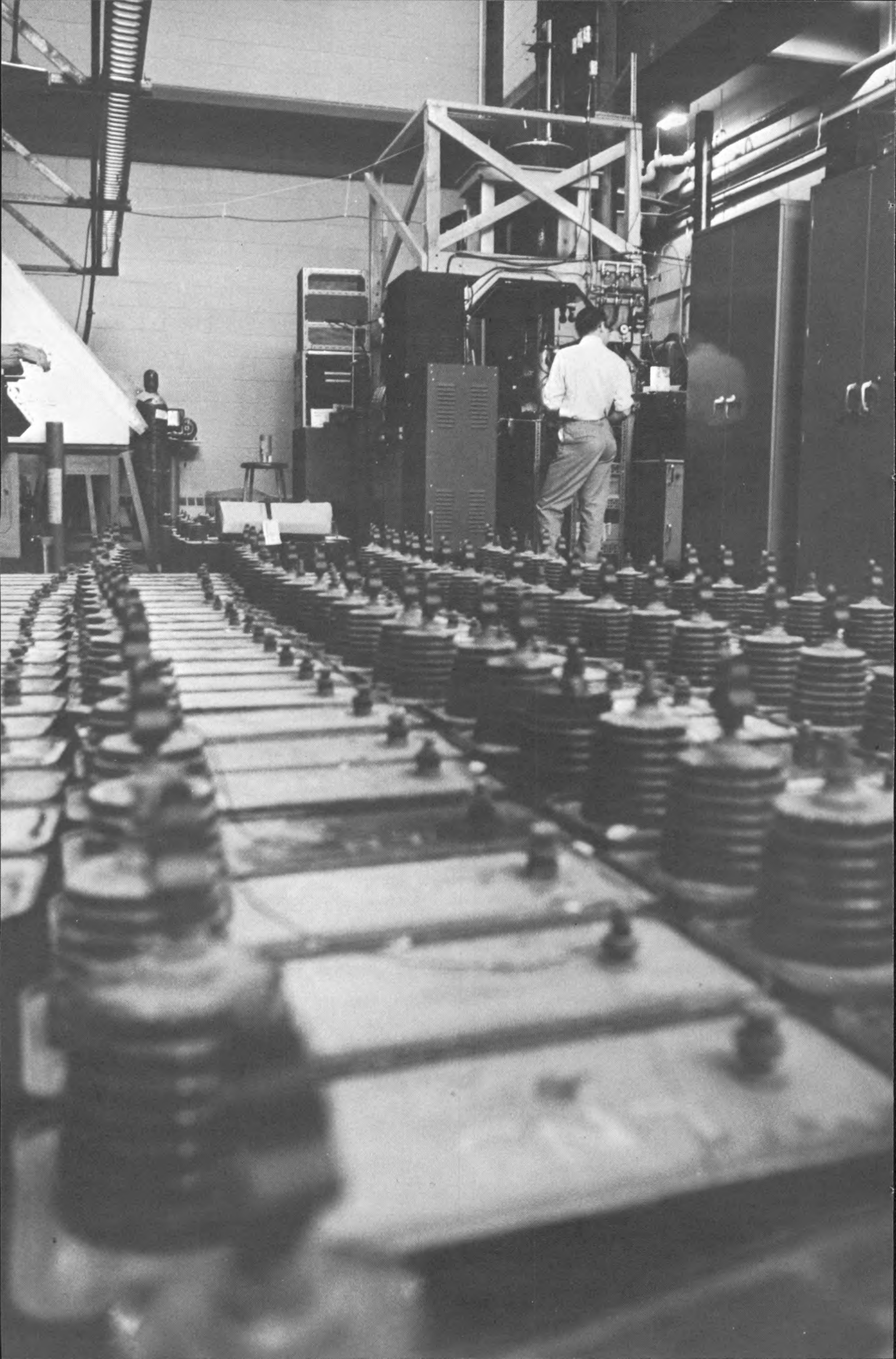
Current projects include several involving aerodynamic noise associated with compressors, turbines, and helicopters. Also under way are sound propagation studies designed to find methods for controlling the noise of aircraft, particularly around airports. The propagation of sonic boom through the atmosphere and associated phenomena are being investigated.

Chemical reactions initiated by giant laser pulses are being studied and the results are being applied to the design of other lasers. The study of interactions of high-energy laser beams with streams (laser aerodynamics) is being pursued.

Fluids that behave like a liquid magnet (ferro fluids) are being studied for propulsion applications and power-generating schemes. Fundamental fluid mechanical considerations are being applied to a study of convection cells driven by radioactivity inside the earth and the moon, and their geophysical consequences.

The application of computing techniques to the solution of fluid mechanical problems is also being investigated. The possibilities of fusion power are being explored and pollution control is being studied.

Some of the specific subjects of research by aerospace engineering faculty members and their students are indicated by the following selected list of recent publications.



Amiet, R., and Sears, W. R. 1971. The aerodynamic noise of small-perturbation subsonic flows. *Journal of Fluid Mechanics* 44:227.

Auer, P. L., and Evers, W. H., Jr. 1971. Collision free shock formation in finite temperature plasmas. *The Physics of Fluids* 14:1177.

deBoer, P. C. T. 1970. Cross sections for energy transfer in chemical coulomb collisions. *Physical Review A* 1:1631.

George, A. R. 1971. Propagation of sonic booms and other weak nonlinear waves through turbulence. *The Physics of Fluids* 14:548.

Lifshitz, A., Bar-Nun, A., deBoer, P. C. T., and Resler, E. L., Jr. 1970. Boundary layer effects on chemical kinetics studies in a shock tube. *Journal of Chemical Physics* 53:3050.

Resler, E. L., Jr. Lifting aerodynamic configurations with no sonic boom. *In Proceedings of AFOSR-UTIAS symposium on aerodynamic noise,* p. 435. Toronto: AFOSR-UTIAS.

Resler, E. L., Jr. 1971. *Ferrohydrodynamic propulsion.* Annual Report to Power Program, Office of Naval Research.

Sears, W. R., and Telionis, D. P. 1971. Unsteady boundary layer separation. In *Proceedings of IUTAM symposium on unsteady boundary layers.* Quebec, forthcoming.

Seebass, A. R. 1969. Sonic boom theory. *Journal of Aircraft* 6:177.

Shen, S. F., with Slinn, W. G. N., and Mazo, R. M. 1970. A kinetic theory of diffusely reflecting Brownian particles. *Journal of Statistical Physics* 2:251.

Turcotte, D. L., with Wilson, C. R. 1970. Similarity solution for a spherical radiation-driven shock wave. *Journal of Fluid Mechanics* 43:399.

Turcotte, D. L., with Oxburgh, E. R. 1970. Thermal structure of island arcs. *Geological Society of America Bulletin* 81:1665.

Faculty Members and Their Research Interests

Peter L. Auer, Ph.D. (California Institute of Technology): *plasma dynamics, high-power lasers, nonlinear plasma phenomena*

P. C. Tobias deBoer, Ph.D. (Maryland): *gasdynamics and gas chemistry, plasma dynamics, kinetic theory of gases, gasdynamics, automotive pollution control*

Albert Richard George, Ph.D. (Princeton): *hypersonics, fluid dynamics, aerothermochemistry, sonic boom, aerodynamic noise, general acoustics*

A plasma wind tunnel is used in an aerospace engineering research project to simulate the solar wind surrounding the earth.

Edwin L. Resler, Jr., Ph.D. (Cornell): *gasdynamics and gas chemistry, ferrohydrodynamics, laser aerodynamics*

William R. Sears, Ph.D. (California Institute of Technology): *fluid mechanics, aerodynamics, magnetohydrodynamics, aerodynamic noise*

A. Richard Seebass, III, Ph.D. (Cornell): *fluid mechanics, aerodynamics, hypersonics, magnetohydrodynamics, sonic boom*

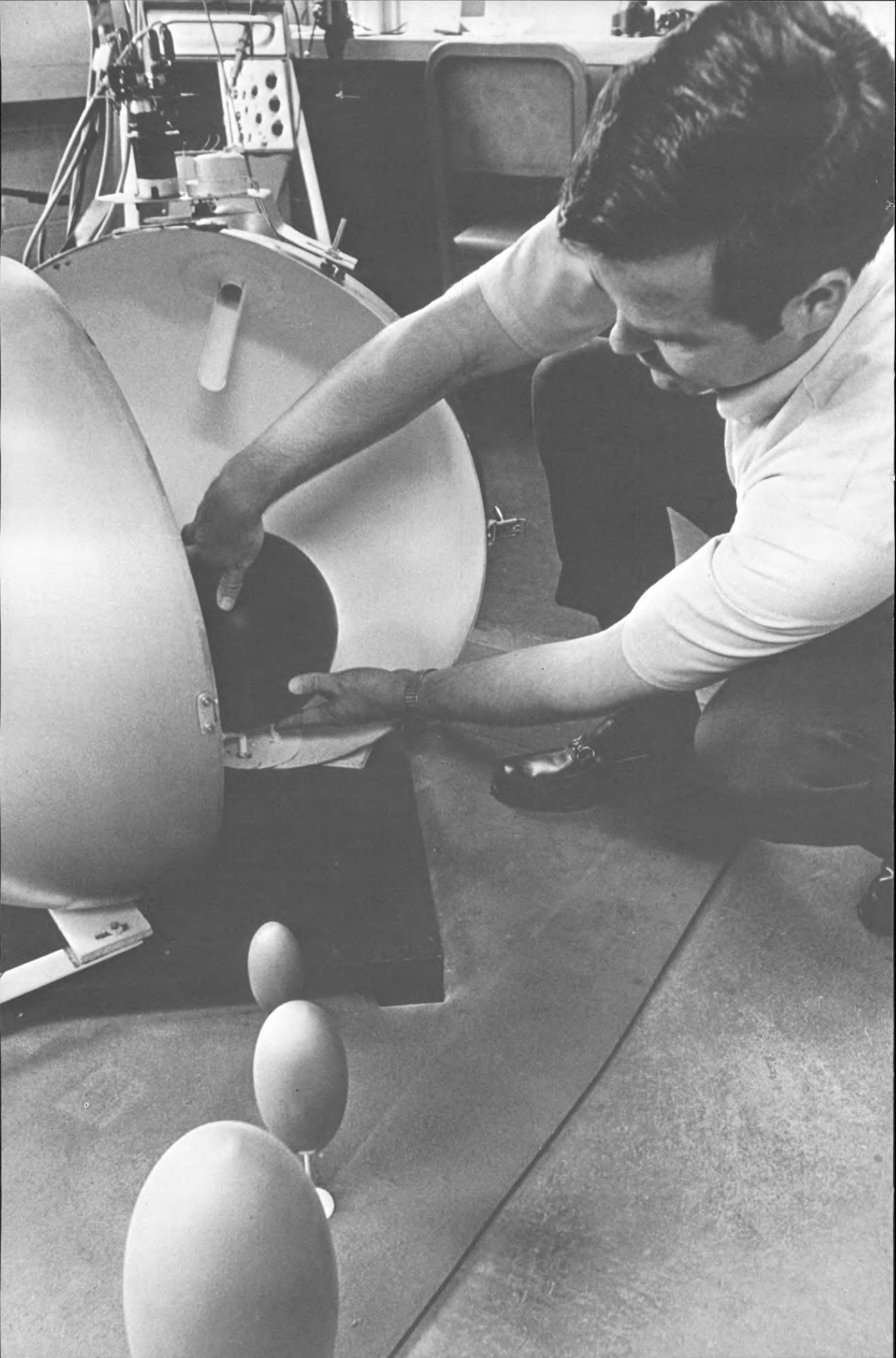
Shan-fu Shen, Sc.D. (M.I.T.): *rarefied gasdynamics, stability of flows, aerodynamics, radiation gasdynamics, computational fluid mechanics*

Donald Lawson Turcotte, Ph.D. (California Institute of Technology): *magnetohydrodynamics, plasma dynamics, aerothermochemistry, rarefied gasdynamics, geophysical fluid dynamics*

The regular faculty is supplemented by distinguished visitors from the United States and abroad. Visitors have included Hannes Alfvén, G. K. Batchelor, J. M. Burgers, L. F. Crabtree, Nima Geffen, Isao Imai, Theodore von Kàrmàn, J. W. Linnett, P. S. Lykoudis, F. E. Marble, R. S. B. Ong, E. R. Oxburgh, D. A. Spence, Ko Tamada, and Itiro Tani.

Further Information

Further information may be obtained by writing to the Field Representative, Graduate School of Aerospace Engineering, Grumman Hall, Cornell University, Ithaca, New York 14850.



Agricultural Engineering

Graduate programs of study and research in the Field of Agricultural Engineering are individually planned, but in general are organized around the major and minor subject areas listed below.

Agricultural Engineering

Bioengineering, engineering properties of biological materials, materials handling, agricultural mechanization and mechanization teaching, safety engineering, rural resource development, and all other subject areas listed below.

Agricultural Structures

Structural analysis and design, production systems synthesis, structural-biological relationships, environmental composition and control, biological response to environment, and thermodynamic processes.

Agricultural Waste Management

Biological, physical, and chemical waste treatment, moisture removal, odor control, waste handling, source control of wastes, waste management systems, and waste characterization.

Electric Power and Processing

Electrical control systems, processing of agricultural materials, and application of electromagnetic radiation to agriculture.

Power and Machinery

Agricultural machinery design and development, terramechanics, crop harvesting, handling and processing systems, metering and distribution of agricultural chemicals, physical and biological factors pertaining to machine design (such as soil mechanics in relation to seedling development), crop establishment, and secondary road systems.

Soil and Water Engineering

Surface water hydrology, drainage, irrigation, soil-plant-water relationships, hydraulics, erosion control, and tropical water management.

Geometric shapes employed as standards await their turn during calibration of an infrared reflectance measuring system used to evaluate quality changes in plant specimens.

Ph.D. candidates select one major subject area from those listed, and two minor subjects, at least one of which must be from outside the Field. Candidates for the M.S. degree take agricultural engineering as their major subject and select one minor outside the Field. Course work, though, is by no means limited to those offerings available in the major and minor subject areas; courses are individually selected on the basis of the student's background, needs, and graduate program objectives. A thesis research project is required of all M.S. and Ph.D. degree candidates. All students are expected to become proficient in statistics, computer programming, and the use of both digital and analog computers, and Ph.D. candidates are expected to complete courses in advanced mathematics.

A third graduate program leads to the degree of Master of Engineering (Agricultural). This one-year program is intended primarily to provide preparation for design and engineering practice in industry and public agencies.

Enrollment in these graduate degree programs is in the range of twenty to forty students. Details of the programs are given in the *Announcement of the Graduate School.*

Facilities

Graduate study is supported by extensive physical facilities in Riley-Robb Hall, the main agricultural engineering building. Major items of equipment include three electric dynamometers (5, 15, and 100 horsepower), a universal testing machine (120,000 pounds capacity), an Instron testing machine, and a complete machine shop. There is substantial equipment available for research studies, along with refrigerated and controlled atmosphere chambers. Computer facilities in Riley-Robb Hall, which supplement the University's general system, include electronic programmable calculators, one with X-Y recorder output, key punches, and SD 20 and 80 analog computers.

Facilities in Riley-Robb Hall and in many additional buildings allow for extensive investigation of laboratory aspects of agricultural waste management

and for waste management pilot plant studies. Plant growth chambers are located in other laboratories on the campus. In addition, the facilities of the New York State Agricultural Experiment Stations are available for graduate student research in food science and technology, entomology, plant pathology and horticulture, and fruits and vegetables.

Areas of Research

The broad spectrum of research opportunities in the Field of Agricultural Engineering is illustrated by the following brief descriptions of recent and current activities in several areas.

Biological Engineering

Knowledge of the biology of plants and animals, and their mechanical and other physical properties, is becoming increasingly important in agricultural engineering design.

For example, the high priority given to the mechanization of the harvesting, handling, and processing of all economically important fruits and vegetables has stimulated greater interest in the engineering properties of plant materials. Environmental factors affecting plant growth are being studied in order to more intelligently design the tools and machines used in crop production. These studies have been concerned with a plant's response to its environment from germination to storage. The work includes studies of such factors as heat and moisture transfer in the seedbed, oxygen diffusion to the germinating seed, and the ability of roots to penetrate compacted soils. Other investigations are concerned, for example, with assessment of the textural properties of fruits and vegetables and with the preservation of these products in storage through the regulation of the gaseous environment.

Similarly, animal production (of milk, eggs, or meat, for example) is known to be limited by environmental, nutritional, and pathological factors. Basic information is needed on those physiological mechanisms that limit animal productivity and are influenced by environment. At Cornell, biomathematical modeling, direct and indirect calorimetry, telemetry, and analog simulation techniques have been applied in attempts to understand the influences of environmental factors on animal systems.

Engineering problems involving plants and animals present a wide range of opportunity for imaginative research. The following examples of recent papers suggest the kinds of research projects now being carried out in the area of biological engineering.

Cooke, J. R. 1970. A Theoretical Analysis of the Resonance of Intact Apples. Paper read at Annual Meeting of the American Society of Agricultural Engineers, 7–10 July 1970, Minneapolis.

Machines and methods for the mechanical harvesting of fruits and vegetables are being developed in agricultural engineering projects.

Scott, N. R., Johnson, A. T., and van Tienhoven, A. 1970. Measurement of hypothalamic temperature and heart rate of poultry. *Transactions of the ASAE* 13(3): 342.

Townsend, J. S., Shepardson, E. S., Wehe, R. L., Gunkel, W. W., and Guest, R. W. 1971. An analysis of milk extraction. *Transactions of the ASAE* 14(3): 417.

Crop Establishment

Establishing the necessary plant population in the best possible geometric pattern is an essential part of any crop production system. There are many possible research studies related to seedling establishment. Examples of such studies are the selection of seeds that will be viable under a broad range of conditions; the definition and provision of an optimum environment for seed germination, seedling emergence, and root development; the precision placement of seeds with respect to depth, other seeds, and plant nutrients; the protection of emerged seedlings from pests and weather elements; and the final selection of plants to be left in the field to produce the crop.

Current research related to crop establishment deals with seed coatings, precision planting, stone removal, and plant thinning. Recent publications in this area include the following.

Millier, W. F. and Sooter, C. 1967. Improving emergence of pelleted vegetable seed. *Transactions of the ASAE* 10(5): 658.

Millier, W. F. 1971. Progress report on seed pellets. *New York's Food and Life Sciences Quarterly* 4(2–3): 13.

Highway Engineering

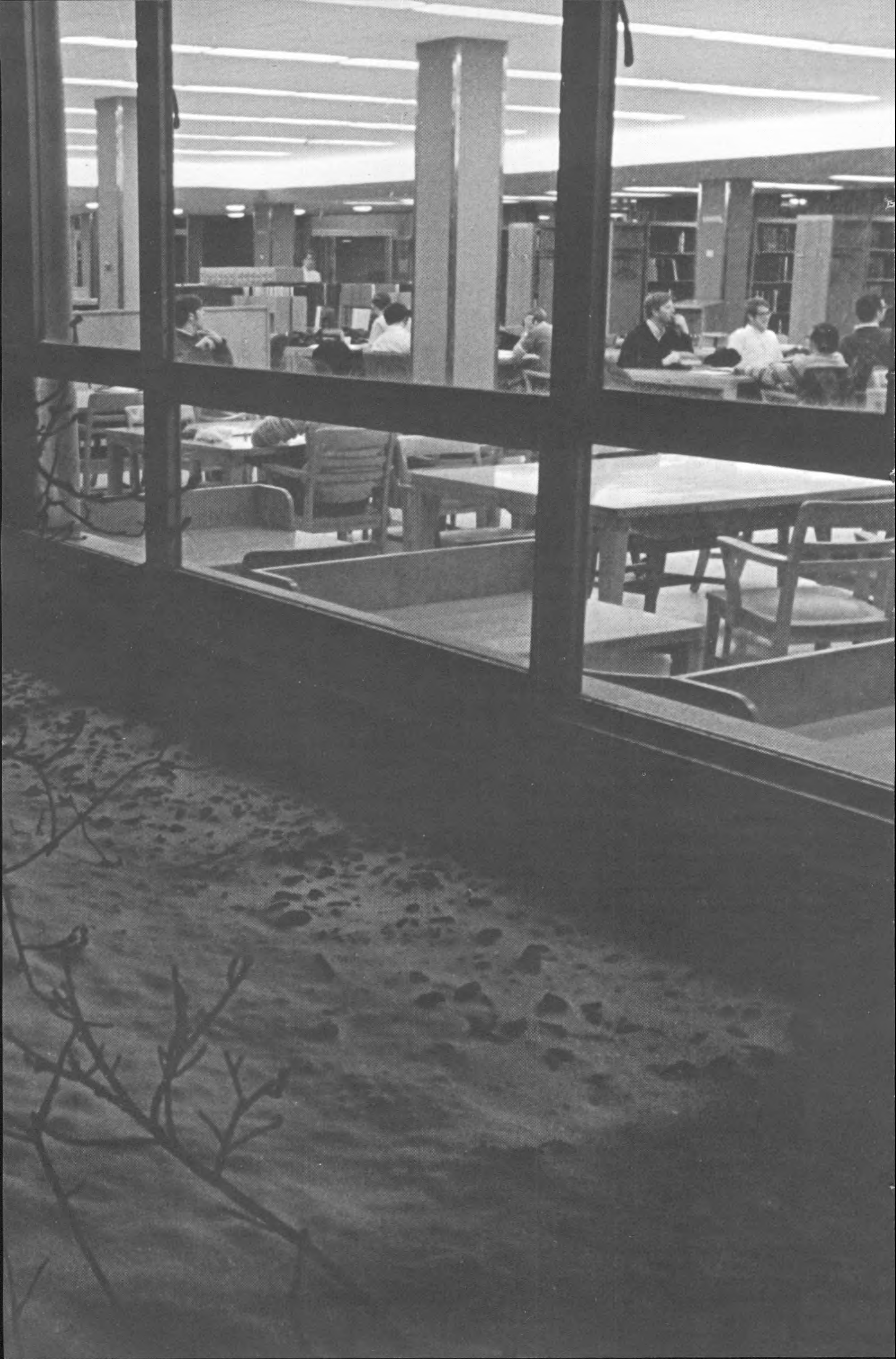
Research in the area of highway engineering has been stimulated primarily by problems with local rural roads in New York State. Facilities for research in road materials include equipment for performing physical tests on soils, stabilized soils, and bituminous paving mixtures. Recent papers in this field include the following.

Hewitt, W. L., and Slate, F. O. 1967. The effects of the rheological properties of asphalt on strength characteristics of asphalt concrete. In *Proceedings of the second international conference on the structural design of asphalt pavements,* p. 757. University of Michigan.

Spencer, J. W. 1970. Controlling Bleeding of Bituminous Surfacings. Paper read at Sixth World Highway Conference, 4–10 October 1970, Montreal.

Mechanical Harvesting

A continuing program of developing mechanical harvesting techniques for fruits and vegetables is now concentrated on the harvest of fresh market apples, apples for processing, cabbage, lettuce, grapes, and cherries. Projects under way are generating data on fundamental physical properties of the products and on the static and dynamic behavior of their plant structures, and this information is being used in the development of harvesting techniques and equip-



ment. The preservation and sorting of products is also being studied. A complete systems approach, including economic as well as engineering factors, is stressed in this research.

Examples of recent departmental publications in this area are:

Davis, D. C. and Rehkugler, G. E. 1969. A Theoretical and Experimental Analysis of the Apple-Limb Impact Problem. Paper read at the Winter Meeting of the American Society of Agricultural Engineers, 9–12 December 1969, Chicago.

Rand, R. H. and Cooke, J. R. 1970. Vibratory fruit harvesting: a nonlinear theory of fruit-stem dynamics. *Journal of Agricultural Engineering Research* 15(4): 347.

Shepardson, E. S., Markwardt, E. D., Millier, W. F., and Rehkugler, G. E. 1970. *Mechanical harvesting of fruits and vegetables.* New York's Food and Life Sciences Bulletin, no. 5 (Physical Sciences: Agricultural Engineering bulletin no. 1). Ithaca: Cornell University.

Specialized Machinery Design

The design of specialized agricultural and industrial equipment is required when high costs, scarcity of labor, and lack of suitable machinery prevent efficient operation. Detailed studies of design requirements, linked with imaginative exploitation of scientific knowledge, are imperative to achieve the desired result. A few examples of research in this area include the development of transplanting equipment, a seed tape, a leaf baler, a stone-soil separator, snow removal equipment, and a highway litter removal machine. Investigations of milking machines are also currently under way. The following recent papers illustrate typical projects.

Gunkel, W. W., Lorbeer, J. W., Kaufman, J., and Smith, H. A., Jr. 1971. Artificial drying—a method for control of botrytis neck rot in bulk stored onions. In *28th Annual Progress Report, New York Farm Electrification Council, Agricultural Engineering Department, N.Y.S. College of Agriculture and Life Sciences,* p. 71. Ithaca: Cornell University.

Rowe, R. J. and Gunkel, W. W. 1971. Simulation of Temperature and Moisture Content of Alfalfa during Thin-Layer Drying. Paper no. 71–112 read at the Annual Meeting of the American Society of Agricultural Engineers, June 1971, Pullman, Washington.

Structures and Environment

The accelerating trend toward highly specialized farmstead production systems presents research challenges related to the handling, processing, and storage of agricultural products and the housing and maintenance of animals. Associated areas of research include operational design; structural design; response to environmental factors, including modified atmospheres; spatial organization; and enclosure conditioning.

Present research projects include work on the controlled-atmosphere storage of fruits and vegetables and in construction techniques and materials for controlled-atmosphere enclosures.

Recent papers in this area include the following.

Allison, J. M. and Furry, R. B. 1971. Diffusion of Oxygen through Cabbage Leaf Disks under Controlled Atmosphere Conditions. Paper no. 71–346 read at the Annual Meeting of the American Society of Agricultural Engineers, June 1971, Pullman, Washington.

Lorenzen, R. T. 1970. Modes of Structural Failure at Critical Snow Load. Paper read at Annual Winter Meeting of the American Society of Agricultural Engineers, 8–11 December 1970, Chicago.

Wahla, M. I., Scott, N. R., and Nilson, A. H. 1971. Direct measurement of bond-slip in reinforced concrete. *Transactions of the ASAE* 14(4): 141.

Surface and Subsurface Drainage, Water Conservation, and Irrigation

This area of concentration deals with the application of engineering principles to problems of soil and water control in agriculture. It is also concerned with the design and construction of drainage systems (surface and subsurface), the development and evaluation of drip or trickle and sprinkler irrigation systems, and frost protection techniques.

Primary research interests at the present time are hydrologic response of agricultural practices, hydraulics of agricultural structures, irrigation system design, and soil-plant-water relationships. The following publications are among recent ones in this area of research.

Black, R. D. 1971. Land drainage. In *Encyclopedia of Science and Technology,* vol. 7, p. 440. New York: McGraw-Hill.

Dunne, T. and Black, R. D. 1970. An experimental investigation of runoff production in permeable soils. *Water Resources Research* 6(2): 478.

Tropical Irrigation and Drainage

Modern agricultural technology has demonstrated the potential for great increases in agricultural productivity in the tropics. The application of this technology is limited, however, by irrigation and drainage problems in these regions. Numerous problems in the areas of soil-plant-water relationships, system design, operation, and maintenance remain to be solved. Research in this area is being conducted primarily in the Philippines, although opportunities exist for studies in Taiwan and Malaysia. The following papers are examples of publications resulting from research on these problems.

DeDatta, S. K., Levine, G., and Williams, A. 1970. Water management practices and irrigation requirements for rice. In *Rice production manual,* pp. 89–95. College, Laguna: University of the Philippines, College of Agriculture, in cooperation with the International Rice Research Institute.

The Engineering Library is located in Carpenter Hall, which also houses the administrative offices of the College.

Levine, G. 1970. The Water Environment and Crop Production. Paper read at Cornell Workshop on Some Emerging Issues Accompanying Breakthroughs in Food Production, 30 March–3 April 1970, Cornell University, Ithaca.

Waste Management

The agricultural waste management problem in the United States is as complex and challenging as the problem of improving the quality of our environment. The trend toward confinement feeding of livestock, the increasing size of food processing operations, and the high concentrations of waste per unit area, as well as the necessity to avoid water, air, and soil pollution, make a successful attack on the waste management problems facing agriculture imperative.

A well-equipped laboratory is available at Cornell for research on many aspects of waste management, including odor reduction and control, liquid waste treatment, handling and disposal techniques, waste characteristics, solid waste management, treatment process control, and systems analysis and modeling. A large pilot plant and a laboratory are available for demonstrating the handling and treatment processes that prove feasible on a smaller scale.

Current research efforts include projects on tertiary treatment of animal waste waters; feasible handling and treatment processes and analytical models for animal waste management; poultry waste disposal and odor control; disposal and utilization of dairy and poultry manure by land application; poultry manure properties, handling, and disposal; and the establishment of design parameters for agricultural waste management systems.

A great many publications result from work in this area; a few examples are listed below.

Loehr, R. C. 1971. Alternatives for the treatment and disposal of animal wastes. *Journal of the Water Pollution Control Federation* 43: 668.

Proceedings of the Cornell Agricultural Waste Management Conference, 1969, 1970, 1971, 1972.

Faculty Members and Their Research and Teaching Interests

Richard D. Black, P.E., Ph.D. (Illinois): *drainage of agricultural land, small watershed hydrology, soil conservation structures*

J. Robert Cooke, Ph.D. (North Carolina State): *biological engineering, environmental control of plants and plant growth, engineering properties of biological materials, mathematical engineering analysis*

Edward W. Foss, M.S.A. (Cornell): *safety engineering, community resources development, and teaching agricultural mechanization*

Orval C. French, M.S.A.E. (Kansas State): *mechanization for agricultural production*

Ronald B. Furry, Ph.D. (Iowa State): *plant and animal structures and environments, controlled-atmosphere storage of fruits and vegetables, similitude methodology*

Richard W. Guest, P.E., M.S. (North Dakota State): *mechanics of machine milking dairy cows; harvesting, storage, and utilization of high moisture corn*

Wesley W. Gunkel, Ph.D. (Michigan State): *design of specialized agricultural and industrial machinery, mechanical methods of disease control, seed environment*

Douglas A. Haith, Ph.D. (Cornell): *management of agricultural systems for environmental quality control, water resource systems*

Fred G. Lechner, Ed.D. (Michigan State): *teaching agricultural mechanization in secondary schools, two-year technical colleges, and four-year colleges*

Gilbert Levine, Ph.D. (Cornell): *irrigation system design, tropical irrigation, water management, soil-water-plant relationships*

Raymond C. Loehr, P.E., Ph.D. (Wisconsin): *waste treatment, process control, solid wastes, industrial wastes, treatment systems, agricultural waste management*

Robert T. Lorenzen, P.E., M.S. (California): *farmstead production systems design including structural and environmental aspects of enclosures, functional tenets of systems*

David C. Ludington, Ph.D. (Purdue): *management of agricultural wastes to reduce air and water pollution*

Everett D. Markwardt, M.S. (Cornell): *mechanical fruit and vegetable harvesting, irrigation systems*

William F. Millier, P.E., Ph.D. (Cornell): *seed coating, crop establishment, tree harvesting, farm machinery*

Gerald E. Rehkugler, P.E., Ph.D. (Iowa State): *mechanical harvesting of fruits and vegetables, physical properties of biological products, automatic control of agricultural machinery, use of internal combustion engines and other energy sources in agriculture*

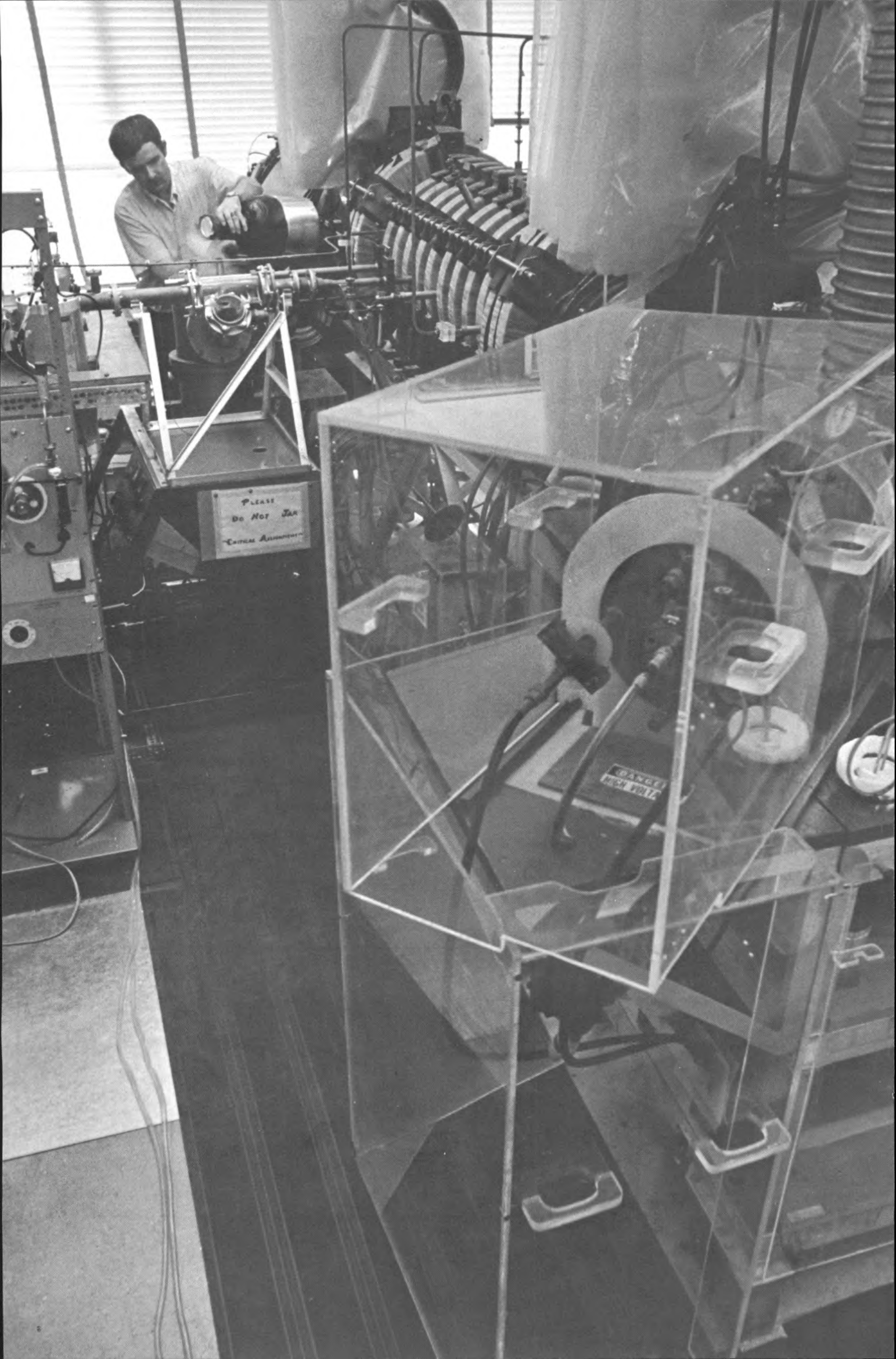
Norman R. Scott, Ph.D. (Cornell): *biomathematical modeling of animal systems; animal calorimetry; environmental physiology; thermal environment; integrated application of structural theory, thermodynamics and biological sciences to synthesis of structural systems; electronic instrumentation techniques in physical and biological measurements*

E. Stanley Shepardson, M.S. (Cornell): *power and machinery, mechanical harvesting, electric power and processing*

James W. Spencer, Ph.D. (Stanford): *bituminous road surfacings, evaluating and upgrading gravels for use in road foundations, engineering-economic analysis of alternatives for road improvement*

Further Information

For more detailed information on current teaching, research, and extension activities of the Department of Agricultural Engineering, request a copy of *Department of Agricultural Engineering: The Staff and Program,* which is published each fall. Included are descriptions of continuing and new research projects, listings of the faculty and staff members and graduate students involved in each project, and the major cooperating units in interdisciplinary projects. Inquiries concerning any aspect of the graduate program may be directed to the Coordinator of Graduate Instruction in Agricultural Engineering, Riley-Robb Hall, Cornell University, Ithaca, New York 14950.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Applied Physics

The graduate Field of Applied Physics offers opportunities for the pursuit of advanced studies leading to original work in many areas of applied science in which the activity is based on the principles and techniques of physics. Programs provide a means for students with undergraduate training in physics to branch out into applied science while continuing the study of physics, and for students with a background in engineering or another science to extend their knowledge of basic physics.

Individual programs are planned to meet the needs and interests of each student. They may involve several academic disciplines and topics that are undergoing transition from fundamental physics to applied science. Approximately sixty graduate students are now pursuing a wide variety of programs in Applied Physics.

The faculty of the Field is centered in the School of Applied and Engineering Physics of the College of Engineering, but it includes members of various other departments of the University. Many members are associated with one or more of the interdisciplinary laboratories at Cornell, such as the Laboratory of Plasma Studies, the Materials Science Center, and the Center for Radiophysics and Space Research.

Because of the diversity of faculty capabilities and interests, the Field of Applied Physics provides graduate students an unusually wide range of choice in their areas of specialization. An equally important benefit of the interdisciplinary nature of the Field is the extensiveness of the research facilities that are available.

An important consideration in the choice of a field for graduate study is the availability of career opportunities; in the area of applied physics the prospects are good. Although the opportunities for careers in basic physics have substantially leveled off in recent years, there has been a strong long-range need in industry, government, and universities for graduates who not only have a sound education in physics but also have the capability for attacking practical problems. Approximately four out of five Cornell Applied Physics graduates assume positions with industrial organizations that are seeking to develop new technologies and new products. About one in five enters academic work, and a smaller number begin careers in governmental or related laboratories or programs.

Mechanisms for plasma heating by turbulence are being studied by means of microwave scattering and neutral particle analysis.

Facilities

Because of the interdepartmental and interdisciplinary nature of the Field of Applied Physics at Cornell, the available research facilities are much more extensive and unique than those generally provided by a single department.

For example, sophisticated techniques for electron microscopy and electron spectroscopy, for x-ray analysis and metallography, for special materials preparation, for chemical analysis, and for studies at very high or low pressure or very high or low temperatures are provided by the facilities of the University's Materials Science Center (see page 91 for a description of the Center). Other facilities include the radar-radio observatory in Arecibo, Puerto Rico (see page 89) and the unique high-current relativistic electron beam facility of the Laboratory of Plasma Studies (see page 91). In the Ward Laboratory of Nuclear Engineering (see page 73) students can use a fast-pulsed TRIGA neutron reactor, an x-ray irradiation cell, a low-flux nuclear critical facility, and a high-current charged-particle accelerator (Dynamitron) for energies up to 3 MeV.

Areas of Research

Broad applicability is a characteristic of physical methods of analysis and measurement, and a great number of these methods are being applied in many research areas within the Field of Applied Physics. Examples of the various programs now under way are described briefly in nine general groups. The names of professors who are working with specific projects are indicated in parentheses.

Solid State Physics

Research in solid state physics is conducted over a range of specific subject areas, such as defects and physical properties, superconductivity, quantum electronics and microwaves, phase transformations, and surface physics; and many approaches, from theory to experiment, are employed. As an example, phase transformations and transport properties are studied in ferroelectrics and superconductors, on crystal surfaces, at high pressures, and within single crystals of a two-component solid. The tools for the studies include theoretical analysis, x-ray and electron diffraction, light and microwave scattering, electron spectroscopy, field ion microscopy, and ultrasonics.

Many of the research projects in the area of solid state physics involve faculty members who hold appointments in other engineering disciplines such as electrical engineering, mechanical engineering, and materials science and engineering, and additional information may be found in the sections of this *Announcement* that are devoted to those Fields.

A major area of interest in solid state physics is the study of imperfections and their relation to the physical properties of crystals. Crystal imperfections are studied by relaxation techniques, in particular by anelastic and dielectric measurements. When extended over wide frequency and temperature ranges, such investigations provide information about the symmetry of the defects, their mobility, their mutual interactions, and their coupling to the lattice (Sack).

Current research in superconductivity is involved with many different solid state aspects of matter. The dynamical features of x-ray scattering are being used in a study of both imperfections and phase transformations in solids (Batterman). Study of the fluctuations in superconductors is of interest because of the macroscopic quantum coherence, characteristic of the superconducting state, that limits the fluctuation process. The structural effects on hysteresis are of interest because they determine the critical supercurrent density, a property of great technical importance (Webb). Superconductivity is being studied at magnetic fields up to 100,000 gauss and temperatures between 0.03 and 30°K; magnetometers with magnetic field resolutions of 10^{-9} at fields up to 2,000 gauss have been developed and are being used.

Other research in this general area is concerned with structure studies of phase transformations associated with high-field superconductors such as V_3Si and Nb_3Sn (Batterman), and with the properties of flux line lattices in Type II superconductors where pinning of the flux line by crystal defects can be very important in achieving high critical currents (Kramer). Direct electron microscopy observations of flux line lattices by surface decoration with small (40 Å) ferromagnetic particles are under way (Silcox).

There are many phenomena associated with the periodic or the defect properties of three-dimensional solids that are strongly influenced by the presence of surfaces and interfaces. The study of electron and atomic structure of crystal surfaces is a well-established program in solid state physics. Surface phenomena of current interest include inelastic and elastic scattering of electrons, atoms, and ions by solid metal surfaces and the development of dynamical theory of multiple scattering by electrons in the low energy range (Rhodin). The macroscopic surface properties associated with surface-thermodynamics and with transport are also under active study for ionic crystals and semiconductors (Blakely). Surface studies of gas-metal reactions by both low-energy electron diffraction (Blakely and Rhodin) and by high-energy electron diffraction (Batterman and Siegel) are also major research areas. Electron energy loss measurements at high electron energies (75 Weber) focus on electron excitations in the energy range 1-100eV (Silcox).

An active research program is under way in the area of solid state semiconductor physics. This involves quantum electronics and microwave behavior associated with harmonic emission from solid state microwave oscillators such as Gunn-effect, limited-space-charge-accumulation, and avalanche diodes (Ballantyne). The epitaxial growth of intermetallic compound crystals such as gallium arsenide and the use of these for microwave oscillators based on the transferred electron effect are also being studied (Eastman). Other projects under way involve study of epitaxial growth of silicon crystals and diffusion and sputtering processes in silicon and other semiconductor microwave devices (Lee). Aspects of these projects are also described in the section on Electrical Engineering in this *Announcement.*

Since many important solid state properties are structure-sensitive, study of phase transformations is often an important approach to such specific phenomena as charge distribution and electron transport in solids. Phase transitions in ferroelectric crystals and their relationship to the lattice dynamics of the material are being studied with use of dielectric spectroscopy (Ballantyne).

The relation of phase transformation to the phenomenon of superconductivity is of interest in several projects. The low-temperature phase transformation in the hard superconductors V_3Si and Nb_3Sn is under investigation (Batterman). Also of great interest from this viewpoint is an investigation of the possibility that metallic hydrogen produced at high pressures will exhibit a superconducting transition temperature in the neighborhood of room temperature. This work involves pressure-volume measurements on solid molecular hydrogen at pressures of up to 30 kilobars (Ruoff). (See also a discussion of this project under the section on Materials Science and Engineering.)

Some recent typical publications in the area of solid state physics are the following.

Batterman, B. W., and Colella, R. 1970. X-ray determination of the phonon spectrum in vanadium. *Physical Review B* 1:3913.

Baukus, J., and Ballantyne, J. 1971. Extension of Fourier spectroscopy to centimeter wavelengths. In *Proceedings of the Aspen international conference on Fourier spectroscopy,* p. 415.

Byer, N. E., and Sack, H. S. 1968. Ultrasonic velocity and attenuation in alkali halides containing CN^-. *Physica Status Solidi* 30:569.

Henkels, W. H., and Webb, W. W. 1971. Intrinsic fluctuations in the driven Josephson oscillator. *Physical Review Letters* 26:1164.

Silcox, J., and Curtis, G. H. 1971. A Wien filter for use as an energy analyzer with an electron microscope. *Review of Scientific Instruments* 42:630.

Tong, S. Y., and Rhodin, T. N. 1971. Interpretation of low-energy electron-diffraction spectra for a free-electron metal in terms of multiple scattering involving strong inelastic damping. *Physical Review Letters* 26:711.

Plasma Physics

A unified, interdisciplinary approach to plasma studies at Cornell provides the opportunity for graduate study in this area in combination with work in applied physics, aerospace engineering, chemistry, electrical engineering, thermal engineering, or physics. Much of the experimental work is conducted at the interdepartmental Laboratory of Plasma Studies (see page 91). Several professors within the Field of Applied Physics are actively involved in plasma research, with approximately equal attention to experimental and theoretical aspects.

Most of the current effort at Cornell is centered on confinement and heating problems in controlled thermonuclear research. Studies of various magnetic configurations and of instabilities and waves in plasmas are under way. Investigations of turbulence induced by strong electric fields are also in progress; the new high-current relativistic electron beam has good potential applications in this field. In addition to controlled thermonuclear studies, research is being done on collisionless shock-waves, solar, magnetospheric and ionospheric plasma physics, plasma turbulence, kinetic theory, and magnetohydrodynamic power converters.

The dynamical behavior of fully ionized plasmas is being studied with use of a plasma wind tunnel under conditions in which collective plasma effects are important but ordinary collisions between single particles are not. (Auer, deBoer, and Resler). These studies relate to the understanding of collision-free shock formation and the nature of the earth's bow shock in the solar wind. Experimental studies of magnetohydrodynamics involve the use of shock tubes and both pressure-driven and electrically driven gas discharge devices in the radio-frequency plasma range. Now under study are channel flow and body flow, and forward-facing waves and wakes (Resler and Turcotte).

One of the most potentially useful experimental facilities in plasma studies is the high-power, fast-pulsed relativistic electron beam. At the present time two potential applications of these beams for thermonuclear fusion are being investigated. First, the magnetic field associated with the electron beam may be useful for producing magnetic-field configurations that, according to theoretical predictions, will provide stable confinement of fusion plasmas. Second, the total energy content of these beams is quite sizeable compared with plasma energies generally encountered in controlled-fusion experiments, and the beam may thus be used for heating such plasmas (Fleischmann). In another project, the possibilities for the heating of a fusion plasma by strong turbulence effected by the electron beam is being investigated (Wharton). This research is also discussed in the section on Electrical Engineering (see page 51).

Theoretical aspects of plasma problems are also being studied. A considerable part of this effort concentrates on theoretical aspects of the mentioned applications of high-current relativistic electron beams for fusion research (Sudan, Rostoker, and Auer). Also being considered are nonlinear processes in plasmas and in plasma turbulence (Sudan), instabilities in space plasmas (Sudan), the interaction of microwaves with electron beams (McIsaac), shock waves in plasmas (Auer), and kinetic theories of plasmas (Liboff).

The following papers on aspects of plasma physics are among those recently published.

Andrews, M. L., Davitian, H., Fleischmann, H. H., Kusse, B., Kribel, R. E., and Nation, J. A. 1971. Generation of astron-type E-layers using very-high-current electron beams. *Physical Review Letters* 27:1428.

Auer, P. L. 1970. Ion gyroradius effect in the solitary pulse. *Bulletin of the American Physical Society, Series II* 15:1433.

de Boer, P. C. T., Grimwood, P. R., and Johnson, R. A. 1970. Electric ion-collecting probes governed by connection and production. In *Proceedings of the 7th international shock tube symposium,* ed. I. I. Glass, p. 795. Toronto: University of Toronto.

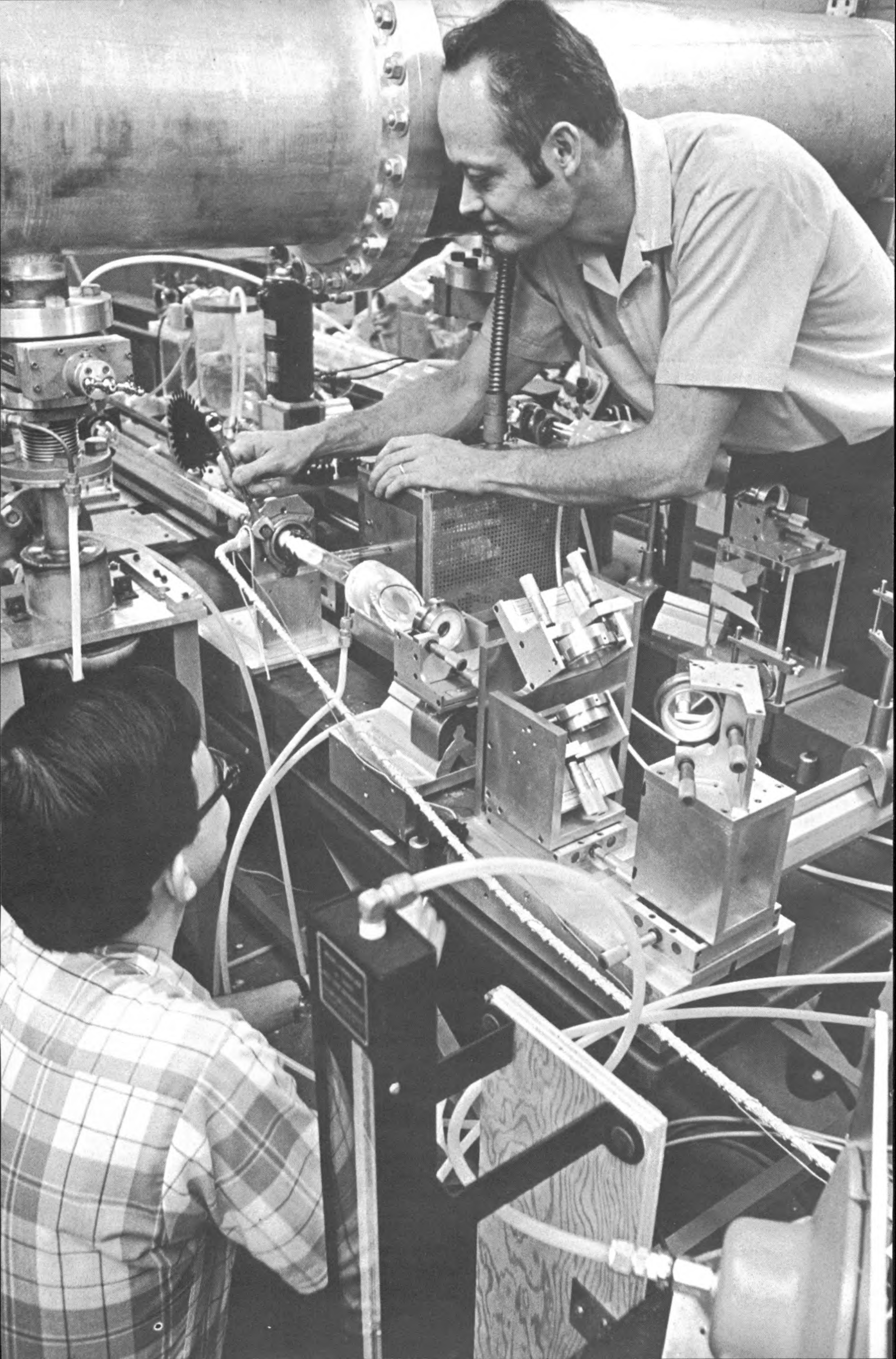
Ott, E., and Sudan, R. N. 1971. Finite beta equilibrium of relativistic beams in toroidal geometry. *Physics of Fluids* 14:12.

Rostoker, N., Fleischmann, H. H., Bzura, J., and Andrews, M. L. 1970. Effects of a magnetic guide field on the propagation of intense relativistic electron beams. *Physics of Fluids* 13:1322.

Quantum Optics, Laser Physics, and Nonlinear Optics

One of the more dramatic recent developments in basic physics is the discovery and application of the laser as a source of coherent intense radiation. Research in this field combines many aspects of optics, atomic and molecular physics, solid state physics, and general quantum mechanics, and a number of groups at Cornell collaborate closely in laser research projects. Involved are groups in Electrical Engineering and Mechanical Engineering (see also the discussions in this brochure under these Fields) as well as in basic and applied physics.

The engineering work is concerned mainly with studies of atomic and molecular gas lasers and associated problems. One of the most significant features of this work is the recent development of a DF-CO_2 fluid-mixing laser, which is the first continuous wavelength laser to derive its radiation solely from chemical sources (see the September 1968



issue of *Scientific American* for a general review). A new, high-capacity flow system has been constructed to accommodate a variety of experiments with continuous wavelength high-speed flow lasers, operating with either subsonic or supersonic flows. Gain measurements transverse to the flow direction provide much insight into the physical mechanisms that are important for practical laser operation (Cool).

Other aspects of modern laser physics that are under investigation include ionized rare gas lasers, molecular lasers, dynamic and nonlinear properties of lasers, and the properties of nonlinear optical crystals (Tang). Spectroscopic and quantum electron properties of atomic lasers (Cd^+), molecular lasers (CO_2 and N_2O) and chemical lasers also offer a broad program of fruitful research (Wolga, McFarlane, and Bauer).

Some recent typical publications in this area are:

Cool, T. A., Shirley, J. A., and Stephens, R. R. 1970. Operating characteristics of a transverse-flow DF-LD_2 purely chemical laser. *Applied Physics Letters* 17:278.

Lin, M. C., and Bauer, S. H. 1970. A chemical CO laser. *Chemical Physics Letters* 7:223.

Wolga, G. J., and Djeu, N. 1971. Optical saturation of a single vibration-rotation transition in the fundamental of SF_6. *Journal of Chemical Physics* 54:774.

Low-Energy Nuclear Physics

Research and instruction in nuclear structure and low-energy nuclear physics is conducted by staff who are members of both the graduate Field of Applied Physics and the graduate Field of Nuclear Science and Engineering. The student interested in this area can follow essentially the same program in either Field; the choice depends on the aspect he wishes to emphasize. If he wishes to concentrate his minor in engineering applications such as nuclear power, Nuclear Science and Engineering is the more appropriate Field. If his interests are more basic or are in applications of nuclear physics in other sciences such as astrophysics or geophysics, Applied Physics may be the more suitable Field. In either Field he can construct an individualized program in consultation with faculty members on his Special Committee.

The facilities for experimental research in nuclear physics are housed in the Ward Laboratory. For a description of the facility, see the section of this *Announcement* on Nuclear Science and Engineering. Descriptions of specific research projects now under way are also given in that section.

Astrophysics

Astrophysics is an area in which Cornell has gained world-wide attention over the past few years. Special efforts are directed toward studies of the lunar surface, planetary surfaces and atmospheres, infrared radiation from cosmic objects, the theory of high-energy objects such as quasars and pulsars, and radio and radar astronomy. Some of the faculty members of the Field of Applied Physics who are involved in these projects hold appointments in the Department of Astronomy or in the School of Electrical Engineering. Additional information may be found in the Electrical Engineering section in this *Announcement.*

By mixing reactive gases, powerful coherent infrared radiation is produced directly in this laser without any external power source.

In addition to extensive astrophysics laboratory facilities in Ithaca, there is available the National Astronomy and Ionosphere Center Observatory, which is operated by Cornell University at Arecibo, Puerto Rico. This facility, which has a 1,000-foot radio-radar telescope, the world's largest, is presently being upgraded to operate at much shorter wavelengths than had heretofore been possible, and so improve radar sensitivity by a factor of 2,000. This will provide exceptional research opportunities for graduate students. Previously, some students in applied physics have started on outstanding careers through their work in astrophysics at Cornell.

Through careful observations with high signal-to-noise ratio, made at Arecibo, the characteristics of pulsars are being defined. The observations have already provided the fundamental information that neutron star matter exists in the universe and is encountered in pulsars; and that the enormous energy release from these objects comes from the braking of their spins. The measurements, made sometimes with microsecond resolution, identify complex sets of phenomena that occur within the individual pulsar pulses. In this phenomenon each pulsar has its own signature, but the underlying physics is not yet understood (Drake).

Infrared observations of regions where stars are now being formed have been conducted using a variety of new techniques. The instruments are developed at Cornell and ground-based observations are made at observatory sites in the western United States. Because the atmosphere is opaque in most of the infrared spectral range, rocket-borne telescopes have been constructed and launched to observe the sky from above the atmosphere. Besides yielding information on the infrared radiation coming from cosmic sources, rocket flights have also provided new data on the thermal structure and composition of the upper atmosphere (Harwit).

A study of very low-frequency emissions that originate in the magnetosphere includes experimental testing of a theoretical explanation of the phenomenon. The mechanism for the generation of these emissions is thought to be closely associated with a process in which high-energy electrons drive whistler waves to instability. In an experiment to verify some of the theoretical predictions, the approach is to launch circularly polarized electromagnetic waves on a plasma column and observe the interactions with an electron beam having both longitudinal and rotational energy (Sudan, Kuckes, and Wharton).

Among recent publications in this field are:

Drake, F. 1970. Radio observations of the Crab Nebula. In *Publications of the Astronomical Society of the Pacific,* vol. 82, no. 486. Provo, Utah: Astronomical Society of the Pacific.

Harwit, M., Houck, J. R., and Fuhrmann, K. 1969. Rocket borne liquid helium cooled telescope. *Applied Optics* 8:473.

Kuckes, A. F. 1971. Lunar electrical conductivity. *Nature* 232: 249.

Geophysics

Cornell has an expanding program in solid earth geophysics, with emphasis on the application of the basic sciences to the solution of problems of geology. Much of the work in this area is being done by members of the Department of Geological Sciences (see page 57), and some is being done in Aerospace Engineering (see page 9).

A program of seismological observations in various parts of the world provides raw data for studies of earthquakes and of earth structure. Through the unifying new geological theory of *plate tectonics,* these studies are related to those of other disciplines and lead to a better understanding of the earth and its use (Oliver and Isacks).

A theoretical and experimental investigation of solid state mantle convection is also being carried out. The purpose of the study is to determine the structure of convection cells within the earth and to interpret their interactions with the surface in terms of the global *plate tectonic* theory. These studies are also being extended to the interiors of other planets and the moon (Turcotte).

Some publications which summarize this research are:

Oliver, J., Isacks, B., and Sykes, L. R. 1968. Seismology and the new global tectonics. *Journal of Geophysical Research* 73:5855.

Turcotte, D. L., and Oxburgh, E. A. 1969. Continental drift. *Physics Today* 22(4):30.

Webb, W. W., and Hayes, L. E. 1967. Dislocations and plastic deformation of ice. *Philosophical Magazine* 16:909.

Biophysics

The interdisciplinary field of biophysics includes the many areas in which the study of biological systems and biogenic materials may be approached using the methods and procedures of physics. The members of the faculty and staff of the Field of Applied Physics at Cornell who direct their research to biophysical problems are particularly interested in photobiology, the functional ultrastructure of cells, and the configuration and molecular structure of biogenic macromolecules. Their close collaboration with researchers in the Division of Biological Sciences and in the molecular biophysics program in the Department of Chemistry provides a wide range of opportunity for interested students. There are also projects under way which have applications in the study of biomedical engineering.

The chemistry of photosynthesis takes place in reaction centers that can be isolated from their natural environment (photosynthetic bacteria as well as green plants). The reaction centers, aside from their importance for understanding the mechanics of photosynthesis, are interesting objects for the study of molecular spectroscopy, quantum electron physics, and oxidation-reduction photochemistry. Experimental research in this area includes biochemical preparations and chemical analyses as well as physical methods of absorption-emission spectroscopy (Clayton).

The electrical properties of plant cell membranes are of particular interest because it is becoming clear that they strongly affect the properties of the systems responsible for active transport (ion pumps) rather than the passive movement of ions. The microelectrode techniques used in these studies are also being used to investigate the role of intercellular connections in long-distance transport and the electrophysiology of the *Drosera* tentacle (Spanswick).

Physical methods are also being used in studies of nerve cells and innervated structures, secretory cells, and developing (embryonic) cells. New methods are being developed for studying the physiology of these cells on a fine-structural level. The most important recent example is the application of quantitative electron microscope autoradiography (that is, the high-resolution detection of radioactivity inside cells) to the study of cellular function. By introducing radioactive precursors into the cell, one can localize the compartments within a cell involved in the production, storage, and transport of secretory products. Studies are also conducted on the sites of action of neurotransmitters and various enzymes involved in nerve function (Salpeter).

Investigations of the configuration and atomic structure of biogenic macromolecules are being pursued with very high-resolution electron microscopy. Nucleic acids—their configuration, association, and polymerization—and ultimately the direct observation of the base sequence in the polynucleotide are of particular interest in these studies. Observations on enzyme configurations, substructure, and active site location are also being made. An electron microscope to achieve still higher resolutions is among procedures and instrumentation being developed (Siegel).

Some recent typical publications in this area are:

Clayton, R. K. 1970 and 1971. *Light and living matter,* vols. I and II. New York: McGraw-Hill.

Salpeter, M. M., and Salpeter, E. E. 1971. Resolution in electron microscope radioautography II Carbon^{14}. *Journal of Cell Biology* 50:324.

Siegel, B. M. 1971. Current and future prospects in electron microscopy for observations in biomolecular structure. *Philosophical Transactions of the Royal Society of London* B261:5.

Atomic and Molecular Physics

In recent years it has been realized that not only atomic and molecular structure but also the details of atomic or molecular collisions have a critical influence on a multitude of phenomena. Current projects in the area of atomic and molecular physics are mainly concerned with three aspects of such collisions: thermal-energy collisions (chemical kinetics and shock waves), gas-surface phenomena (catalysis and chemisorption), and medium-energy, inelastic collision processes.

The theoretical treatment of collisions at low- and medium-collision velocities is hampered by a lack of exact quantum mechanical methods of treatment, and experimental measurements are therefore valuable tests of the validity of theoretical models and approximations. An experimental program in the Field of Applied Physics is aimed at measuring total and differential cross sections of a number of the inelastic collision processes (excitation, ionization, charge transfer, excitation transfer, quenching) involving neutral hydrogen and helium atoms and ions with kinetic energies in the range of 50 eV to several keV (Fleischmann).

Experiments are also being carried out on inelastic collision processes in high-temperature gases; that is, for collision energies up to a few eV. These processes include dissociation, ionization, recombination, and relaxation of vibrational and electronic excitations. Most of this work is carried out with use of shock tubes for the preparation of the high-temperature gas. Emphasis is given to processes of importance for gas lasers and for reentry of a space vehicle into the atmosphere (Resler and deBoer).

Details of energy transfer and particle rearrangement in collisions involving vibrationally or rotationally excited molecules are being studied in view of their importance for the operation of molecular gas lasers. For this purpose, nonequilibrium distributions of molecular excitations in gases are initiated by nonchemical shocks or electrical discharges. Using various diagnostics, the kinematic evolution of these systems is investigated and the results analyzed in terms of the basic processes. Shock tube techniques have also been applied to the study of droplet nucleation in the vapor phase of iron and other metals (Bauer).

The collisions of atoms, ions, and electrons with surfaces of metals and semiconductors in ultrahigh vacuum and chemically reactive environments are also being studied. The theoretical investigations are concerned with the quantum-mechanical description of the interatomic forces and charge transfer associated with the calculation of energy levels and the mobility and binding of atoms on surfaces. Experimental measurements of the parameters associated with these models are being made by low-energy electron scattering techniques and by energy-loss spectroscopy. The program is directed at formulating a general theory of absolute reaction rates for both physical and chemical processes, such as chemisorption, oxidation, and related phase transformations occurring at surfaces. (Rhodin and Blakely).

The small-angle scattering of 50-100 keV electrons by gas molecules is being investigated experimentally. From the measured diffraction pattern, structural information, particularly on bond distances between atoms, can be derived. This method is applicable to a wide variety of gases (Bauer).

Some of the recent publications in this area are the following.

Gadzuk, J. W., Hartman, J. K., and Rhodin, T. N. 1971. Approach to alkali-metal chemisorption within the Anderson model. *Physical Review B* 4:241.

Kung, R. T. V., and Bauer, S. H. 1971. Nucleation study of Fe vapor in shock tube flow. In *Proceedings of the 8th international shock tube symposium,* p. 61.

Resler, E. L., Jr., Bar-Nun, A., deBoer, P. C. T., and Lifshitz, A. 1970. Boundary layer effects on chemical kinetics studies in a shock tube. *Journal of Chemical Physics* 53:3050.

Smith, F. T., Fleischmann, H. H., and Young, R. A. 1970. Scattering in low-energy charge transfer collisions of He^+ and Ar. *Physical Review A* 2:379.

Statistical Physics

Statistical physics provides the theoretical connection between the detailed microscopic motions of atomic particles and the macroscopic, physically measurable quantities. Many measurable quantities can be described rigorously by evaluable functions of a small number of variables—correlation functions—which are far less detailed and specific than the microscopic state itself. Several members of the faculty in the Field of Applied Physics are concerned with developing improved techniques for determining these correlation functions and their associated macroscopic properties. An active interplay between theory and experiment is characteristic of the vitality of this area, which has so greatly increased our understanding of such varied forms of matter as liquids, gases, plasmas, superfluid helium, superconductors, and magnetic systems.

A current theoretical study of phase transactions and critical phenomena involves work in statistical mechanics, including both its applications and its rigorous mathematical formulation. Questions in mathematics concerning combinatorics, counting, linear graphs, and special determinants and matrices arise in the course of such work (Fisher).

Experimental studies of cooperative phenomena are making use of newly devised optical correlation techniques based on modern lasers. For example, time correlation techniques have permitted analysis of inelastic scattering of visible light with an effective resolution of 10^{-16}. Modern optical techniques are applied also to investigations of critical phenomena in fluids, turbulence, homogeneous nucleation, fluctuations in quantum fields, and surface waves.

Fluctuations in superconductors and cooperative phenomena in metals at extremely low temperatures are also being investigated. Several superconducting quantum interference magnetometers have been developed and the attempt is now being made to extend the measurable range of the absolute temperature scale with a thermometer that works at temperatures between 10^{-2} and 10^{-5} °K by measuring nuclear magnetization with a superconducting magnetometer.

Also of interest are potential applications in biophysics and geophysics of the approaches that have been developed in chemical physics for observing cooperative phenomena (Webb).

In the area of the statistical physics of fluids, studies now under way focus on the interpretation of experimental information on the inelastic scattering of slow neutrons and the Brillouin scattering of light. These experiments give detailed information on the time dependence of the density-density correlation function in the fluid. Collective and individual particle motions are "mixed together" in a manner which is beginning to be understood, but new dynamical approximations in the theory of many-particle systems and a better understanding of the explicit predictions of existing approximations are needed (Nelkin).

Some recent typical publications in this area are:

Huang, J. S., and Webb, W. W. 1969. The diffuse interface in a critical fluid mixture. *Journal of Chemical Physics* 50:3677.

Nelkin, M. S., and Parks, W. A. 1970. *Slow neutron scattering and thermalization.* New York: Benjamin Press.

Suzuki, M., and Fisher, M. E. 1971. Zeros of the partition function for the Heisenberg, ferroelectric and general Ising models. *Journal of Mathematical Physics* 12:235.

Faculty Members and Their Research Interests

The faculty of the graduate Field of Applied Physics includes members of a number of departments in the College of Engineering as well as other units of the University. These include Materials Science and Engineering, Aerospace Engineering, Electrical Engineering, Geological Sciences, Thermal Engineering, Chemistry, Astronomy, Mathematics, and Biological Sciences.

Dieter G. Ast, Ph.D. (Cornell): *amorphous materials and polymeric materials*

Peter L. Auer, Ph.D. (California Institute of Technology): *plasma physics*

Joseph M. Ballantyne, Ph.D. (M.I.T.): *dielectric spectroscopy, solid state physics*

Robert W. Balluffi, Sc.D. (M.I.T.): *diffusion, defects in metals*

Boris W. Batterman, Ph.D. (M.I.T.): *x-ray diffraction, solid state physics*

Simon H. Bauer, Ph.D. (Chicago): *electron diffraction and shock tube techniques, chemical lasers*

John M. Blakely, Ph.D. (Glasgow): *surface physics, chemistry*

K. Bingham Cady, Ph.D. (M.I.T.): *reactor physics*

David D. Clark, Ph.D. (California at Berkeley): *experimental nuclear and reactor physics*

Roderick K. Clayton, Ph.D. (California Institute of Technology): *biophysics, photosynthesis*

Terrill A. Cool, Ph.D. (California Institute of Technology): *fluid dynamics, physical chemistry*

P. C. Tobias deBoer, Jr., Ph.D. (Maryland): *fluid dynamic plasma physics*

Frank D. Drake, Ph.D. (Harvard): *studies of the radio emission from pulsars, radio and radar studies of the moon and planets*

Lester F. Eastman, Ph.D. (Cornell): *microwaves, solid state plasma*

Michael E. Fisher, Ph.D. (King's College, London): *mathematical physics, statistical mechanics, phase transitions and critical phenomena*

Hans H. Fleischmann, Dr. rer. nat. (Technische Höchschule, Münich): *plasma physics and atomic physics*

Paul L. Hartman, Ph.D. (Cornell): *optical properties of solids*

Bryan L. Isacks, Ph.D. (Columbia): *seismology and global tectonics*

Martin O. Harwit, Ph.D. (M.I.T.): *astrophysics*

Herbert H. Johnson, Ph.D. (Case): *mechanical behavior of solids*

Vaclav O. Kostroun, Ph.D. (Oregon): *low-energy nuclear and atomic physics*

Edward J. Kramer, Ph.D. (Carnegie-Mellon): *low-temperature physics*

James A. Krumhansl, Ph.D. (Cornell): *theoretical applied physics*

Arthur F. Kuckes, Ph.D. (Harvard): *geophysics and plasma physics*

Charles A. Lee, Ph.D. (Columbia): *solid state physics*

Che-Yu Li, Ph.D. (Cornell): *surface physics*

Richard L. Liboff, Ph.D. (New York University): *plasma physics, statistical mechanics*

Ross McFarlane, Ph.D. (McGill): *quantum electronics*

Paul R. McIsaac, Ph.D. (Michigan): *microwave electronics*

Ross McPherson, Ph.D. (McGill): *low-energy nuclear physics*

Mark S. Nelkin, Ph.D. (Cornell): *statistical physics*

Jack E. Oliver, Ph.D. (Columbia): *seismology, global tectonics*

Edward Ott, Ph.D. (Polytechnic Institute of Brooklyn): *plasma physics and electrophysics*

Edwin L. Resler, Jr., Ph.D. (Cornell): *high-temperature gas dynamics, magnetohydrodynamics*

Thor N. Rhodin, Ph.D. (Princeton): *solid state physics, physics and chemistry of solid surfaces*

Norman Rostoker, Sc.D. (Carnegie): *plasma physics, solid state physics, gas dynamics*

Arthur L. Ruoff, Ph.D. (Utah): *high-pressure phenomena, imperfections in crystals, creep*

Henri S. Sack, D.Sc. (Eidg. Technische Höchschule, Zürich): *imperfections in solids*

Miriam M. Salpeter, Ph.D. (Cornell): *biophysics*

David N. Seidman, Ph.D. (Illinois): *defects in solids*

Benjamin M. Siegel, Ph.D. (M.I.T.): *electron microscopy, surface physics, biophysics*

John Silcox, Ph.D. (Cambridge): *electron microscopy, imperfections in crystals, superconductivity, ferromagnetism*

Roger M. Spanswick, Ph.D. (Edinburgh): *biophysics, ion transport*

Ravindra N. Sudan, Ph.D. (London): *plasma physics*

Chung L. Tang, Ph.D. (Harvard): *quantum electronics*

Donald L. Turcotte, Ph.D. (California Institute of Technology): *aerospace engineering, gas dynamics and geophysics*

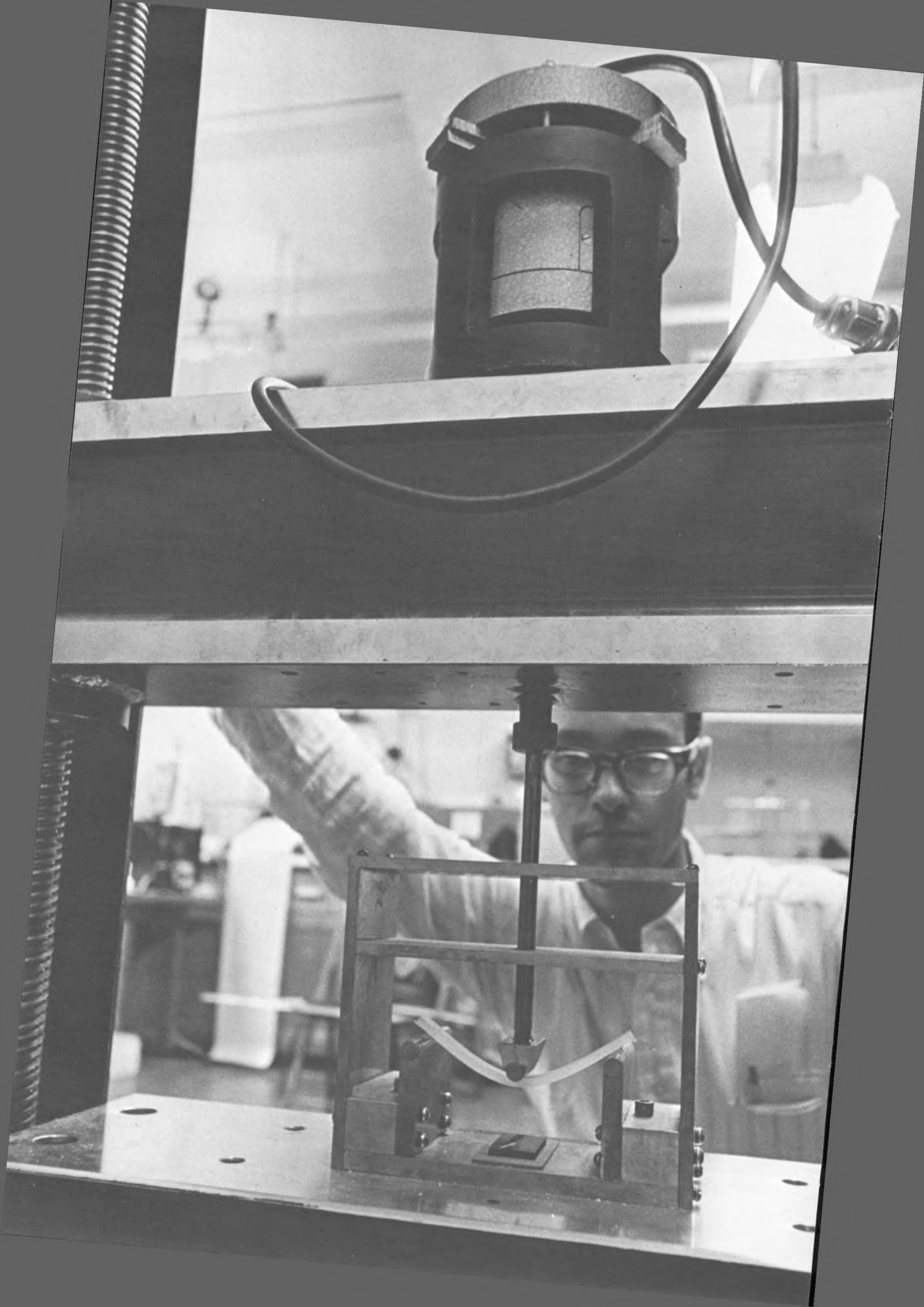
Watt W. Webb, Sc.D. (M.I.T.): *solid state physics, superconductivity, crystal mechanics, cooperative phenomena, fluids, biophysical kinetics*

Charles B. Wharton, M.S. (California at Berkeley): *plasma physics, microwave electronics*

George J. Wolga, Ph.D. (M.I.T.): *magnetic resonance, quantum electronics*

Further Information

Additional information may be obtained by writing to the Graduate Field Representative, Applied Physics, Clark Hall, Cornell University, Ithaca, New York 14850.



Chemical Engineering

The graduate Field of Chemical Engineering at Cornell offers programs in developing and interdisciplinary specialties as well as in the more traditional areas of chemical engineering. Approximately fifty students are now pursuing graduate work in a variety of areas corresponding to the research subjects outlined below.

As in most engineering Fields, three graduate degree programs are offered in chemical engineering. Students may enter a research-oriented course of study leading to the degree of Doctor of Philosophy or Master of Science, or may study for the professional degree of Master of Engineering (Chemical).

In addition to taking courses offered by the School of Chemical Engineering, students may elect courses offered by a number of other University schools or departments. For example, Cornell's widely recognized Department of Chemistry offers many advanced courses that are appropriate for graduate students in chemical engineering, as do the Departments of Mathematics and Physics. Courses may be taken in other engineering specialties such as applied physics, electrical engineering, industrial engineering and operations research, materials science and engineering, theoretical and applied mechanics, water resources engineering, and thermal engineering. In the biological sciences, graduate courses are available in bacteriology, biochemistry, and nutrition. Some graduate students in chemical engineering select minors in such nonengineering fields as law or economics.

Facilities

Study and research in chemical engineering is carried out in Olin Hall of Chemical Engineering, a modern, well-equipped building. It includes many small laboratories for graduate student research, and also houses such specialized laboratories as the Geer Laboratory for Rubber and Plastics, the extensive unit operations laboratory, and others for biochemical engineering, microscopy, process control, and kinetics. The School maintains its own library of reference books and periodicals to supplement the larger libraries in the College of Engineering and the University.

Facilities of special interest in certain areas are described under the various areas of research.

The effect of various polymerization processes on the mechanical properties of multicomponent polymer systems is being studied in a graduate research project.

Areas of Research

Transport phenomena, reaction kinetics, thermodynamics, and process control are the fundamentals of chemical engineering; and projects in these areas are an important part of the total research activity of the University. A special area of research is process systems and economics. Candidates for the M.S. and Ph.D. degrees may work on thesis problems related to the expanding product interests of the chemical industry. The extension of chemical engineering techniques to the fields of biology and medicine, desalination, polymers, and high-energy radiation has been a natural outgrowth of the diverse staff research interests, and all of these areas of research are available to graduate students.

Most of the School's current research activities can be grouped into the categories listed below, although there is considerable interaction among these areas—for example, there may be studies of the effects of radiation on polymeric properties—and the groupings are necessarily arbitrary. The scope of the School's research activities is indicated by the listings of recent faculty publications.

Bioengineering

The many chemical engineering aspects of activity in biological fields range from large-scale cultivation of microorganisms and the production of useful chemicals or enzymes from living cells, to environmental and pollution problems, and to medical, agricultural, and basic biological studies. At Cornell, work in biochemical engineering includes studies in the kinetics and dynamics of growth and product formation, process design optimization, the shearing effects of agitation, oxygen transfer, and microbial oxidations.

Several projects, directed by Professors Finn and Edwards, involve the production of proteins from chemical waste streams. Other research, directed by Professor Bischoff, involves collaborative work with biological scientists on problems of mathematical models of drug distribution in the body and extension of this to environmental toxicology, transport in artificial organs, and other public health and medically oriented areas. Staff members in the Field of Chemical Engineering have had experience in working with electrophoresis, azeotropic drying, chromatography, membrane separations, mathematical description of biological phenomena, and other techniques useful to the food processing and pharmaceutical industries or in medical and environmental studies.

Special equipment for research projects in bioengineering is housed in a bench-top laboratory and a pilot-scale laboratory. The equipment includes an electron microscope, a 40-liter stainless steel fermentor with pH control, a New Brunswick 7-liter or 14-liter continuous fermentation unit, a Warburg apparatus, and a variety of optical and analytical instruments.

Students majoring in bioengineering may minor in areas such as biochemistry or microbiology, which are offered by the Division of Biological Sciences; in nutrition and food science through the Graduate School of Nutrition; in physical biology, physiology, or pharmacology through the School of Veterinary Medicine; or in other engineering areas such as water resources or electrical engineering.

Typical recent publications of faculty members working in the area of bioengineering are:

Bischoff, K. B., *et al.* 1971. Methotrexate tissue distribution: Prediction by a mathematical model. *Journal of the National Cancer Institute* 46:775.

Edwards, V. H. 1970. The influence of high substrate concentrations on microbial kinetics. *Biotechnology and Bioengineering* 12:679.

Edwards, V. H., and Finn, R. K. 1969. Chemical effluents as fermentation media. *Process Biochemistry* 4:29.

Chemical Engineering Fundamentals

Improvement of design in the process industries is dependent on new knowledge in the areas of chemical engineering fundamentals, and research in these areas therefore constitutes a large part of the total research program in the Field of Chemical Engineering. Most faculty members supervise thesis work in this area, often as a supplement to studies in their other fields of specialization.

Fluid mechanics studies at Cornell have been concerned with the hydrodynamic stability of liquid jets, falling films, and natural convection distorted flow-fields in pipes; drop formation and coalescence; and the characteristics of stirred tanks. Heat transfer work has centered on fluidized bed and variable property non-Newtonian pipe flow studies. Mass transfer in solid-liquid systems, and simultaneous mass and heat transfer in liquid-liquid extractors have been investigated. Phase equilibria in liquid-vapor and liquid-liquid systems, and the flow and blending of solid particles have also been studied.

Among recent faculty publications in this area are:

Anderson, J. L., and Quinn, J. A., 1970. Bubble columns: Flow transitions in the presence of trace contaminants. *Chemical Engineering Science* 25:373.

Bernard, R. A., Dove, W. T., and Smith, J. C. 1969. *Drum drying of polymeric materials.* U.S. Patent no. 3,442,026.

Edwards, V. H., and Helft, J. M. 1970. Gel chromatography: Improved resolution through compressed beds. *Journal of Chromatography* 47:490.

DeYoung, S. H., and Scheele, G. F. 1970. Natural convection distorted non-Newtonian flow in a vertical pipe. *AIChE Journal* 16:712.

Von Berg, R. L. 1971. Simultaneous heat and mass transfer. In *Recent advances in liquid-liquid extraction,* ed. C. Hanson, p. 407. Oxford: Pergamon.

Chemical Microscopy

Chemical microscopy has been taught at Cornell since 1896, and is still a vital, growing field of study. In recent years many new and exciting microscopes have been developed, and these have been widely used in chemistry and chemical engineering. Today, microscopical techniques are so far developed that one of the ultimate goals of chemical microscopy—to see individual atoms and molecules and to observe the reactions between them—may soon be realized.

The equipment of the microscopy laboratory at Cornell includes a variety of light microscopes, including polarizing, phase, stereo, metallurgical, and interference microscopes; metallographs; a research model (JEM-7A) electron microscope; regular and ultramicrotomes; equipment for time-lapse cinemicrography; grinding and polishing equipment for metals, ceramics, or polymeric materials; a vacuum evaporator; furnaces; dark rooms; equipment for developing and printing micrographs and photographs; and a pulsed argon ion laser and related equipment for experimental work on either microscopical or macroscopical holographic imaging and interferometry.

Research in this or related areas is directed by Professors Cocks, Finn, Rodriguez, and Winding. Additional work may be undertaken with groups outside the School of Chemical Engineering that are involved in research in microscopy, particularly electron microscopy. These groups include the School of Applied and Engineering Physics, which is working with high resolution microscopy; the Materials Science Center and the Department of Materials Science and Engineering, which are primarily interested in materials; and various other departments concerned with biological microscopy.

Some typical faculty publications in this area are:

Brodsky, P. H., Cocks, G. G., and Winding, C. C. 1968. Phase structure in blends of incompatible polymers. In *Proceedings of the electron microscopy society of America,* p. 416. New Orleans: Claitors Book Publishing Division.

Cocks, G. G., and Cluthe, C. E. 1971. The structure of radiation cross-linked poly (ethylene oxide) gels. Structures formed by cryoprotective agents used in freeze etching. In *Proceedings of the electron microscopy society of America,* pp. 76 and 448. New Orleans: Claitors Book Publishing Division.

Desalination

One important aspect of the total problem of providing potable water is that of purifying sea water. Cornell University was chosen by the United States Office of Saline Water as a site for studying desalination by freezing, a process that utilizes secondary, immiscible, direct-contact refrigerants. This process has favorable thermodynamics and offers intriguing engineering possibilities.

The scope of studies related to the desalination project is quite broad. For example, heat transfer research is required for study of the cooling of brine feed, a process that utilizes direct vaporization of the refrigerant which then condenses by direct contact with the cold product water and spent brine. Crystallization by refrigerant evaporation is being studied in slurry crystallizers and spray freezers; these investigations involve experimental work on nucleation, crystal-growth kinetics, agglomeration, and the washing characteristics of beds of these crystals. The washing of the crystals is done in a moving piston-bed; design studies using electrical analogs permit better evaluation of new piston-bed wash column techniques. The dynamic behavior of three-phase flow through a porous bed of nonuniform structure is studied in terms of heat transfer experimentation on the melting of the salt-free crystals by direct contact with butane vapor. Overall engineering and economic evaluations are used to incorporate the results of this experimental work at Cornell and the contributions of experimenters outside the University into the total desalination program.

Professors Cocks, Harriott, Von Berg, and Wiegandt are associated with this work, some of which is done in conjunction with the Cornell Water Resources and Marine Sciences Center.

Among recent publications in this area are:

Michelsen, D., and Harriott, P. 1970. The transport of NaCl and water through compressed hydrophilic films. *Applied Polymer Symposia* 13:27.

Tester, J. W., and Wiegandt, H. F. 1969. The fluid hydrates of methylene chloride and chloroform: Their phase equilibria and behavior as influenced by hexane. *AIChE Journal* 15(3):239.

Kinetics and Catalysis

Although kinetics has been a vital part of chemical engineering instruction and research for several years, kinetic data are often the weakest link in the assessment of a new process.

At Cornell, more than half of the chemical engineering staff has supervised kinetics research in which the chemistry of the reactions has usually been of prime interest. The yield of desired product and the rates of consecutive or parallel reactions have been major concerns in recent studies of partial oxidation and alkylation in the liquid phase. Other projects have dealt with the mechanisms of free radical polymerization and radiation-induced reactions. Current work also includes studies of catalyst deactivation. Future work will include studies of the structure of solid catalysts and their influence on rate and selectivity of hydrogenation and oxidation.

A laboratory for instruction in kinetics has been established through a grant from the National Science Foundation. This laboratory houses reactors of several types which are equipped with a variety of analytical equipment. A B.E.T. apparatus and an electron microscope for use in characterizing catalysts are available in the laboratory, and NMR and x-ray diffraction equipment are available in other departments of the College.

Recent publications in this area by faculty members include:

Bischoff, K. B. 1971. Fixed bed adsorption kinetics with pore diffusion control. *Industrial and Engineering Chemistry Fundamentals* 10:327.

Daley, L. R., and Rodriguez, F. 1969. Glass-catalyzed hydrolysis of silane coupling agents. *Polymer Engineering and Science* 9:428.

Harriott, P. 1971. The oxidation of ethylene using silver on different supports. *Journal of Catalysis* 21:56.

Nuclear Engineering

The uses of high-energy radiation in the chemical industry show great potential, but additional research is needed before many of its applications become practical. Research conducted at Cornell has focused on the effects of radiation on chemical reactions and on the properties of polymeric materials.

Research involving radiation or radioactive materials may be carried out under the supervision of Professor Von Berg in the Ward Laboratory of Nuclear Engineering, which houses a gamma radiation cell. The general chemical engineering laboratories in Olin Hall are suitable for other work in this field. Ph.D. candidates may also work on their thesis problems at the Brookhaven National Laboratories on Long Island.

The instruction of chemical engineering graduate students in nuclear engineering is done almost exclusively through the Department of Applied Physics, although related courses are available in the Department of Materials Science and Engineering and in the School of Chemical Engineering.

Faculty publications in this area include:

Ashline, R. C., and Von Berg, R. L. 1969. The aqueous phase oxidation of cyclohexane using gamma radiation. *AIChE Journal* 15:387.

van Brederode, R. A., and Rodriguez, F. 1970. Gelation of poly (ethylene oxide) solutions by gamma radiation: Effects of molecular weight and irradiation conditions. *Journal of Applied Polymer Science* 14:979.

Polymeric Materials

Polymer studies conducted in the School of Chemical Engineering center on mechanical, electrical, and optical properties of multicomponent polymer systems, including copolymers, polymer blends, filled polymers, crosslinked polymers, and polymer solutions. Rheological investigations, especially of the non-Newtonian flow of polymer solutions and suspensions, have been conducted at Cornell for more than twenty-five years. Also being studied are the kinetic relationships of polymerization processes, which are often rapid reactions of free-radical or ionic character, and the distribution of reaction products.

The Geer Laboratory for Rubber and Plastics in Olin Hall contains much equipment that is useful in polymer studies. This equipment includes infrared and ultraviolet spectrophotometers, an electron microscope, an Instron testing machine and capillary rheometer, a recording torsional pendulum, a gel permeation chromatograph, an automatic membrane osmometer, a Brabender Plasticorder, mixing devices (roll mill, Banbury mill), a BioSonic Utrasonic generator, and various other specialized equipment. The gamma radiation cell in the Ward Laboratory of Nuclear Engineering is also used in polymer work.

Research in this area is directed by Professors Cocks, Rodriguez, Stevenson, Thorpe, and Winding of the School of Chemical Engineering. Work may also be done with Professor Edward J. Kramer of the Department of Materials Science and Engineering, who studies the mechanical behavior of crystalline polymers, and with Professor Harold A. Scheraga of the Department of Chemistry, who heads a large research group which studies protein chemistry. Polymer research is also pursued in the graduate Field of Biochemistry.

Among recent publications in this area of research are:

Fruh, S. M., and Rodriguez, F. 1970. Recoverable shear measurements in a parallel plate rheometer. *AIChE Journal* 16:907.

Rodriguez, F. 1970. *Principles of polymer systems.* New York: McGraw-Hill.

Stevenson, J. F., and Bird, R. B. 1971. Elongational viscosity of nonlinear elastic dumbbell suspensions. *Transactions of the Society of Rheology* 15:135.

Wald, S. A., and Winding, C. C. 1971. Differential thermal analysis using high frequency dielectric heating. *Polymer Engineering and Science* 11:57.

Process Dynamics and Control

In the last few years, a variety of complex control methods for hypothetical processes have been described and tested. In the application of these methods to real processes, however, a major limitation has often been uncertainty about the process dynamics. Work at Cornell has been concentrated on the dynamics of processes that are difficult to control, such as exothermic chemical reactions and distillation of materials to high purity. The objectives have been to develop more accurate theories or models, to verify these models by experiment, and to present simplified transfer functions suitable for control system design. Future projects will include work on the composition control of chemical reactors, the effects of interacting control loops in distillation, and the dynamics of distributed parameter two-phase units such as gas absorption or extraction columns.

A modern process control laboratory suitable for instruction and research is under the supervision of Professor Harriott, who has written a basic text in the field, *Process Control* (New York: McGraw-Hill, 1964). Students doing thesis work in this area usually take additional courses in servomechanisms, analog computation, or digital computation in the School of Electrical Engineering or with the Department of Computer Sciences.

Some faculty publications in this area are:

Himmelblau, D. M., and Bischoff, K. B. 1968. *Process analysis and simulation.* New York: Wiley.

Wahl, E. F., and Harriott, P. 1970. The understanding and prediction of the dynamic behavior of distillation columns. *Industrial and Engineering Chemistry Process Design and Development* 9:396.

Process Systems and Economics

In a broad sense, the process systems comprise, for a single product, market research; process research and development; process design; plant layout, location, and construction; manufacturing; and marketing. When a study is conducted on any part of a process system, a simultaneous economic evaluative study of the overall process is performed in order to establish the product's profitability at its various stages of development, and to determine what its optimal profitability at any of these stages could be.

Research at Cornell has been primarily concerned with the economics of the chemical process industries, especially design optimization. A specific project that has had considerable attention is the development of molecular sieve adsorption processes for separating normal paraffins.

Professors Hedrick and York supervise research and instruction in this area. Supplementary courses are offered by the Departments of Computer Science and Operations Research.

Typical of publications in this field is:

Schumacher, W. J., and York, R. 1967. Separation of hydrocarbons in fixed beds of molecular sieves. *Industrial and Engineering Chemistry Design and Development* 6(3):321.

Faculty Members and Their Research Interests

John L. Anderson, Ph.D. (Illinois): *membrane transport, bioengineering*

Kenneth B. Bischoff, Ph.D. (Illinois Institute of Technology): *medical and microbiological bioengineering, chemical reaction engineering*

George G. Cocks, Ph.D. (Cornell): *light and electron microscopy, properties of materials, solid-state chemistry, crystallography*

Victor H. Edwards, Ph.D. (California): *kinetics and process control in fermentation*

Robert K. Finn, Ph.D. (Minnesota): *continuous fermentation, agitation and aeration, processing biochemicals, electrophoresis, microbial conversion of hydrocarbons*

Peter Harriott, Ph.D. (M.I.T.): *kinetics and catalysis, process control, diffusion in membranes and porous solids*

J. Eldred Hedrick, Ph.D. (Iowa State): *economic analyses and forecasts, new ventures development*

Ferdinand Rodriguez, Ph.D. (Cornell): *polymerization, properties of polymer systems*

George F. Scheele, Ph.D. (Illinois): *hydrodynamic stability, coalescence, fluid mechanics of liquid drops and jets, convection-distorted flow fields*

Julian C. Smith, Chem. E. (Cornell): *conductive transfer processes, heat transfer, mixing, mechanical separations*

James F. Stevenson, Ph.D. (Wisconsin): *transport phenomena, rheology*

Raymond G. Thorpe, M. Chem. E. (Cornell): *phase equilibria, fluid flow, kinetics of polymerization*

Robert L. Von Berg, Sc.D. (M.I.T.): *liquid-liquid extraction, reaction kinetics, effect of radiation on chemical reactions*

Herbert F. Wiegandt, Ph.D. (Purdue): *crystallization, petroleum processing, saline-water conversion, direct contact heat transfer*

Charles C. Winding, Ph.D. (Minnesota): *degradation of polymers, polymer compounding, filler-polymer systems, differential thermal analysis*

Robert York, Sc.D. (M.I.T.): *molecular sieves, chemical market analyses, chemical economics, process development, design, and evaluation*

Further Information

Prospective candidates for graduate degrees in chemical engineering may obtain further information by writing to the Graduate Field Representative, Olin Hall of Chemical Engineering, Cornell University, Ithaca, New York 14850.

Civil and Environmental Engineering

Civil and Environmental Engineering deals primarily with the large fixed works, systems, and facilities that are basic to community living, industry, and commerce and vital to man's well-being. The planning design, construction, and operation of transportation systems, bridges, buildings, water and sewage treatment facilities, dams, and other major artifacts of society are civil and environmental engineering activities. Civil and environmental engineers are major contributors to the solution of problems of urbanization, city planning, and environmental quality control. A burgeoning national population and the desire of people to cluster in city complexes require a great increase in the number of well-trained engineers who can meet the basic needs of society with efficiency, economy, and safety.

The wide range of subjects which are the concerns of civil and environmental engineers are generally grouped into a number of subfields and specializations. At Cornell, there are two subject departments in Civil and Environmental Engineering which provide courses for graduate as well as undergraduate study and whose faculties direct thesis research and supervise design projects. They are structural engineering and environmental engineering, which includes the areas of environmental protection and management, geophysical engineering, and public systems planning and analysis.

Nearly one hundred students are now enrolled in graduate programs offered by the Field of Civil and Environmental Engineering. These programs lead to the degrees of Doctor of Philosophy, Master of Science, and Master of Engineering (Civil). Major subject areas for Ph.D. and M.S. candidates are aerial photographic studies (M.S. only), environmental systems engineering, geodetic and photogrammetric engineering, geotechnical engineering, hydraulics and hydrology, sanitary engineering, structural engineering, transportation engineering, and water resource systems (Ph.D. only). Minor subjects may be in these areas, in other branches of engineering, or in mathematics, physics, chemistry, or computer science. In the M.Eng. (Civil) degree program, emphasis is on design and design-oriented courses.

A research project in structural engineering involves setting up strain gages for measurement of distortion of a fabricated section.

Facilities

A large volume of research, sponsored by government agencies and industry, is carried out in three large and fully equipped structural laboratories: a structural laboratory for full-scale testing, including a biaxial load frame; an extensively equipped models laboratory; and a versatile cement and concrete laboratory, comprising x-ray and microscope facilities for the study of cracks.

The environmental engineering facilities include controlled-temperature rooms, laboratories for work in specialized areas such as water microbiology and water chemistry, and rooms specially equipped for bench and pilot-level unit process studies in biological treatment, carbon adsorption, ion exchange, electrodialysis, and reverse osmosis.

In the photogrammetric area, a three-projector stereo plotter and a number of other instruments which are the only ones of their kind at any educational institution in the United States and which provide a unique educational facility are available. A large collection of aerial photographs from all over the world is used in both photogrammetric and aerial photographic studies. A large variety of geodetic instruments is available.

The soil mechanics laboratories contain a wide variety of both standard and specialized soil-testing equipment. Excellent facilities for the testing of stabilized soils and asphaltic mixtures are provided.

The hydraulics laboratory is equipped for demonstrations in wave mechanics and rotating flows and for a variety of conventional experiments. A large wind tunnel will be available for the modelling of atmospheric transfer phenomena, which are encountered in the study of hydrology and air pollution.

In addition, the School has within the building a remote access computer terminal.

Research in environmental law is greatly facilitated by the accessibility of the Cornell Law School library—a major legal resource—which is across the street from Hollister Hall, the main facility of the School of Civil and Environmental Engineering.

Areas of Research

An idea of the scope of research activity in the graduate Field of Civil and Environmental Engineering may be obtained from the listing of project topics which follows. Examples of recent publications in the various areas indicate the kinds of specific problems being worked on and the faculty members who are directing the research.

Analysis of Trickling Filter Behavior

Behn, V. C., and Monadjemi, P. 1970. New Approach to the Analysis of Trickling Filters. Paper read at Fifth International Congress on Water Pollution Research, July 1970, in San Francisco.

Deoxygenation Phenomena in Deep Stratified Lakes

Gates, C. D. 1969. Hypolimnetic oxygen demands. In *Ecology of Cayuga Lake*. Water Resources and Marine Sciences Center, no. 27, p. 404. Ithaca: Cornell University.

Oxidation of Inorganic Nitrogen in Wastewater and in Lakes (a study of nitrogen removal in sewage treatment plants)

Design of Wastewater Treatment Systems to Satisfy Effluent Quality Requirements Based on Intended Use (sponsored by the Office of Water Resources Research of the United States Department of the Interior)

Lawrence, A. W. 1971. Application of process kinetics to design of anaerobic treatment processes. In *Anaerobic biological treatment processes*. Advances in Chemistry Series. Washington, D.C.: American Chemical Society.

Lawrence, A. W., and McCarty, P. L. 1970. Unified basis for biological treatment design and operation. *Journal of the Sanitary Engineering Division, Proceedings of ASCE* 96 (SA3):757.

Kinetics of Microbiologically Mediated Transformations of Heavy Metals in Aquatic Environments (project sponsored by the Office of Water Resources Research of the United States Department of the Interior)

Demonstration of Feasible Methods for the Treatment and Disposal of Animal Wastes (project sponsored by the Environmental Protection Agency)

Loehr, R. C. 1970. Drainage and pollution from beef cattle feedlots. *Journal of the Sanitary Engineering Division, Proceedings of ASCE* 96 (SA6):1295.

Tertiary Treatment of Animal Wastewaters (project sponsored by the Environmental Protection Agency)

Loehr, R. C. 1971. Principles of nutrient control for agricultural wastewaters. In *Proceedings of the second national food wastes symposium*, p. 605. Corvallis, Oregon: Environmental Protection Agency.

Problems of soil stability on the Cornell campus are studied by a graduate student-faculty research group.

Heat and Water Vapor Exchange Between a Water Surface and the Atmosphere

Brutsaert, W., and Yeh, G. T. 1970. Implications of a type of empirical evaporation formula for lakes and pans. *Water Resources Research 7:734, 1202.*

Flow of Water in a Partly Saturated Porous Medium

Verma, R. D., and Brutsaert, W. 1970. Unconfined aquifer seepage by capillary flow theory. *Journal of Hydraulics Division, Proceedings of ASCE* 96:1331.

Hydrologic Systems Analysis

Yu, S. L., and Brutsaert, W. 1969. Generation of an evaporation time series for Lake Ontario; and Stochastic aspects of Lake Ontario evaporation. *Water Resources Research* 5:785, 1256.

Formulation of a Finite Element Approach to the Pollution Analysis of Lakes (project sponsored by the National Science Foundation; just initiated)

Currents and Circulation in Large Water Bodies

Liggett, J. A. 1971. Properties of circulation in stratified lakes. *Journal of the Hydraulics Division, Proceedings of ASCE* 97 (HY1):15.

Open Channel Flow

Liggett, J. A. 1968. Mathematical flow determination in open channels. *Journal of the Engineering Mechanics Division, Proceedings of ASCE* 94 (EM4):947.

Naturally Cemented Sensitive Soils

Sangrey, D. A., and Paul, M. J. 1971. A regional study of landsliding near Ottawa. *Canadian Geotechnical Journal* 8(2):315.

Optimization of Solid Waste Disposal for Leachate Control and Subsequent Use of Site (Agricultural Solid Waste Training Grant; just initiated)

Marine Soil Engineering

Sangrey, D. A. 1971. Changes in Strength of Soils Under Earthquake and Other Repeated Loading. Paper read at First Canadian Conference on Earthquake Engineering, 25 May 1971, Vancouver.

Land Use and Natural Resources Inventory (project sponsored by the New York State Office of Planning Coordination)

Belcher, D. J., et al. 1971. *New York State land use and natural resources inventory*. Final report, in 10 vols., duplicated. Ithaca: Center for Aerial Photographic Studies, Cornell University.

Land Use, Environmental Features and Natural Resources of the Hudson River Valley (project sponsored by the Hudson River Valley Commission)

Belcher, D. J., et al. 1969. *Land use, environmental features and natural resources of the Hudson River valley*. In duplicated form, to be published. Hudson River Valley Commission.

Land Use Classification with Simulated Satellite Photography (project sponsored by the Economic

Research Service of the United States Department of Agriculture)

Belcher, D. J., et al. 1969. *Land use classification with simulated satellite photography.* Agricultural Information Bulletin no. 352 of the Economic Research Service Information of the United States Department of Agriculture.

Studies of Mariner Photography for Terrain Evaluation (project sponsored by the Cornell University Center for Radiophysics and Space Research)

Belcher, D. J., Veverka, J., and Sagan, C. 1971. *Mariner photography of Mars and aerial photography of Earth: Some analogies.* Cornell University Center for Radiophysics and Space Research Bulletin no. 439.

Inventory Methods Applied to Agricultural Zonation in El Salvador (project sponsored by the Puerto Rico Department of Public Works; just initiated)

Tropical Environment (project sponsored by the United States Department of Defense)

Liang, T., Holdridge, L. R., et al. 1971. *Forest environments in tropical life zones.* Oxford: Pergamon.

Mapping the Human Optic Disc

Pollard, W. S., and Yassa, G. F., with Medical Center of Tufts University. 1971. Use of Wild A-7 Stereoplotter to Map the Inside of the Human Eyeball. National Award student paper read at the Annual Meeting of the American Society of Photogrammetry, March 1971, Washington.

Gravity Field Representation by Point Mass Set

Ealum, R. L. 1971. Gravity Field Representation by Point Mass Set. Paper read at 52nd Annual Meeting of the American Geophysical Union, April 1971, Washington, D.C.

Inventory of Land Uses and Environmental Resources for the State of Colorado, Department of Natural Resources

McNair, A. J. 1970. A cartographer inventories environment: the CLARI project. In *Proceedings of the technical conference of the American society of photogrammetry, American congress on surveying and mapping,* p. 276.

Applications of Economic Theory to Environmental Quality Management

Falkson, L. M. 1967. Water shortages and pricing. In *Proceedings of the third American water resources association conference,* p. 254.

Applications of Systems Analysis to Water Resources

Loucks, D. P., and Falkson, L. M. 1970. A comparison of some dynamic, linear and policy iteration methods for reservoir operation. *Water Resources Bulletin* 6(4):384.

Among the attractions of the Finger Lakes region are three state parks situated within a few miles of the Cornell campus.

Transportation Economics

Falkson, L. M. 1969. Comments on Simon's almost practical solution to airline overbooking. *Journal of Transport Economics and Policy,* 3(3):252.

Statistical Analysis

Laessig, R., and Falkson, L. M. 1971. Racial disparity in housing quality in urban areas of the United States. To be published in *Proceedings of the 8th annual meeting of the society of engineering sciences.*

Efficiency of Multimodal Transport with Emphasis on Intermodal Transfer

Fisher, G. P., Ittig, P., and Welker, F. R. 1970. *Efficiency of multimodal transport with emphasis on intermodal transfer.* Research Report no. 7004, Department of Environmental Systems Engineering, Cornell University.

Operational Analysis and Design of Demand-Responsive Systems

Stidham, S., Jr., Toregas, C., and Fisher, G. P. 1971. *Operational analysis and design of demand-responsive systems.* Research Report no. 7101, Department of Environmental Systems Engineering, Cornell University.

Managerial Aspects of Community Medicine

Lynn, W. R. 1969. Systems analysis approach to public health. In *Human ecology and public health,* ch. 7, p. 181. New York: Macmillan.

Water Resources Systems and Policy Analysis

Loucks, D. P. 1971. Some long run effects of water pricing policies. To be published in *Water Resources Research.*

Loucks, D. P. 1972. Flow regulation for water quality management. In *Models for managing regional water quality,* ed. Dorfman, et al. Cambridge: Harvard University Press, forthcoming.

Policy Models for Natural Resource Systems

Loucks, D. P. 1971. Residuals—environmental quality management. To be published in *Natural Resource Journal.*

Environmental Noise Management (project supported by Resources for the Future, Inc.)

Loucks, D. P. 1971. *Environmental noise—technology, economics and management.* Report for Resources for the Future, Inc.

Optimal Location of Transportation Facilities; Transportation Impact Analysis

Werner, C., Meyburg, A. H., et al. 1968. A research seminar in theoretical transportation geography: Networks and their service areas. In *Geographic studies of urban transportation and network analysis,* ed. F. Horton, no. 16 of Studies in Geography. Evanston: Northwestern University.

Behavioral, Disaggregate Models of Travel Demand—Development and Refinement

Stopher, P. R. 1969. *A probability model of travel mode choice for the work journey.* Highway Research Record no. 283.

Stopher, P. R., and Lisco, T. E. 1970. Modelling travel demand: a disaggregate behavioral approach—issues and applications. In *Transportation research forum proceedings,* p. 195.

Value of Travel Time (project sponsored by the Highway Research Board)

Thin Shell Instability Analysis by the Finite Element Method (project sponsored by NASA)

Gallagher, R. H. 1971. Direct Flexibility Finite Element Elastoplastic Analysis. Paper read at First International Conference on Structural Mechanics in Reactor Technology, 24 September 1971, in Berlin, Germany.

Model Analysis of Reinforced Concrete Structures (Frames and Shells) (project sponsored by the National Science Foundation)

White, R. N., and Harris, H. G. 1971. *Inelastic behavior of reinforced concrete cylindrical shells.* ASCE preprint no. 1401.

White, R. N., ed. 1970. *Models for concrete structures.* ACI special publication SP-24.

Shear Transfer in Reinforced Concrete (project sponsored by the National Science Foundation)

White, R. N., and Holley, M. J., Jr. 1971. *Membrane shear transfer in reinforced concrete containment vessels.* ASCE preprint no. 1395.

Channels and Z's Braced by Diaphragms

Peköz, T., and Winter, G. 1969. Torsional-flexural buckling of thin-walled sections under eccentric load. *Journal of the Structures Division, Proceedings of ASCE* 95:941.

Celebi, N., Peköz, T., and Winter, G. 1971. Behavior of channel and Z-section beams braced by diaphragms. In *Proceedings of the first specialty conference on cold-formed steel structures,* p. 118. Rolla: University of Missouri.

Local and Overall Buckling (project sponsored by the American Iron and Steel Institute (AISI))

Cold-Formed Compact Sections (project sponsored by AISI)

Wall Stud Design Criteria (project sponsored by AISI)

Connectors for Cold-Formed Steel (project sponsored by AISI)

Decision Analysis Applied to Structural Reliability (project sponsored by the National Science Foundation)

Sexsmith, R. G., and Mau, S-T. 1971. Optimum design of structures with a minimum cost criterion. In *Proceedings of the 3rd Canadian conference on applied mechanics,* p. 329. Calgary: Canadian Conference on Applied Mechanics.

Interaction of Diaphragms and Multistory Building Frames (project sponsored by AISI)

Deformation, Microcracking and Fracture of Concrete

Buyukozturk, O., Nilson, A. H., and Slate, F. O. 1971. Stress-strain response and fracture of a concrete model in biaxial loading. *Journal of the American Concrete Institute* 68(8):590.

Meyers, B. L., and Slate, F. O. 1970. Creep and creep recovery of plain concrete as influenced by moisture conditions and associated variables. *Magazine of Concrete Research* 22(70):37.

Methodological Questions

Bereano, P. L. 1971. Proposed methodology for technology assessment. To be published in *Public Policy.*

Environmental Law and Planning

Bereano, P. L. 1971. The role of law in environmental management. *Cornell Engineer* 36(6):4.

In addition to projects now under way, there are a number of pending research and training proposals which reflect the interests of the faculty members in the Field. Titles of these proposals are:

Model for Operating Thermally Stratified Reservoirs

Solid Waste Resource Recovery and Recycling

Engineering Analysis of ERTS Data for Southeast Asian Agriculture

Flexural Behavior of Bars

Contact Pressures

Inelastic Torsional-Flexural Buckling

Inelastic Flexural Behavior of Rectangular Bars

Heat and Water Vapor Exchange Between Water Surface and Atmosphere

Exploratory Development of Disaggregate Behavioral Models of Travel Demand

Improvement of Water Quality in Thermally Stratified Impoundments

Soil and Foundation Engineering Decision Analysis

Acquiring, Abstracting, and Indexing Literature on Policy Models for Water Resources and Related Systems—A Grant Amendment

Faculty Members and Their Research Interests

Vaughn C. Behn, P.E., Dr.Eng. (Johns Hopkins): *sanitary engineering*

Donald J. Belcher, C.E., P.E., M.E., M.S. (Purdue): *aerial photography*

Philip L. Bereano, J.D., M.R.P. (Cornell): *environmental law and planning*

Wilfried H. Brutsaert, Ph.D. (California at Davis): *hydrology*

Leonard B. Dworsky, M.S. (American University): *water resources, pollution control*

Louis M. Falkson, M.A. (Harvard): *applied welfare economics*

Gordon P. Fisher, P.E., D.Eng. (Johns Hopkins): *environmental systems*

Richard H. Gallagher, P.E., Ph.D. (SUNY-Buffalo): *structures*

Charles D. Gates, M.S. (Harvard): *sanitary engineering*

Peter Gergely, P.E., Ph.D. (Illinois): *structures*

Douglas A. Haith, Ph.D. (Cornell): *water resource systems*

Alonzo Wm. Lawrence, Ph.D. (Stanford): *sanitary engineering*

Ta Liang, Ph.D. (Cornell): *aerial photography, physical environment*

James A. Liggett, Ph.D. (Stanford): *hydraulics*

Raymond C. Loehr, Ph.D. (Wisconsin): *agricultural wastes*

Daniel P. Loucks, Ph.D. (Cornell): *water resource systems*

Walter R. Lynn, Ph.D. (Northwestern): *environmental systems*

George B. Lyon, P.E. M.S. (University of Iowa): *surveying*

William McGuire, P.E., M.C.E. (Cornell): *structures*

Arthur J. McNair, C.E., P.E., M.S. (Colorado): *geodesy—photogrammetry*

Arnim H. Meyburg, Ph.D. (Northwestern): *urban transportation and planning*

Arthur H. Nilson, P.E., Ph.D. (California at Berkeley): *structures*

Teoman Peköz, Ph.D. (Cornell): *structural engineering experimental research*

Dwight A. Sangrey, Ph.D. (Cornell): *soils*

Robert G. Sexsmith, Ph.D. (Stanford): *structures*

Floyd O. Slate, Ph.D. (Purdue): *engineering materials*

Shaler Stidham, Jr., Ph.D. (Stanford): *environmental systems*

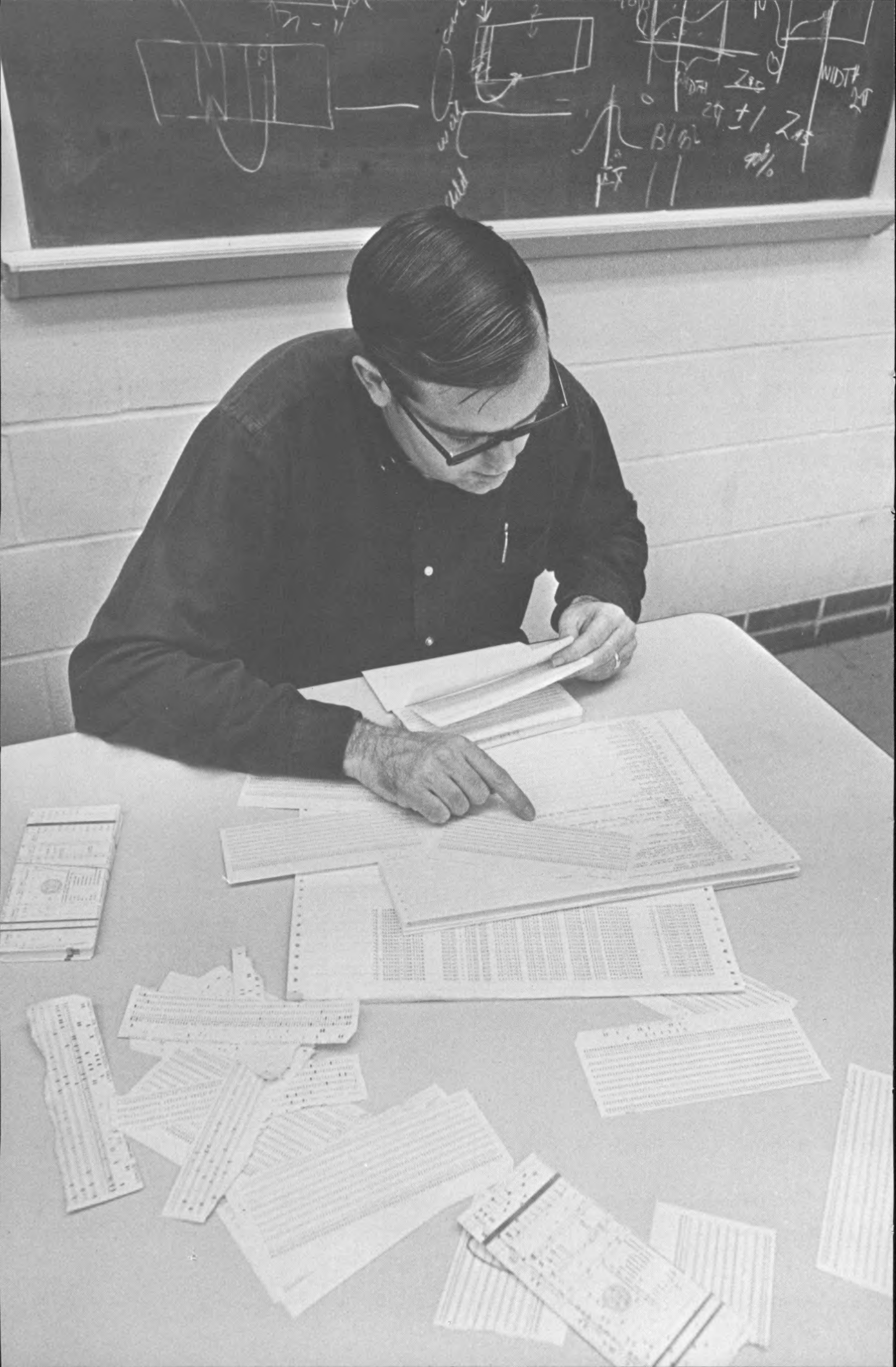
Peter R. Stopher, Ph.D. (University of London): *urban transportation and planning*

Richard N. White, P.E., Ph.D. (Wisconsin): *structures*

George Winter, Ph.D. (Cornell): *structures*

Further Information

Further information may be obtained by writing to the Graduate Field Representative, Civil and Environmental Engineering, Hollister Hall, Cornell University, Ithaca, New York 14850.



Computer Science

Computer science, the science of information, includes study in the nature and properties of information, its structures and classification, its storage and retrieval, and the various types of processing to which it can be subjected. The physical machines that perform these operations, the elemental units of which the machines are composed, and the organization of these units into efficient information-processing systems are also of concern.

Various aspects of computer science are closely related to many other fields. The fundamental theory of information processing and the exploration of the limits of the abilities of computing machines are topics in pure and applied mathematics. Numerical analysis, which has to do with the development as well as the accuracy and efficiency of practical numerical procedures, is in the area of applied mathematics. Students of computer science and electrical engineering share an interest in the characteristics of physical machines and in computer design. Language structure and translation are of concern in computer science and linguistics. The implications of current data processing technology for the organization and control of industrial and business operations are also pertinent to industrial engineering and business administration. Investigations in the area of artificial intelligence are of interest in the study of psychology and biology. In the past, these subjects usually have been pursued as parts of various fields. Today, increasing recognition is being given to the strong common basis of all of this work, and computer or information science is an independent discipline at many leading institutions.

Cornell's leadership in the development of computer science is indicated by the following texts written at Cornell and widely used by other institutions.

Conway, R. W., Maxwell, W. L., and Miller, L. W. 1967. *Theory of scheduling.* New York: Addison-Wesley.

Gries, D. 1971. *Compiler construction for digital computers.* New York: Wiley.

The processing of information and its storage and retrieval are among subjects of research in computer science.

Hartmanis, J., and Stearns, R. E. 1966. *Algebraic structure theory of sequential machines.* Englewood Cliffs, New Jersey: Prentice-Hall.

Hopcroft, J. E., and Ullman, J. D. 1969. *Formal languages and their relation to automata.* New York: Addison-Wesley.

Salton, G. 1969. *Automatic information organization and retrieval.* New York: McGraw-Hill.

Wegner, Peter. 1968. *Programming languages, information structures and machine organization.* New York: McGraw-Hill.

There are about fifty-five graduate students in computer science at the present time; these include ten women and seventeen foreign students from ten different countries. The Field admits twenty to twenty-five new students each year, but it is expected that there will be more applicants than there are places. For this reason, persons who cannot enroll as full-time students are discouraged from applying. (Students having assistantships or fellowships are normally regarded as full-time students.)

As prerequisites for candidacy for an advanced degree in computer science, a student is expected to have had significant experience in programming a digital computer and, depending upon the particular area of specialization chosen, an appropriate background in mathematics, engineering, or related areas which would permit immediate enrollment in graduate-level courses. A student is also expected to have had at least an introductory course in computer science, although this deficiency can be remedied after admission.

Students interested primarily in computer components and logical design rather than in the use of computers may find it more appropriate to consider the Field of Electrical Engineering.

Facilities

The computing facility at Cornell is a complex of IBM 360 systems. The central machine is a 360/65, which is directly linked to 360/20 satellite computers at three different campus locations. The College of Engineering is served through one of these satellite stations, as well as by a number of teletypewriter terminals in various buildings. An IBM 1800 computer is linked to the central computer to provide an analog-digital interface and graphical display equipment. In addition to this remote access system, Cornell operates a 1401 and 360/40, a DEC PDP-9, and several PDP-8's.

Areas of Research

The research program is designed to provide an atmosphere in which both students and faculty can make major contributions and influence the development of computer science.

Major research efforts are directed toward analysis of algorithms, the theory of computation, compiler construction, operating systems, programming languages, information storage and retrieval, symbol manipulation, and numerical analysis.

Instruction and research in related topics are carried out in other Fields. These topics include simulation, data processing, linguistics, control theory, mathematical programming, network and graph theory, and electrical engineering. In particular, the Field of Computer Science maintains a close relationship with the Field of Operations Research at Cornell. Two faculty members hold joint appointments and many students major in one field and minor in the other.

It will be helpful to the prospective student to give a brief description of the major research activities in the Field of Computer Science. The examples range from abstract mathematics to practical implementations and experiments in programming systems.

Theory of Algorithms

There is a growing belief that a relatively small number—perhaps a score—of fundamental processes dominate all of computing, both applications and systems programs. The study of algorithms is the attempt to identify these fundamental processes and to find efficient and possibly optimal algorithms for their execution. Recent results have concerned high-precision multiplication, matrix multiplication, evaluation of polynomials, pattern matching, sorting, and manipulation of graphs. In many cases, marked improvements in performance have been obtained. For example, while it has long been "known" that matrix multiplication varies with the cube of the order n, it has recently been shown that at most $n^{2.81}$ operations are required.

In general, work by Professors Hopcroft, Horowitz, and Tarjan is being concentrated on the fundamental features of the basic algorithms. Concise models of the pertinent features are being formulated and theoretical results concerning asymptotic running times and lower bounds are being obtained.

Theory of Computation

Primary activities in this area are concerned with the theory of automata, formal languages, computational complexity, applications of recursive function theory and logic in computer science, and program schemata.

Besides the two books mentioned on p. 45 (by Hartmanis and Stearns and by Hopcroft and Ullman), the following publications are of interest in this area.

Constable, R. 1972. Subrecursive programming schemata. To be published in *Journal of the ACM* 19.

Hartmanis, J., and Hopcroft, J. 1971. Overview of the theory of computational complexity. *Journal of the ACM* 18:444.

Compiler Construction

The PL/C compiler, a very efficient compiler for a subset of PL/I, was implemented under Professor Conway's leadership. The compiler, which attempts to make plausible repairs of errors so that every program reaches execution, is in use at over eighty-five universities in eight countries. Two Ph.D. theses have already resulted from the project. Further work on PL/C will attempt to increase the power of the corrective ability, and to produce an interactive version.

PL/C was written in assembly language with extensive use of powerful macros. The department is also involved in the study of automatic translator writing systems and their *practical* application. Professor Gries' book *Compiler Construction for Digital Computers* (1971) reflects this work. Part of the future work will be to experimentally replace individual modules of the PL/C compiler with functionally equivalent units generated by automatic processes.

Information Organization and Retrieval

This research deals with the design and analysis of fully automatic information retrieval systems. Work includes analysis procedures for linguistic information, automatic search and classification systems, and interactive search procedures.

Current research has led to the publication of a new book written by Professor Salton and his students and staff.

Salton, G., ed. 1971. *The SMART retrieval system: experiments in automatic document processing.* Englewood Cliffs: Prentice-Hall.

Numerical Analysis

Professors Bunch, Dennis, and Moré are carrying on research in the areas of numerical linear algebra, solutions of nonlinear systems of equations, and nonlinear optimization. Mathematics professors Bramble, Payne, and Schatz are primarily interested in the numerical solution of partial differential equations. Ph.D. theses have been written in approximation theory, solutions of nonlinear systems of equations, and solutions of matrix polynomial and λ-matrix problems.

Faculty Members and Their Research Interests

The faculty of the graduate Field of Computer Science consists of the staff of the Department of Computer Science and members of other departments who teach graduate courses and supervise students in areas of study related to computer science. The other departments represented in the Field are Mathematics, City and Regional Planning, Plant Breeding and Biometry, Theoretical and Applied Mechanics, and Operations Research.

Henry Block, Ph.D. (Iowa State): *theory of automata, pattern recognition*

James Bramble, Ph.D. (Maryland): *numerical analysis*

James R. Bunch, Ph.D. (California at Berkeley): *numerical analysis*

Robert Constable, Ph.D. (Wisconsin): *computational complexity*

Richard Conway, Ph.D. (Cornell): *digital simulation, management, information systems, operating systems*

John E. Dennis, Ph.D. (Utah): *numerical analysis*

David Gries, Dr. rer. nat. (Technische Höchschule, München): *programming languages, compiler construction*

Juris Hartmanis, Ph.D. (California Institute of Technology): *theory of computation*

John Hopcroft, Ph.D. (Stanford): *theory of computation, analysis of algorithms*

Ellis Horowitz, Ph.D. (Wisconsin): *symbolic manipulation, analysis of algorithms*

William Maxwell, Ph.D. (Cornell): *digital simulation, operations research*

Joseph Moré, Ph.D. (Maryland): *numerical analysis*

Howard Morgan, Ph.D. (Cornell): *simulation languages and systems programming*

Anil Nerode, Ph.D. (Chicago): *logic, applied mathematics*

Lawrence Payne, Ph.D. (Iowa State): *numerical analysis*

Christopher Pottle, Ph.D. (Illinois): *signal processing, systems theory*

Gerad Salton, Ph.D. (Harvard): *information organization and retrieval*

Sidney Saltzman, Ph.D. (Cornell): *data processing, econometrics*

Alfred Schatz, Ph.D. (New York University): *numerical analysis*

Shayle Searle, Ph.D. (Cornell): *statistics*

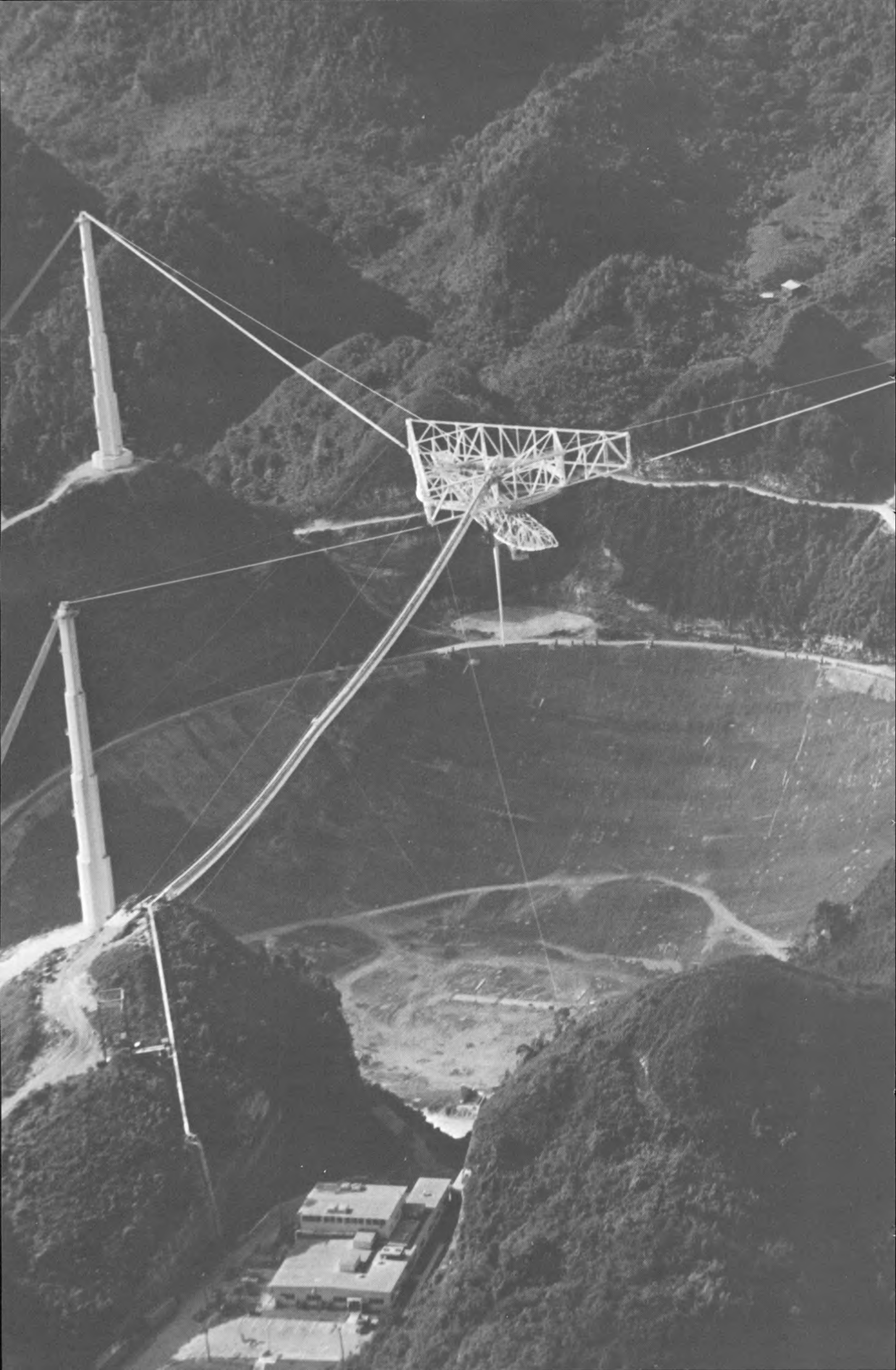
Robert Tarjan, Ph.D. (Stanford): *analysis of algorithms*

Robert Walker, Ph.D. (Princeton): *numerical analysis, combinatorics*

John Williams, Ph.D. (Wisconsin): *formal languages, programming languages, compiler construction*

Further Information

Additional information may be obtained by writing to the Graduate Field Representative, Computer Science, Upson Hall, Cornell University, Ithaca, New York 14850.



Electrical Engineering

The largest group of graduate students in any of the engineering and applied science Fields at Cornell is enrolled in the Field of Electrical Engineering.

These students are conducting research on topics that range from planetary studies to electronic circuit design. A few examples of current research areas are the outer atmospheres of the Earth and Jupiter, feedback control systems, integrated circuit technology, pattern recognition and digital picture processing, high-energy plasmas and thermonuclear fusion, computer-aided circuit design, bioelectronics, microwave devices, molecular and chemical lasers, algebraic coding and applications to satellite communication systems, electric automobiles, and an unmanned Martian roving vehicle.

The broad spectrum of research activities in electrical engineering can be roughly divided into two general areas—electrophysics and systems. Research in electrophysics encompasses the study of the physical properties of matter and our environment and of devices that utilize these properties; systems research is concerned with complexes formed by the interconnection of devices and with the response of these systems to various inputs. At Cornell these two disciplines are not rigidly separated, since it is clear that a student must be adequately educated in both areas in order to function effectively in either one. Graduate programs are usually quite specialized, of course, but the relationships among physical principles, devices, and large systems are never ignored.

There are currently about eighty students enrolled in the Master of Science and Doctor of Philosophy degree programs; about half have major interests in electrophysics and about half in systems. This number is large enough to achieve the "critical mass" that is conducive to effective research in most areas, and yet is small enough to enable the students and faculty to get to know one another. Graduate students often learn as much from each other as they do from their formal studies, and so it is important to have students working in related research areas and to provide an environment in which interaction is promoted. About forty additional students are enrolled in the one-year Master of Engineering (Electrical) program.

Students are given wide latitude in planning a course of study appropriate to their interests. There are no formal course requirements in the M.S. and Ph.D. programs, for example; the choice is left up to the student in consultation with his faculty advisers. The Field of Electrical Engineering offers over sixty graduate level courses, and many other advanced courses of interest to graduate students in electrical engineering are offered throughout the University. Of particular importance are those in the Fields of Applied Physics, Astronomy and Space Sciences, Computer Science, Mathematics, and Physics.

The world's largest radio-radar telescope is used by Cornell research workers at the National Astronomy and Ionosphere Center in Puerto Rico, a facility operated by Cornell.

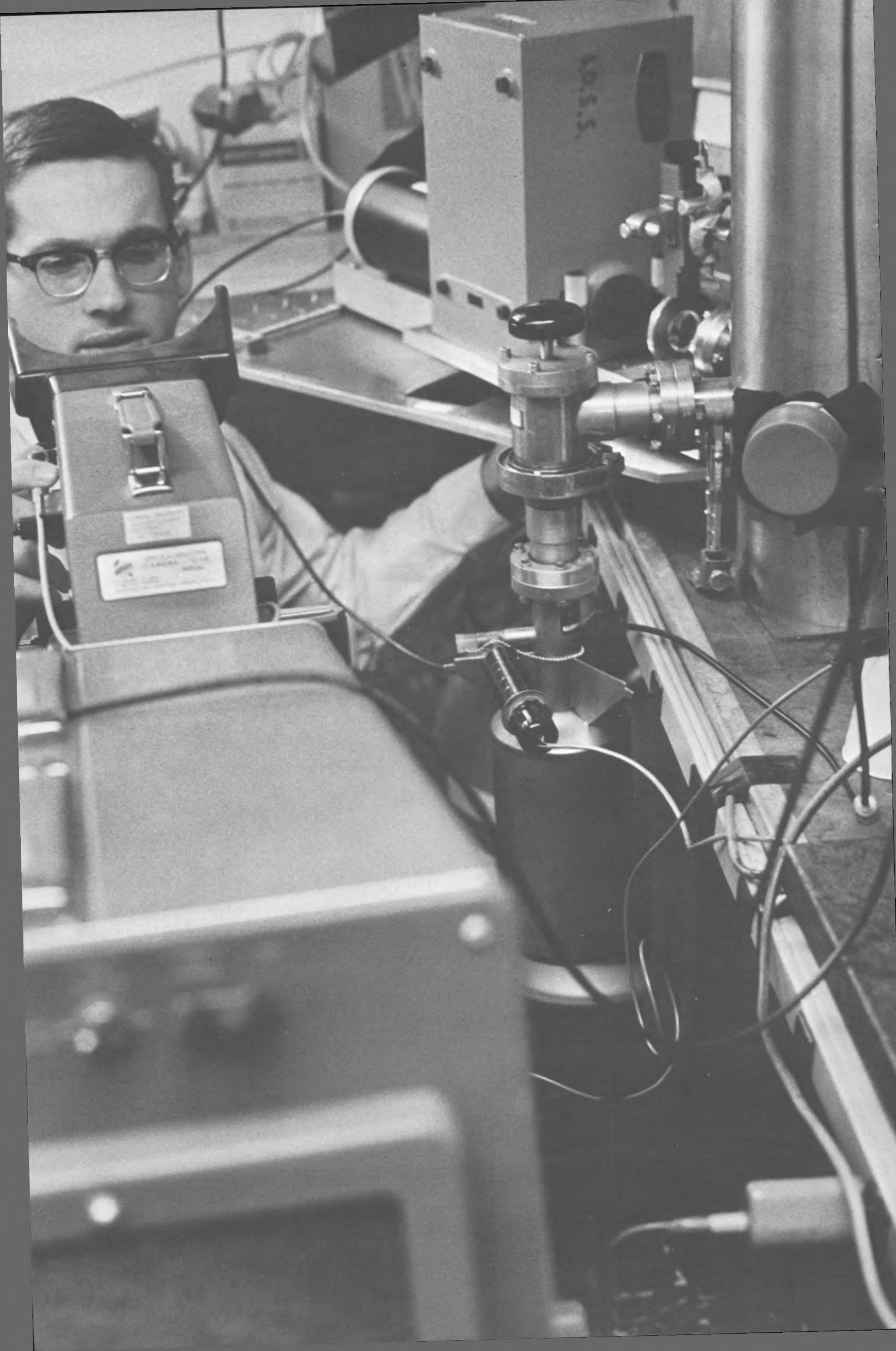
Facilities

Many of the research projects in the Field of Electrical Engineering are accommodated in Phillips Hall, the electrical engineering center of the College of Engineering, but several other laboratories and research centers at the University are also available.

In the area of electrophysics the facilities at Cornell include the Laboratory for Plasma Studies and special laboratories for quantum electronics, solid state electronics, optics and spectroscopy of solids, ionospheric physics, and radio-wave propagation. Much of the research in ionospheric physics and radio astronomy is now carried out at the National Astronomy and Ionosphere Center operated by Cornell in Puerto Rico.

In the area of systems, research is carried on in the systems research, the control system, the analog computer, and the switching circuit laboratories. The University's extensive computer services are also important to many projects in this area.

The facilities of the Materials Science Center, the acoustics laboratory, and the physical biology laboratory are also used in some research projects.



Areas of Research

Some of the current research areas are described below, along with a few examples of recent publications. A complete list of faculty publications is available from the School of Electrical Engineering in Phillips Hall.

High-Energy Plasmas

Plasma research conducted by the faculty and students of the School of Electrical Engineering is coordinated by the interdepartmental Laboratory of Plasma Studies (see page 91), which affords a broad base from which to operate. Both theoretical and experimental programs are pursued. The extensive laboratory facilities include both large-scale plasma devices and small-scale apparatus.

Programs in which members of the School are participating include projects and studies in: intense relativistic electron beams and their interaction with plasmas; lasers and their interaction with plasmas; collisionless plasma turbulence (waves and transport); nonlinear waves and plasma instabilities; and numerous problems involved in controlled thermonuclear power research.

Research on megavolt, terawatt electron beams, and on turbulent heating are especially noteworthy, since pioneering work in these areas has been carried out at Cornell. The relativistic electron beam research is largely directed to the study of heating and confinement of thermonuclear plasmas. Other work using these beams is directed to microwave generation and beam dynamics. In the turbulent heating experiment, the possibilities for heating a fusion plasma by strong turbulence are being investigated. This turbulence is characterized by large nonlinear fluctuations in electric and magnetic fields and in particle density. As the particles collide with turbulent waves they gain energy, leading to plasma heating having the highest known efficiency.

The Electrical Engineering staff directing plasma research includes Professors Liboff, Linke, McFarlane, Nation, Ott, Sudan, Wharton, and Wolga. Other units at Cornell that participate in the Laboratory of Plasma Studies include Aerospace Engineering, Applied Physics, Chemistry, Nuclear Engineering, Physics, and Thermal Engineering.

Among recent publications in this research area are the following.

Gardner, W., and Nation, J. 1971. An experimental investigation of the microwave radiation emitted by a high-current relativistic electron beam. *Nuclear Fusion* 11:5.

Liboff, R. L. 1970. Relativistic fields in a grounded cylindrical box. *Journal of Mathematical Physics* 11:1295.

Ott, E., and Sudan, R. N. 1971. Finite beta equilibria of relativistic electron beams in toroidal geometry. *Physics of Fluids* 14:1226.

Measurement of the electroluminescent properties of thin-film metal-insulator-semiconductor structures was part of a graduate research project in electrical engineering.

Wharton, C. B., Korn, P., and Robertson, S. 1971. Skin effect and anomalous resistivity accompanying turbulent heating. *Physical Review Letters* 27(8):499.

Radiophysics and Geophysical Plasmas

Research in this area is concerned with a variety of electromagnetic-wave-propagation phenomena and their utilization in studies of the properties of geophysical plasmas and the neutral atmosphere.

Current topics of study include the interaction of waves and particles in the earth's magnetosphere (VLF emissions), theoretical models of planetary magnetospheres, plasma instabilities occurring in the earth's magnetosphere and ionosphere, the scattering of electromagnetic waves from the random fluctuations in density present in a stable plasma such as the ionosphere, and the use of such scatter measurements as a diagnostic tool to study the physical properties and behavior of the ionosphere. Much of this work utilizes data from the giant radar installation (with an antenna diameter of 1,000 feet and transmitter power of 2.5 megawatts) operated by Cornell in Arecibo, Puerto Rico. This radar allows the rapid measurement of many important parameters of the ionosphere over an altitude range of more than 1,000 kilometers. Some research in the systems area is devoted to devising efficient digital techniques for handling the vast quantities of data which such radar measurements can produce.

Other research is concerned with the microstructure of the neutral atmosphere (particularly the troposphere, stratosphere, and mesosphere), the fluid mechanical aspects of such structure, and the measurement of this structure by electromagnetic wave techniques.

Professors Bolgiano, Brice, Farley, Ott, and Sudan are involved in these research efforts.

A few of the publications in this field are:

Brice, N. M., and Smith, R. L. 1971. Whistlers: Diagnostic tools in space plasma. In *Methods of experimental physics,* vol. 9B, eds. H. R. Greim and R. H. Lovberg, Ch. 13. New York: Academic Press.

Farley, D. T. 1971. Radio wave scattering from the ionosphere. In *Methods of experimental physics,* vol. 9B, eds. H. R. Greim and R. H. Lovberg, Ch. 14. New York: Academic Press.

Ott, E., and Sudan, R. N. 1971. A theory of triggered VLF emissions. *Journal of Geophysical Research* 76(19):4463.

Electromagnetic Theory and Microwave Devices

Research is being conducted on the application of symmetry analysis to electromagnetic theory, particularly as it applies to microwave circuits and devices. The electromagnetic properties of dispersive media are also being investigated.

This research is directed by Professor McIsaac. Among recent publications is:

Knorr, J. B., and McIsaac, P. 1971. A group theoretic investigation of the single wire helix. *IEEE Transactions on Microwave Theory and Techniques* MTT-19(11):854.

Microwave Solid State Electronics

Experimental studies with potential engineering applications are emphasized in research in the field of microwave semiconductors. Active elements for microwave generators and amplifiers for both low and high levels of power are being investigated, as is the operation of these devices in TV microwave links, intrusion alarms, Doppler speed and distance indicators, radars, and other practical systems. The basic physical mechanisms and practical applications of devices using gallium arsenide and silicon are being studied; these include Gunn effect devices and avalanche diodes operating in a variety of operating modes, and a new low-noise silicon space-charge-limited transit-time diode which can generate or amplify microwave signals.

Basic research in materials involves studying and manipulating band structure with the aim of discovering new mechanisms of bulk negative-differential conductivity. The properties of superlattices are of special interest. In addition, crystal growth and structure, diffusion, ion implantation, and device technology are being studied in relation to new or improved microwave devices. Applications research includes the development of optimum integrated circuits for these devices, studies of electrical noise, and the development of methods for characterizing the electrical properties of the active elements and their circuits.

Professors Dalman, Eastman, Frey, and Lee are directing research in these areas. Examples of recent publications are the following.

Dalman, G. C., and Chen, W. T. 1970. Dynamic i-v characteristics of a quenched mode oscillating Gunn diode. *IEEE Proceedings* 58(3):503.

Eastman, L. F., Camp, W. O., and Bravman, J. S. 1971. LSA—new peaks in microwave power. *Microwaves* 10(2):42.

Kuvas, R., and Lee, C. A. 1970. Carrier diffusion in semiconductor avalanches. *Journal of Applied Physics* 41(7):3108.

Quantum Electronics and Solid State Physics

Several distinct programs in these areas include research on chemical and molecular lasers, nonlinear optics, and optical properties of insulators and semiconductors.

In the chemical and molecular laser field, research oriented toward the discovery and study of new laser systems is in progress. The relaxation of vibrational excitation in molecules through atomic and molecular collisions is being studied over an extremely wide range of experimental parameters. The properties of high-pressure molecular laser plasmas are also being studied. This work is interdisciplinary, with joint participation of faculty members and students in the graduate Fields of Chemistry and Aerospace Engineering.

In the area of nonlinear optics, an experimental program is in progress to develop a coherent laser source tunable from the ultraviolet to the near infrared. This program complements ongoing theoretical studies of nonlinear optical effects in the interaction of matter and radiation.

A separate research program centers on electroluminescent Metal-Insulator-Semiconductor structures, with the objectives of obtaining basic information on recombination mechanisms, interface states, barrier energies, and current transport in these samples. These MIS structures offer exciting possibilities for new electroluminescent and lasing devices. Basic properties of the constituents and interfaces are being determined with use of electron-beam-pumped semiconductor lasers and electrical photoexcitation and electroluminescence measurements.

Faculty members involved in these research efforts are Professors Ballantyne, McFarlane, Nation, Tang, and Wolga. Some representative publications in these fields are listed below.

Baukus, J., and Ballantyne, J. 1971. Fourier spectroscopy of millimeter wave sources. In *Proceedings of the symposium on submillimeter waves,* vol. XX, p. 583. New York: Polytechnic Press.

Djeu, N., and Wolga, G. J. 1971. Optical saturation of a single vibration-rotation transition in the ν_3 fundamental of SF_6. *Journal of Chemical Physics* 54:774.

Hodges, D. T., and Tang, C. L. 1970. New CW ion laser transitions in Ar, Kr and Xe. *Journal of Quantum Electronics* 70:757.

McArthur, D. A., and McFarlane, R. A. 1970. Optical mixing in cadmium telluride using the pulsed water vapor laser. *Applied Physics Letters* 16(11):452.

Information and Decision Theory

Studies in the transmission of information focus on source coding problems (such as data compression or redundancy removal for sources such as speech or pictures) and channel coding problems (achieving high rates of reliable communication for such applications as computer to computer communication). Questions of information processing and utilization arising in the design of radar, sonar, and pattern classification systems are subjects for research in decision theory.

Recent extensive investigations of probabilistic coding have led to new algorithms and a better understanding of sequential and maximum-likelihood decoding as techniques for efficient information transmission. Algebraic and combinatorial methods are being applied to the study of error-correcting codes. Comparisons of the efficiency of various analog and digital methods, and also of biomedical information transmission techniques, are being made through rate distortion theory. The concepts of comparative probability and computational-complexity-based probability are being investigated together with studies of their potential for realistic decision making. Novel nonstatistical algorithms for pattern classification are being developed and evaluated.

Professors Berger, Fine, and Jelinek work on these projects. A few of their recent publications are the following.

Berger, T. 1971. *Rate distortion theory: a mathematical basis for data compression.* Englewood Cliffs, New Jersey: Prentice-Hall.

Fine, T. 1970. Extrapolation when very little is known about the source. *Information and Control* 16:331.

Jelinek, F., and Cocke, J. 1971. Bootstrap hybrid decoding for symmetrical binary input channels. *Information and Control* 18(3):261.

Network and System Design

Problems of current interest in this area are concerned primarily with computer-aided circuit design, digital filters, nonlinear systems, systems with distributed parameters, and active networks. Both linear lumped networks and active electronic circuits, including integrated circuits, are designed with the aid of computers. Research is being done in the theory and design of broadband active systems, including microwave circuits containing solid state devices such as avalanche diodes, Gunn and LSA oscillators and amplifiers, and transistors.

The synthesis of networks with time-varying and distributed parameters is being investigated. Gain-bandwidth theory, broad band and highly selective narrow band filters, lump loaded transmission line structures, and time-varying circuits such as n-path filters are among the topics under study.

The CORNAP computer program, which was developed at Cornell, is widely used in industry and at other universities to analyze complicated active linear networks using a state-space approach. The methods used in this program are currently being extended to nonlinear and time-varying networks and distributed parameter systems, with particular emphasis on design optimization methods and the exploitation of sparsity in the matrices defining a complicated network.

Professors Carlin, Ku, Pottle, Szentirmai, and Torng are working in these research areas. Examples of their recent publications are listed.

Carlin, H. J. 1971. Distributed circuit design with transmission line elements. *IEEE Proceedings* 59(7):1059.

Ku, W. 1970. Some results in the theory of optimum broad-band matching. *IEEE Transactions on Circuit Theory* CT-17:420.

Pottle, C. 1971. Effective ordering of sparse matrices arising from nonlinear electrical networks. *IEEE Transactions on Circuit Theory* CT-18:139.

Szentirmai, G. 1971. Computer aids in filter design—a review. *IEEE Transactions on Circuit Theory* CT-18:35.

Torng, H. C., and Zalewski, J. 1970. On implementing sequential circuits with shift registers. *IEEE Proceedings* 58:1394.

Control Theory

Theoretical problems associated with lumped and distributed parameter control systems, including problems of stochastic control theory, are being studied. Lumped parameter systems are used in aircraft and rocket guidance and control. Distributed control problems are of major interest in such industrial processes as drying and heating and in the control of vibrational modes in aircraft and rockets.

An important part of the research is focused on successive approximation techniques. Computer techniques (analog, digital, and hybrid) are emphasized, particularly for optimization in real time. Recently, real time controllers, designed on the basis of the research in optimization theory, have been built and tested at an industrial laboratory. Work is being started on the design of a television system, for use on unmanned lunar and planetary exploration vehicles, which will simulate the behavior and sensitivity of the eye.

Professors Kim, Thorp, and Vrana conduct research in this area. The following are a few representative publications.

Kim, M. 1969. Successive approximation method in optimum distributed-parameter systems. *Journal of Optimization Theory and Applications* 4:40.

Lewine, R. N., and Thorp, J. S. 1970. Computation of time optimal controls using a second variation descent search. *IEEE Transactions on Automatic Control* AC-15(3):358.

Bioelectronics

Research in this field includes the study of animal communication, sensory processing in the nervous system, electrophysiological techniques and instrumentation, and bionics, the engineering application of biological system behavior. One project is concerned with pattern recognition and physiological signal processing associated with the croaking of frogs. Another project utilizing the framework of control theory involves the study of a nerve cell in Aplysia which periodically emits bursts of electrical signals and behaves in many ways like an electronic oscillator.

Professors Capranica and Kim are directing the research efforts in bioelectronics. Among their recent publications are the following.

Frishkopf, L. S., Capranica, R. R., and Goldstein, M. H., Jr. 1968. Neural coding in the bullfrog's auditory system: a teleological approach. *IEEE Proceedings* 56:969.

Strumwasser, F., and Kim, M. 1969. Experimental studies of a neuron with an endogenous oscillator and a quantitative model of its mechanism. *The Physiologist* 12:367.

Engineering Design Projects

Students in the Master of Engineering (Electrical) degree program complete a design project as part of the requirements for the degree. Many of these projects are associated with the design of an efficient electric car, prototypes of which have competed in "clean air" races, and with the design of a roving vehicle for unmanned exploration of Mars.

Faculty Members and Their Research Interests

Paul D. Ankrum, M.S. (Cornell): *solid state circuits*

Joseph M. Ballantyne, Ph.D. (M.I.T.): *solid state physics, quantum electronics*

Toby Berger, Ph.D. (Harvard): *information processing, communication theory*

Ralph Bolgiano, Jr., Ph.D. (Cornell): *tropospheric radiophysics, communication theory*

Neil M. Brice, Ph.D. (Stanford): *magnetospheric physics, radio propagation*

Nelson M. Bryant, M.E.E. (Cornell): *electronic circuits, instrumentation*

Robert R. Capranica, Sc.D. (M.I.T.): *bioelectronics, pattern recognition*

Herbert J. Carlin, Ph.D. (Polytechnic Institute of Brooklyn): *microwave circuits, network theory*

G. Conrad Dalman, D.E.E. (Polytechnic Institute of Brooklyn): *microwave solid state devices and circuits*

Lester F. Eastman, Ph.D. (Cornell): *microwave solid state devices, gallium arsenide techniques*

William E. Erickson, M.S. (Canadian Institute of Technology): *power engineering, instrumentation*

Donald T. Farley, Ph.D. (Cornell): *ionospheric physics, radio propagation*

Terrence Fine, Ph.D. (Harvard): *decision theory, pattern classification*

Jeffrey Frey, Ph.D. (California at Berkeley): *microwave solid state devices, integrated electronics*

Frederick Jelinek, Ph.D. (M.I.T.): *coding and information theory*

Myunghwan Kim, Ph.D. (Yale): *bioelectronics, control theory*

Walter Ku, Ph.D. (Polytechnic Institute of Brooklyn): *active networks, digital circuits*

Charles A. Lee, Ph.D. (Columbia): *solid state physics and devices*

Richard L. Liboff, Ph.D. (New York University): *plasma physics, electromagnetic theory*

Simpson Linke, M.E.E. (Cornell): *high voltage pulse power, energy systems*

Ross A. McFarlane, Ph.D. (McGill): *lasers, atomic and molecular spectroscopy*

Henry S. McGaughan, M.E.E. (Cornell): *network and communication theory*

Paul R. McIsaac, Ph.D. (Michigan): *microwave circuits and devices, electromagnetic theory*

John A. Nation, Ph.D. (Imperial College, London): *plasma physics, high energy electron beams*

Benjamin Nichols, Ph.D. (University of Alaska): *education techniques*

Robert E. Osborn, B.S.E.E. (Purdue): *electrical machinery, instrumentation*

Edward Ott, Ph.D. (Polytechnic Institute of Brooklyn): *plasma and ionospheric physics*

Electrical Engineering, a Field in which more than one hundred graduate students are enrolled, is housed mainly in Phillips Hall on the Engineering Quadrangle.

Christopher Pottle, Ph.D. (Illinois): *computer-aided design, network theory*

Joseph L. Rosson, M.E.E. (Cornell): *power engineering, instrumentation*

Howard G. Smith, Ph.D. (Cornell): *communications, electromagnetic theory*

Ravindra N. Sudan, Ph.D. (University of London): *plasma physics, electromagnetic waves*

George Szentirmai, Ph.D. (Polytechnic Institute of Brooklyn): *computer-aided design, network theory*

Chang L. Tang, Ph.D. (Harvard): *lasers, quantum electronics*

James S. Thorp, Ph.D. (Cornell): *optimization and control theory*

Hwa-Chung Torng, Ph.D. (Cornell): *switching theory, computer design and architecture*

Norman M. Vrana, M.E.E. (Cornell): *hybrid computing systems, simulation of systems*

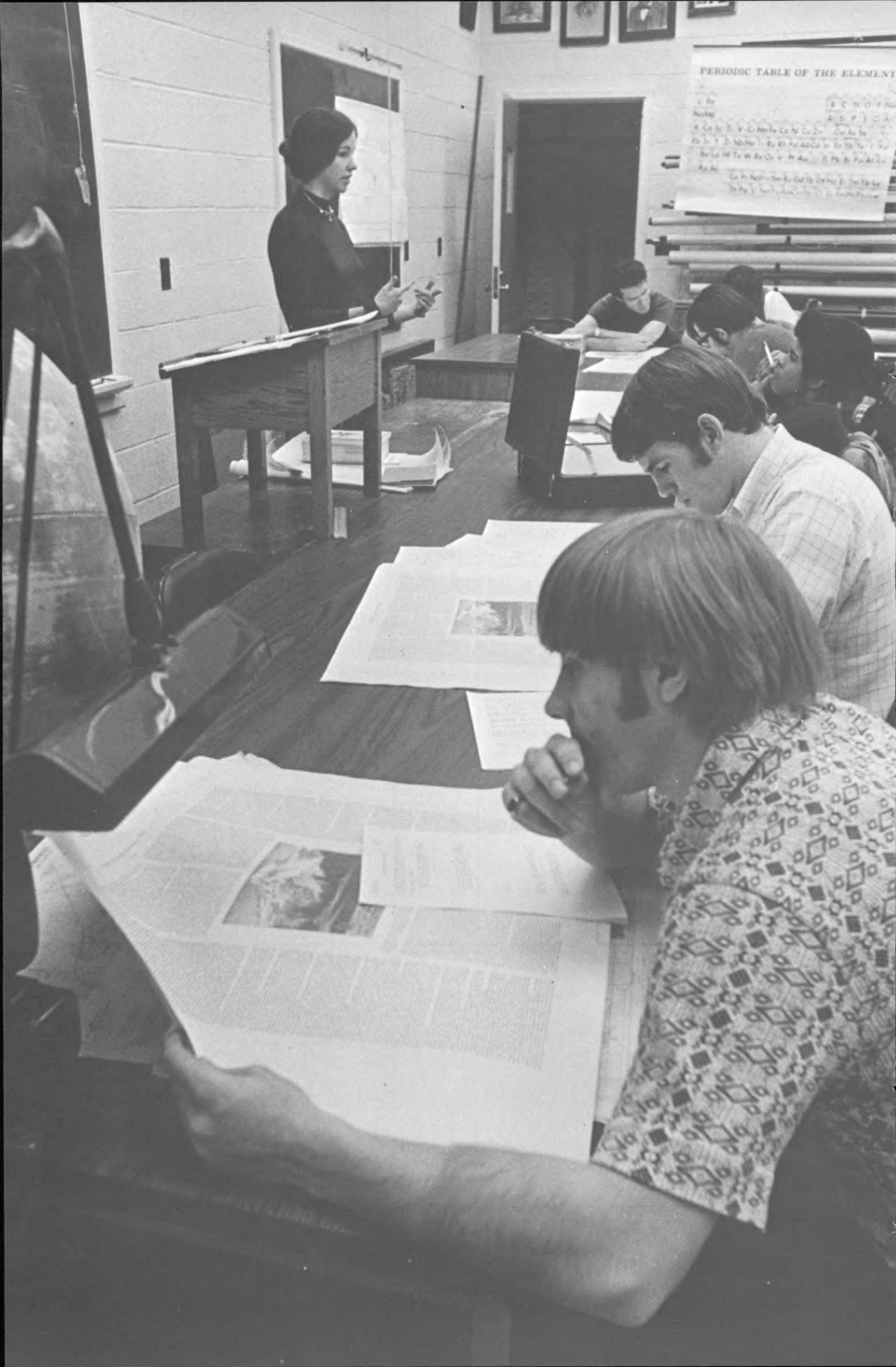
Charles B. Wharton, M.S. (California at Berkeley): *plasma physics, microwave diagnostics*

George J. Wolga, Ph.D. (M.I.T.): *lasers, atomic physics*

Stanley W. Zimmerman, M.S. (Michigan): *power engineering, dielectrics, high voltage*

Further Information

Members of the faculty welcome inquiries about the various graduate programs and research projects. These may be addressed to the Graduate Field Representative, Electrical Engineering, Phillips Hall, Cornell University, Ithaca, New York 14850.


PERIODIC TABLE OF THE ELEMENT

Geological Sciences

Recent major developments such as the advent of the theory of plate tectonics, the increased need for minerals and energy sources, the new wave of concern over the environment, and the exploration of the moon and planets, have brought the time-honored science of geology to a new level of excitement and importance. In recognition of these developments, Cornell has entered a building and strengthening phase in the geological sciences. The University is adding staff in this field, providing new and improved quarters for the Department, and planning a significant upgrading of its already extensive materials and facilities.

Graduate students in the Field of Geological Sciences have the opportunity to participate in these expanding activities. Programs leading to the degrees of Doctor of Philosophy and Master of Science are available, and major fields of study may be chosen from a wide variety of specialties, including economic geology, engineering geology, environmental geology, general geology, paleontology, stratigraphy, geochemistry, geomorphology, geophysics, geotectonics and structural geology, marine geology, mineralogy, petrology, physical geology, Pleistocene geology, and seismology. In all the areas, there is a strong emphasis on the application of the basic sciences to the understanding of the earth and on learning through participation in research projects.

The Field of Geological Sciences seeks graduate students with a variety of interests and backgrounds, for there are many kinds of geologists. An earth scientist may be a keen observer and outdoorsman living under primitive conditions during a field season, or he may be a theoretician using elegant mathematics or the largest computer. He may be a geophysicist or geochemist using sophisticated instruments of high precision and sensitivity. He may be an environmentalist or a prospector. There are many other options. The earth sciences offer opportunities and challenges for talented students of almost any sound technical background. Those students with conventional undergraduate training in geology are, of course, most welcome, but so are those who may have little or no training in geology but who have good preparation in the basic sciences through undergraduate majors in physics, chemistry, biology, mathematics, or a branch of engineering.

An undergraduate class in geology is conducted by a graduate student in geological sciences who holds a teaching assistantship.

Facilities

The department has outstanding rock, mineral, and fossil collections and well-equipped geological sciences laboratories. These facilities are augmented by special and advanced equipment available through other units of the University and provide excellent opportunities for research.

For field research projects, there are available sites and programs in Tonga, New Zealand, and Labrador, as well as in the northeastern and western states, the nearby Adirondack region, and the area around Ithaca.

Areas of Research

A major part of the research activity is focused on the topic of plate tectonics, the far-reaching new concept that brings together for the first time most of the disciplines of geology. This topic is being explored and developed at Cornell through its relation to economic geology, geodesy, geomorphology, gravimetry, paleontology, petroleum geology, petrology, seismology, and stratigraphy, among others. The expanding list of research projects includes studies of deep earthquakes in the Tonga-Fiji Island Arc, of recent crustal movements in New Guinea and in the eastern United States, of ore deposits in Minnesota, of convection in the earth's deep interior, of microearthquakes in New Zealand, of the retreat of Niagara Falls, of coral growth in Pacific reefs, of global geotectonics, of structural deformation bordering the Mediterranean, and of a variety of topics in environmental and engineering geology.

Recent publications of faculty members of the graduate Field of Geological Sciences indicate some of the research projects now under way. Among them are the following.

Isacks, B. 1969. Mantle earthquake mechanisms and the sinking of the lithosphere. *Nature* 223:1121.

Isacks, B., and Molnar, P. 1971. Distribution of stresses in the descending lithosphere from a global survey of focal mechanism solutions of mantle earthquakes. *Review of Geophysics and Space Physics* 9:103.

Oliver, J., Isacks, B., and Sykes, L. R. 1968. Seismology and the new global tectonics. *Journal of Geophysical Research* 73:5855.

Faculty Members and Their Research Interests

Arthur L. Bloom, Ph.D. (Yale): *geomorphology, Pleistocene geology*

Bill Bonnichsen, Ph.D. (Minnesota): *petrography and petrology*

Bryan L. Isacks, Ph.D. (Columbia): *seismology, tectonics*

George A. Kiersch, Ph.D. (Arizona): *engineering geology*

Jack E. Oliver, Ph.D. (Columbia): *geophysics, tectonics*

Shailer S. Philbrick, Ph.D. (Johns Hopkins): *engineering geology*

William Travers, Ph.D. (Princeton): *structural geology, stratigraphy*

John W. Wells, Ph.D. (Cornell): *invertebrate paleontology, paleoecology, stratigraphy*

Further Information

Questions about the expanding graduate program in geological sciences may be addressed to the Graduate Field Representative, Geological Sciences, Kimball Hall, Cornell University, Ithaca, New York 14850.

Research activities in geological sciences are centered in Kimball Hall on the Engineering Quadrangle.

Materials Science and Engineering

The graduate Field of Materials Science and Engineering at Cornell provides students with widely differing undergraduate backgrounds the opportunity to undertake graduate research and study in the area of materials. The forty-five graduate students now in the department have undergraduate degrees in physics, applied physics, and mechanical, metallurgical, chemical, and electrical engineering, as well as in materials science.

Most of the research in the department is conducted in connection with the interdisciplinary Materials Science Center, the largest such university center supported by the federal government. One of the purposes of the Materials Science Center is to support large central facilities (for example, the electron microscope laboratory) which make available to every student and faculty member modern and, often, very expensive equipment. The Center also provides financial assistance for graduate students through research assistantships and equipment for thesis research projects.

Facilities

Laboratories and equipment are located in Bard and Thurston Halls on the engineering campus and in Clark Hall of Science, which houses some of the University's physics groups and most of the Materials Science Center facilities. A description of the Materials Science Center and its various laboratories and facilities is given on page 91.

The extensive facilities available at Cornell make possible a wide variety of research in materials science. For example, a 50,000-pound electrohydraulic materials testing system enables researchers to test engineering specimens of high-strength materials under various loading conditions, including cyclic loading of any arbitrary wave form. This testing system complements various Instron testing machines to provide a wide range of capability for studying macroscopic mechanical behavior of materials.

A graduate student adjusts an electrohydraulic closed-loop testing machine prior to the precision measurement of crack growth in a high-strength steel.

For other types of investigation there are available seven field ion microscopes, six electron microscopes, high-field magnets, x-ray diffraction equipment, ultrahigh-vacuum apparatus, low-energy-electron-diffraction apparatus, high-pressure systems, ultrasonic equipment, cryostats, a residual gas mass spectrometer, and various pieces of optical and electronic equipment. The properties of materials can be probed down to the atomic scale.

The electron microscopes that graduate students in the Field may use are located in two separate laboratories. In Clark Hall there are a Siemens Elmiskop 1 microscope and a Hitachi HU 11A microscope. In Bard Hall there are a JEM 200-kv microscope, an AEI EM6G microscope, a Hitachi HU 11A microscope, and an AMR 900 scanning electron microscope. These instruments are equipped with special stages, such as two-directional tilting stages, a liquid helium stage, a high-temperature stage, and a tensile straining stage for various specific applications.

Areas of Research

A wide range of research projects is available to graduate students. Faculty members are continually developing new areas of materials research; for example, during the past two years projects were started on composite materials, amorphous materials, biomaterials, polymers, and laser holography. Some of the current research areas are described briefly below.

Imperfections in Solids

An extensive program under the guidance of Professors Balluffi and Seidman utilizes transmission electron microscopy, field ion microscopy, and resistivity measurements to study defects in metal crystals.

For example, the nature and production mechanism of small defect clusters produced in single-crystal silver films by bombardment with 5 to 20-keV silver ions were studied with use of electron microscopy.

In another project, a technique has been developed for studying the annealing of supersaturated vacancy defects in gold at elevated temperatures. A wire specimen mounted in a helium-filled cryostat is gas quenched from the quenching temperature to an elevated annealing temperature. The total loss of defects is obtained from residual electrical resistivity measurements at 4.2°K.

Studied by transmission electron microscopy was the annealing of artificially created voids in aluminum by a self-diffusion mechanism. Included were measurements of the fast diffusion of aluminum atoms along dislocations in the metal.

A technique for producing any type of planar grain boundary in thin-film bicrystal specimens under controlled conditions has been developed; observations are made by transmission electron microscopy.

The mobility of single self-interstitial atoms was studied in a series of in situ field ion microscope experiments in which tungsten irradiated under ultrahigh vacuum conditions at very low temperatures was examined by means of a pulse field evaporation technique.

A temperature distribution in a field ion microscope specimen heated simultaneously by thermal radiation, the imaging gas, and an energetic beam of charged particles was calculated in the steady state approximation employing a realistic model for the specimen. Also, a systematic study has been made of the effect of hydrogen gas on the field evaporation characteristics of gold specimens in the field ion microscope.

Professor Li is investigating phenomena in solids, such as metal swelling caused by void formation, which are the result of fast neutron irradiation. These studies are relevant to the development of liquid metal fast breeder reactors and of projected controlled thermal nuclear reactors.

Work with highly perfect crystals is proceeding under the supervision of Professor Batterman. With the use of these crystals, internal x-ray crystal interferences can be observed, and this technique is being used to independently measure the atomic form factors of elements which can form structurally perfect crystals. In recent dynamical diffraction studies, an experiment was devised by which the site of an impurity atom in a host lattice could be determined. Thermal scattering of x rays and neutrons is being used to measure the frequency versus wave number of phonons in a lattice.

Recent publications in the area of imperfections in solids include the following.

Scanlan, R. M., Styris, D. L., and Seidman, D. N. 1970. An in situ field ion microscope study of stage I recovery in tungsten irradiated with 20 keV W^+: I. Experimental results. II. Analysis and interpretation. *Materials Science Center Reports* nos. 1340 and 1385. Ithaca: Cornell University.

Schober, T., and Balluffi, R. W. 1969. Dislocation sub-boundary arrays in oriented thin-film bicrystals of gold. *Philosophical Magazine* 20:511.

Harkness, S. D., and Li, C.-Y. 1971. A study of void formation in fast neutron-irradiated metals. *Metallurgical Transactions* 2:1457.

Keating, D., Nunes, A., Batterman, B., and Hastings, J. 1971. Anharmonicity and the temperature dependence of the forbidden (222) reflection in silicon. *Physical Review Letters* 27:320.

Surfaces and Interfaces

Information about the structure and chemical reactions that occur at crystal surfaces is being obtained by researchers under the supervision of Professor Batterman. Measurements are made of the diffraction of high-energy electrons at low-glancing angles from atomically clean crystal surfaces. A special camera has been developed for these experiments.

Studies by Professor Blakely and his students are concerned with surface phenomena in crystalline solids. Optical diffraction and interference measurements, developed for a study of the mass transport processes that occur in crystalline solids at high temperatures, are yielding information on surface diffusion, volume diffusion, and surface energies. The technique of Auger electron spectroscopy is being used for chemical analysis in studying the phenomenon of solute segregation to free surfaces. Other surface phenomena, such as the variation of electronic work function with surface structure and with adsorption, order-disorder transformations, and oxide growth on the basal planes of the group II hexagonal metals, are being studied with use of low-energy electron diffraction (LEED) and dynamic capacitor techniques. Defects occurring near the free surfaces of ionic crystals are also being studied theoretically and experimentally.

The coupled diffusion problem associated with Ostwald ripening has been analyzed by Professor Li, and this analysis is being applied to the aging process and thermal stability of dispersed systems. In another project, the structure and mechanical behavior (deformation, fracture, and fatigue) of grain boundaries are being investigated by transmission electron microscopy and Auger spectroscopy.

Representative recent publications in this area are:

Blakely, J. M., Baker, J. M., and Strozier, J. A. 1970. Study of low energy electron diffraction at cleaved Zn and Be surfaces. In *Proceedings of international conference on structure and properties of solid surfaces,* p. 69. Paris: Centre National de la Recherche Scientifique.

Blakely, J. M., and Schwoebel, R. L. 1971. Capillarity and step interactions on solid surfaces. *Surface Science* 26:321.

Feingold, A. H., and Li, C.-Y. 1968. Experimental verification of mass transport analysis for Ostwald ripening and related phenomena. *Acta Metallurgica* 16:1101.

Mechanical Behavior of Materials

The relationships among cyclic deformation parameters, fatigue, and lattice defects are being studied in high-purity copper and aluminum by Professor Johnson and his students. Another research program under the guidance of Professor Johnson is concerned with the effects of different aggressive and innocuous environments on the fracture behavior of high-strength steels.

In the area of polymers, Professor Kramer is working on the identification of mechanisms responsible for yield and plastic flow of polymers at and below the glass transition. Small and wide-angle x-ray diffraction is being used to examine polymers.

Professor Sass is using electron microscopy to determine the role crystal defects play in the deformation of crystalline polymers. An image intensifier which should allow the imaging and study of imperfections in single polymer crystals has been built.

The design of advanced power generation systems requires better descriptions of the mechanical behavior of solids at elevated temperatures over long periods of time, and Professor Li is performing pertinent creep and stress relaxation experiments.

Professor Ho is applying various techniques in laser holographic interferometry to study micromechanics in composite materials. Research areas that are being pursued include stress analysis in the elastic-plastic region, in situ observation of the initiation and growth of cracks at fiber-matrix interfaces, and stress determination in composite materials under harmonic loads.

The internal stresses developed in filament- and whisker-reinforced materials seriously affect the engineering potentials of composites, and studies by Professor Scala on polymeric, ceramic, and metal matrices are being carried out to evaluate these internal stresses.

The following publications are representative of the many papers being written by Cornell researchers in this area.

Johnson, H. H., and Paris, P. C. 1968. Sub-critical flaw growth. *Engineering Fracture Mechanics* 1:1.

Kramer, E. J. 1970. Stress aging in anhydrous nylon 6-10. *Journal of Applied Physics* 41:4327.

Scala, E. 1965. Design and performance of fibers and composites. In *Fiber composite materials,* p. 131. Metals Park, Ohio: American Society for Metals.

Yaggel, F. L., and Li, C.-Y. 1971. *Failure mechanisms for internally pressurized thin-wall tubes and their relationship to fuel element failure criteria.* Argonne National Laboratory Report no. 7805.

High-Pressure Studies

The research program on materials under high pressure is under the direction of Professor Ruoff. One current project is a study of the mechanism of creep through measurements of its pressure dependence and the effect of doping. Other studies are concerned with the mechanism of superplasticity and the anharmonic properties of solids. Ultrasonic interferometry and continuous wave techniques are being used to measure the elastic constants of solids, data which are useful in many theoretical and experimental studies. The forming of materials by hydrostatic extrusion promises to be an important commercial process, and investigations are under way to develop techniques of continuous extrusion.

Ultrahigh-pressure work now being conducted has as its goal the production of new synthetic polymorphs (metallic NH_4, metallic hydrogen, and CO_2 with a three-dimensional network.) Metallic hydrogen, for example, is a high-pressure form of the gas which may be metastable at atmospheric pressure. In connection with these experiments, it is hoped to generate static pressure in excess of two million atmospheres, which approaches the pressure at the earth's center.

A few of the recent publications in this area are the following.

McCormick, P. G., and Ruoff, A. L. 1969. Hydrostatic pressure and the mechanism of creep in aluminum. *Journal of Applied Physics* 40:4812.

Ho, P. S., and Ruoff, A. L. 1968. Analysis of ultrasonic data and experimental equation of state for sodium. *Journal of Physics and Chemistry of Solids* 29:2101.

Phase Transformations

Professor Batterman is studying the so-called hard superconductors V_3Si and Nb_3Sn, which have about the highest superconducting transition temperatures known. These materials have the associated property of remaining superconducting in magnetic fields of the order of several hundred kilogauss, a property that makes them suitable for high-field superconducting magnets. The research involves investigation of low-temperature phase transformations.

Professor Sass is using high resolution dark field electron microscopy and electron diffraction to study certain alloys (Zr-Nb, Ti-V, and Ti-Nb) in terms of a transformation that occurs in the parent crystal and has a profound effect on the mechanical and superconducting properties of these alloys. The transformation is to a metastable structure called the omega phase. Attenuation and x-ray measurements as well as low-temperature electron microscopy are being used to follow the phase transformation. Also, elastic constant measurements are being used to check the validity of a suggested mechanism for the transformation. In order to understand the effect of the omega phase on the mechanical properties of the alloys, single-crystal studies are being conducted.

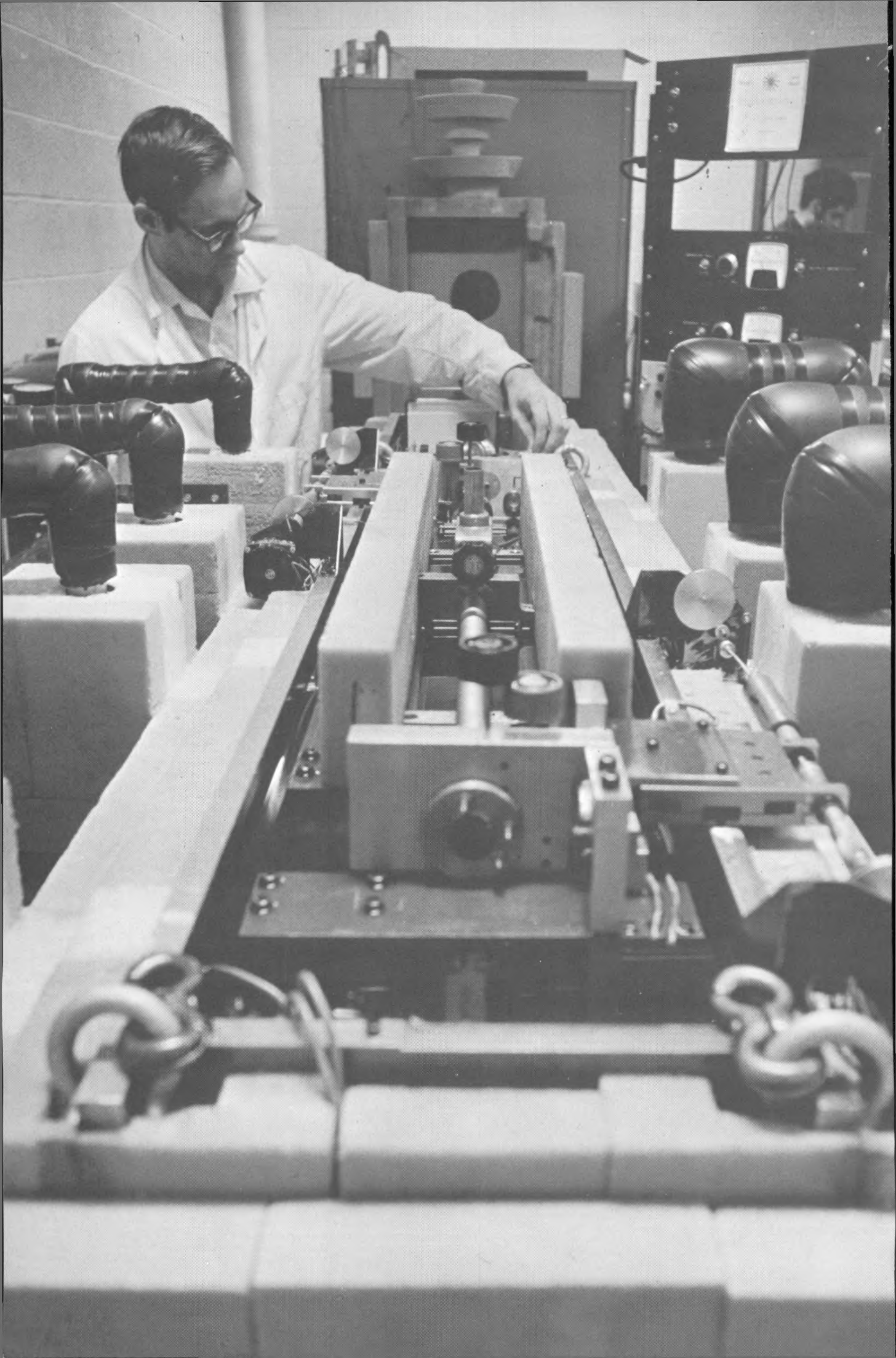
The following are some representative publications in this area of research.

Dawson, C. W., and Sass, S. L. 1970. The as-quenched form of the omega phase in Zr-Nb alloys. *Metallurgical Transactions* 1:2225.

Wanagel, J., and Batterman, B. W. 1970. A crystallographic study of the phase transformation in V_3Si and Nb_3Sn. *Journal of Applied Physics* 41:3610.

Electrical and Magnetic Properties

Professor Ast is directing studies of the electronic properties of amorphous materials, especially chalcogenide glasses. These materials are of interest to the electronics industry because they exhibit a switching behavior which is not as dependent on purity as are the classical semiconducting materials. The main interest is in the phase transformation connected with this switching behavior, and the main research tools are optical and electron microscopy. Reversible phase transformations can be obtained also by means of laser beam writing, a technique which has great potential for the fabrication of high-



density "read only" memory devices. A third area of interest is the influence of contact metals on the thermal stability of these materials.

Experimental and theoretical work under the supervision of Professor Ho is concerned with the effects on metals of potential and thermal gradients and of ion bombardment. These studies are of interest in electronics because it is known that void formation induced by electromigration in metallic films is an important failure mode of microelectronic devices. They are important to studies of metals exposed to neutron irradiation because pore formation under ion bombardment causes swelling of the metal and consequent structural damage. The research effort utilizes transmission and scanning microscopy and laser interferometry.

An understanding of the mechanisms of pinning of the flux line lattice by crystal defects, such as dislocations or surfaces, is basic to the production of superconducting wire with a high critical current. The objective of work under the direction of Professor Kramer is to elucidate these mechanisms. One area of interest is the study of the surface contributions to pinning. Another is flux line lattice motion, a mechanism that is reflected in details of a current-voltage curve.

Examples of recent publications in this area of research are given below.

Good, J. A., and Kramer, E. J. 1971. Yield and recovery of the flux line lattice in a type II superconductor. *Philosophical Magazine* 24:339.

Ho, P. S., and Glowinski, L. 1970. Observation of electromigration in thin films. In *Proceedings of the international conference on atomic transport in solids and liquids.* Marstrand, Sweden.

Faculty Members and Their Research Interests

Dieter G. Ast, Ph.D. (Cornell): *amorphous materials*

Robert W. Balluffi, Sc.D. (M.I.T.): *crystal defects, radiation damage, diffusion*

Boris W. Batterman, Ph.D. (M.I.T.): *x-ray and electron diffraction, solid state phenomena*

John M. Blakely, Ph.D. (Glasgow): *surface physics, point defects, diffraction*

Malcolm S. Burton, S.M. (M.I.T.): *mechanical properties of solids, sintering*

Paul S. Ho, Ph.D. (R.P.I.): *electromigration and thermomigration, lattice defects, composite materials*

Herbert H. Johnson, Ph.D. (Case Institute of Technology, now Case Western Reserve University): *dislocation mechanics, gases in metals, cyclic deformation, environment and fracture*

A laser interferometer is used for equation of state measurements at high pressure.

Edward J. Kramer, Ph.D. (Carnegie-Mellon): *superconductivity, internal friction, high-polymer physics*

Che-Yu Li, Ph.D. (Cornell): *surface and interface studies, irradiation effects*

Arthur L. Ruoff, Ph.D. (Utah): *high pressure phenomena, higher order elastic constants, hydrostatic extrusion, creep, superplasticity*

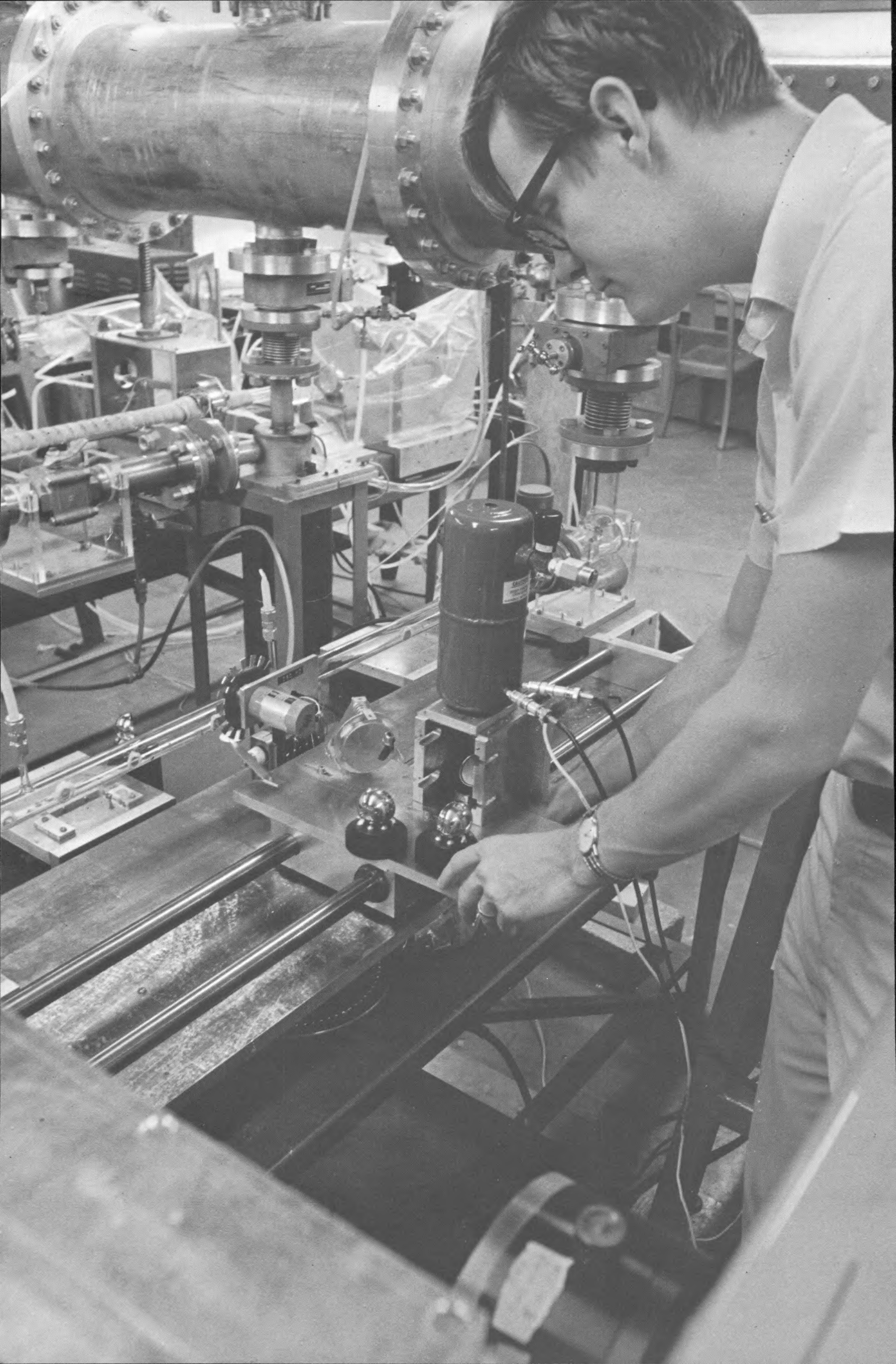
Stephen L. Sass, Ph.D. (Northwestern): *phase transformations, transmission electron microscopy, polymers*

E. N. Scala, D. Eng. (Yale): *composites, ceramics, materials engineering*

David N. Seidman, Ph.D. (Illinois): *lattice defects, radiation damage, field ion microscopy*

Further Information

Inquiries about graduate study in the Field of Materials Science may be addressed to the Graduate Field Representative, Materials Science and Engineering, Bard Hall, Cornell University, Ithaca, New York 14850.



Mechanical Engineering

Mechanical engineering is concerned with two major streams of technology: the production and utilization of energy, and the design and production of goods, machines, equipment, and systems. The graduate Field of Mechanical Engineering at Cornell University is therefore composed of two departments, the Department of Mechanical Systems and Design, and the Department of Thermal Engineering. Instruction and research in these areas are carried out in the Sibley School of Mechanical Engineering.

Students in any of the three graduate degree programs—Doctor of Philosophy, Master of Science, and Master of Engineering (Mechanical)—may select machine design, thermal power, or thermal processes as the major subject to study. Minors may be in these areas or in material processing, or may be taken in other engineering departments or other divisions of the University. Mathematics, nuclear engineering, electrical engineering, or plasma studies may be minor subjects.

The Ph.D. and M.S. programs require research projects. The M.Eng. (Mechanical) program requires participation of the student in a design project, a comprehensive task in engineering design undertaken by a small group of students under the supervision of a faculty member. A design project is frequently performed in cooperation with an industrial organization which suggests a project of current interest, participates in an initial discussion of the problems with the students involved, and reviews the solution upon completion.

At the present time there are approximately sixty graduate students enrolled in the Field of Mechanical Engineering.

Facilities

Special equipment available for graduate research in the Field of Mechanical Engineering includes a Mach-Zehnder interferometer; several schlieren systems; a solar furnace for high-temperature, controlled

The vibrational relaxation times in CO_2 in high-speed flows are measured in experiments with molecular and chemical lasers.

atmospheric heating; extensive hotwire anemometer equipment; devices for measuring secondary flows in rotation passages; a plasma arc facility; a combined steady-torque and reversed-bending fatigue testing machine; bearing-test machines for eccentric loading, for programmed load variations, and for shaft oscillations; special rigs for the dynamic loading of machine parts; automatic data recording instruments; and an extensive laboratory of machine tools and gages.

Also available to mechanical engineering graduate students are the University's large-scale computer facilities, both digital and analog. A terminal of the University computer is located in Upson Hall. A nuclear reactor facility is also available for student use.

By special arrangement, some thesis work may be carried out at the Brookhaven National Laboratory.

Areas of Research

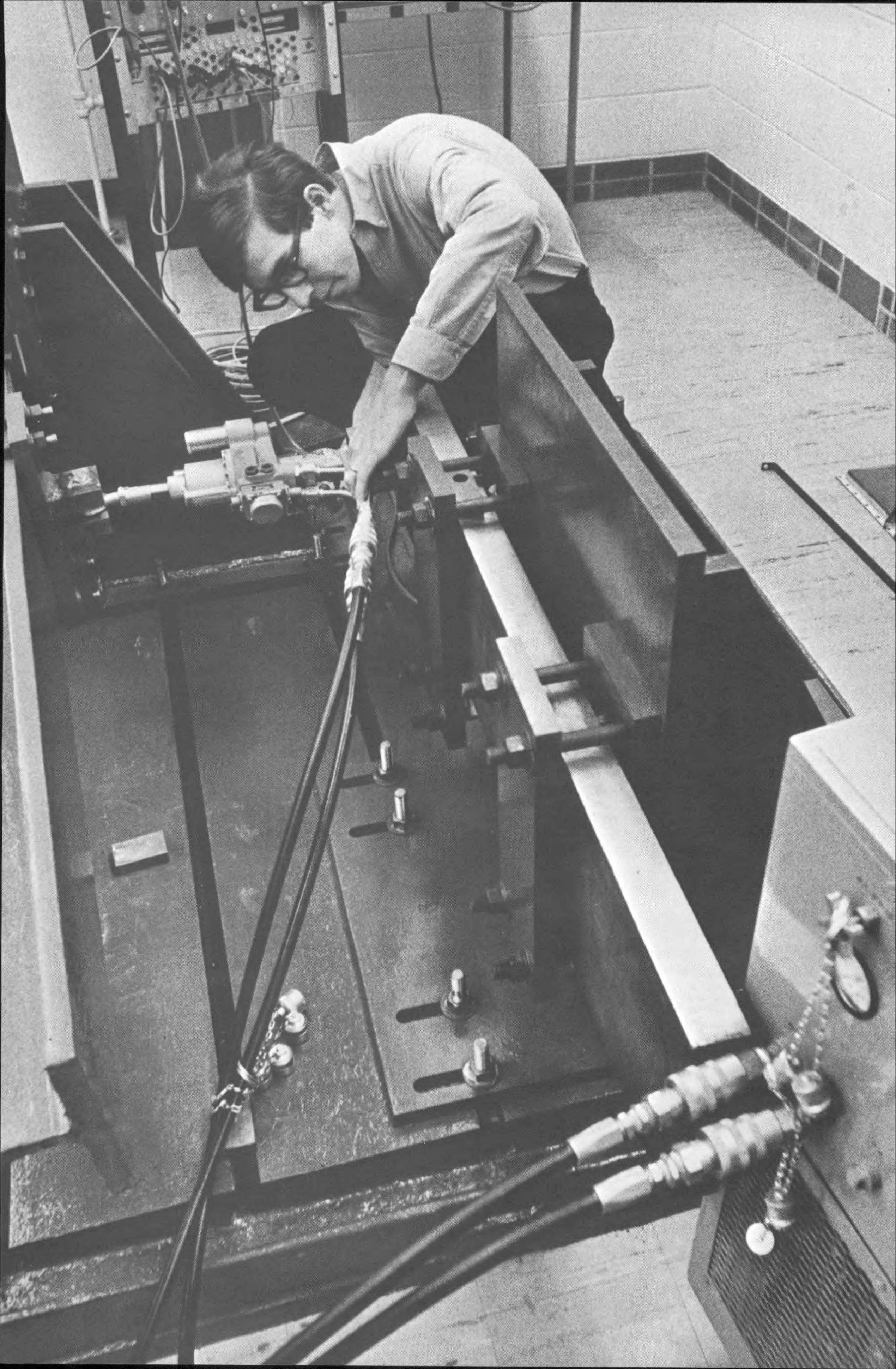
Much of the research being conducted in the School of Mechanical Engineering is supported by government and industry. For example, special NASA grants support a variety of projects relevant to space propulsion and power generation.

Activity in the two main areas of the graduate Field of Mechanical Engineering is described below. The names of faculty members involved in the studies are indicated in parentheses.

Mechanical Systems and Design

The design, analysis, and manufacture of devices, machines, and systems is the broad concern of this department. Current faculty research interests include lubrication (Professors Booker and Wehe), manufacturing engineering (Professor Wang), product design (Professor Krauter), design optimization and reliability (Professors Bartel, Krauter, and McManus), design of components (Professors Burr and Phelan), vibration and controls (Professors Booker, Phelan, and Wehe), and computer-aided design (Professors Bartel and Booker).

In the area of lubrication, analytical solutions describing the behavior of the lubricating film under many different dynamic loadings, such as those that



occur in reciprocating engines, have recently been formulated. Testing is made possible by a machine that was developed to simulate such conditions in the laboratory. The instability or whirl of lightly loaded bearings, dynamic cavitation, and the characteristics of the oil film between gear teeth and rolling disks are also under experimental and analytical investigation. Short bearings, eccentric loading, and temperature conditions have been extensively studied.

Recent investigations in mechanical systems dynamics have been in the areas of vibration, noise, impact, and automatic control. Such studies are facilitated by a well-equipped laboratory with facilities including electronic and hydraulic amplifiers and power supplies, and analog computers for system simulation. Several projects in dynamic and propulsion problems in automotive vehicles are also under way.

Current stress analysis research makes use of a special fatigue machine to investigate the commonly occurring operational condition of reversed bending and steady torsion in rotating shafts. Optimum proportions for built-up cylinders and other mechanical elements, contact stresses, and residual stresses have also been subjects of recent investigations. Research in these areas is carried out in a machine design laboratory which has special facilities for stress analysis including resistance strain gages and equipment for brittle lacquer and photoelastic techniques.

Problems in the general area of machine forces and power are under investigation. A specific example is the determination of temperature and wear of cutters when material is removed under varying conditions.

Some recent publications which suggest faculty interests in the area of mechanical systems and design are the following.

Badgley, R. H., and Booker, J. F. 1970. Rigid-body rotor dynamics: dynamic unbalance and lubricant temperature changes. *Journal of Lubrication Technology* 92 (Series F):415.

Phelan, R. M. 1970. *Fundamentals of mechanical design,* 3rd ed. New York: McGraw-Hill.

Wang, K. K., and Nagappan, P. 1970. Transient temperature distribution in inertia welding of steels. *Welding Journal, Research Supplement* 49:4195.

Titles of recent theses also demonstrate the kind of research being carried out by graduate students. These include:

Analysis of Porous Metal Bearings (Ph.D., 1971)

Future Outlook for Vehicle Propulsion and Air Pollution (M.S., 1971)

Braking Study of Tractor-Semitrailers (M.S., 1971)

Static and Dynamic Characteristics of Electromechanical Torque Motors (Ph.D., 1970)

A graduate student adjusts the electrohydraulic device that is being used in an experimental gimballing system designed to simulate launching control for a space vehicle.

Thermal Engineering

Thermal power and thermal processes are the two general areas of research in this field.

Faculty research interests in the area of thermal power include direct energy conversion, propulsion and nuclear power, use of solar energy, turbomachinery, combustion engines, air conditioning, refrigeration, and heat pumps (Professors Conta, Dropkin, Fairchild, Gouldin, and Shepherd).

In the area of thermal processes, current faculty interests include aspects of fluid dynamics such as high temperature and nonequilibrium effects, viscosity, radiative transfer, flow lasers, fluid flow with application to the confinement of high-temperature gases and to natural processes in the atmosphere and oceans, problems of heat rejection to the environment, thermal and air pollution, and plasma processes (Professors Cool, Gouldin, Leibovich, Moore, and Torrance). Problems of heat transfer that are of special concern are stability convective flows, two-phase flows, boiling heat transfer, ablative heat transfer, combustion processes and fire research (Professors Dropkin, Gebhart, McManus, and Torrance). The application of classical statistical and irreversible thermodynamics to present day technology involving thermal processes is also an area of current interest (Professors Cool and Conta).

In the area of heat transfer, current studies of free convection are concerned with transient response of vertical elements in low Grashof number flows, steady-state heat transfer in confined spaces of liquid metals with and without spin, the stability problems of such flows, and heat transfer from finned and inclined surfaces.

Various problems of liquid boiling in both nucleate and film regimes are being investigated. These include effects of forced convection along heated surfaces, and effects of rotation, ultrasonic vibration, and transverse electric fields. There are related questions which concern flow systems with a phase interface. For example, a current study concerns the dynamic behavior of "dry spots" in a heat exchanger passage with two-phase flow.

As part of a space research effort concerned with problems of entry heat protection, a study is being made of heat transfer to ablating objects subject to arc-generated plasma flows at temperatures up to 15,000°K.

Also under study are problems of radiative heat transfer, especially as combined with gas dynamic phenomena. Examples are wave processes associated with hypersonic flight problems and ultrahigh-temperature gas flows.

In the area of fluid mechanics, theoretical investigations of rotational or vortex flows are in progress. Special attention is being given to those flow patterns which may find application to the problem of fuel containment in gascore nuclear reactors. Consideration of the effects of magnetic fields in maintaining and stabilizing such flows, their stability characteristics, and energy exchange with their environment, especially by radiation, are all factors in this study. It is expected that theoretical work in this area will lead to experimental studies in the near future. Other magneto-hydrodynamic flows, especially those which involve boundary layer separation, are also under study.

Gas-particle flows are under investigation in several projects. Nonequilibrium effects such as velocity and temperature lags of evaporating droplets in a channel flow are being studied. Also of interest is the possibility of the catalysis of chemical recombination in propulsive jets by addition of colloidal particles. Another project in the field of two-phase flow concerns the effects of long-chain polymer additives in the reduction of momentum transfer by turbulence.

Analytical and experimental interferometric studies are being made of laminar instability in steady and transient natural convection flows, and the development of turbulence in such flows.

A basic study of sonic boom is being planned in collaboration with the Graduate School of Aerospace Engineering. Special emphasis will be given to the extension of present theories to conditions characterized by high Mach numbers.

Faculty members and graduate students in thermal engineering participate in the Cornell program of research in plasmas (see page 91 for a description of the interdisciplinary Laboratory of Plasma Studies).

Current experimental and theoretical studies of the rapid mixing of a gaseous plasma with initially unexcited gases are directed toward the creation of nonequilibrium, excited-state populations in atomic systems. Application of such techniques to the development of high-power continuous gaseous lasers and to free-radical chemistry are being considered. As part of this program, the first known atomic continuous-wave mixing laser has been built and successfully operated. The related processes of diffusion, inelastic collisional energy transfer, radiative transport, and electronic recombination occurring in such plasma flows are being investigated with the aid of a high-resolution monochrometer spectrograph.

Other recent work includes investigations of the properties of nonequilibrium seeded plasma for magnetohydrodynamic power conversion.

Projects in the field of energy conversion are being approached in various ways: from the standpoint of the system, on the basis of thermodynamic considerations, or in terms of the fundamental processes involved.

In the area of direct energy conversion, studies of a thermoelectric device have been made and an extension of this work is planned. Another project in this area is a study of thermionic conversion, including problems of thermal transport in diodes.

Very high temperature processes, depending chiefly on radiative exchange of energy, are also being studied. The gascore fission reactor furnishes an example of this class of energy conversion device. An opportunity exists for interested students to engage in engineering feasibility studies in connection with the development of a new type of magnetohydrodynamic generator. These studies would be in cooperation with the School of Electrical Engineering and the Graduate School of Aerospace Engineering.

Pollution problems associated with the generation and use of power are being considered not only in special courses, but in research in the areas of combustion-generated pollution, dispersal of pollutants, including waste heat, and alternative or improved power sources. Examples of the research activity include a recent thesis on the effect of thermal pollution on Cayuga Lake, studies of core containment problems in gaseous core nuclear power reactors, a study of a low thermal pollution alternative to conventional power plants, and experimental studies of buoyant plumes. Investigations are now beginning in a number of new areas: cooling tower technology, the impact of urban heat generation on local weather, modeling of pollutant dispersal in an urban atmosphere, and oil slick clean-up problems. Future research is expected to include combustion problems related to pollution generation.

Some typical publications in the area of thermal engineering are:

Carofano, G. C., and McManus, H. N., Jr. 1969. An analytical and experimental study of the flow of air-water and steam-water mixtures in a converging-diverging nozzle. In *Progress in heat and mass transfer,* vol. 2, p. 395. Oxford: Pergamon.

Cool, T. A., Shirley, J. A., and Stephens, R. R. 1970. Operating characteristics of a transverse flow DF-CO_2 purely chemical laser. *Applied Physics Letters* 17:278.

Dropkin, D., and Gelb, G. H. 1965. Measurements in the thermal field of mercury undergoing natural convection with and without rotation. *International Journal of Heat and Mass Transfer* 8:1341.

Gebhart, B., and Pera, L. 1971. Mixed convection from long horizontal cylinders. *Journal of Fluid Mechanics* 45:49.

Leibovich, S. 1970. Weakly nonlinear waves in rotating fluids. *Journal of Fluid Mechanics* 42:803.

Moore, F. K., and Mackenzie, J. F. 1971. *A prediction of changes in the thermal cycle of a stratified lake used to cool a 1,000 MW power plant.* Cornell University Water Resources and Marine Sciences Center publication no. 32.

Shepherd, D. G. 1971. Gas turbine. In *Encyclopedia Americana.* New York: Americana Corporation.

Torrance, K. E., and Turcotte, D. L. 1971. Structure of convection cells in the mantle. *Journal of Geophysical Research* 76:1154.

Titles of recent theses which suggest the kind of projects undertaken in the area of thermal engineering include:

An Experimental and Analytical Investigation of Teflon Ablation Heat Transfer Parameters by the Method of Nonlinear Estimation (Ph.D., 1971)

Numerical Study of Structure of Vortex Breakdowns M.S., 1971)

Hydrodynamic Stability of a Plane Vortex Sheet Between Thermally Radiating Dissimilar Gases (Ph.D., 1971)

An Experimental Study of Heat Transfer in a Simulation of Horizontal Annular Two-Phase Flow (M.S., 1970)

In the general area of pollution control studies, recent theses were written on the following topics.

A Two-Layer Model Calculation of the Effects of Discharged Heat and Enhanced Mixing on the Annual Temperature Cycle of Stratified Lakes (M.S., 1970)

Power Plant Design for the Reduction of the Sonic Boom Generated by Supersonic Transport Aircraft (Ph.D., 1970)

Faculty Members and Their Research Interests

Donald L. Bartel, Ph.D. (Iowa); *design optimization and reliability, computer-aided design*

John F. Booker, Ph.D. (Cornell): *lubrication, vibration and controls, computer-aided design*

Arthur H. Burr, Ph.D. (Michigan): *design of components*

Bart J. Conta, M.S. (Cornell): *thermodynamics, thermal power, energy conversion*

Terrill A. Cool, Ph.D. (California Institute of Technology): *fluid dynamics, thermodynamics, chemical lasers, fluid mixing lasers, gas dynamic lasers*

David Dropkin, Ph.D. (Cornell): *heat transfer, thermal power*

Howard N. Fairchild, M.E. (Cornell): *thermal power, combustion engines, refrigeration and air conditioning*

Benjamin Gebhart, Ph.D. (Cornell): *heat transfer, fluid mechanics, transport processes*

Frederick C. Gouldin, Ph.D. (Princeton): *fluid dynamics, combustion processes*

Allan I. Krauter, Ph.D. (Stanford): *product design, design optimization and reliability*

Sidney Leibovich, Ph.D. (Cornell): *fluid dynamics*

Howard N. McManus, Jr., Ph.D. (Minnesota): *design optimization and reliability, heat transfer*

Franklin K. Moore, Ph.D. (Cornell): *fluid dynamics*

Richard M. Phelan, M.M.E. (Cornell): *design of components, vibration and controls*

Dennis G. Shepherd, B.S. Engr. (Michigan): *thermal power*

Kenneth E. Torrance, Ph.D. (Minnesota): *fluid dynamics*

Kuo-King Wang, Ph.D. (Wisconsin): *manufacturing engineering*

Robert I. Wehe, M.S. (Illinois): *lubrication, vibration and controls*

Further Information

Further information about the Master of Science and Doctor of Philosophy degree programs may be obtained by writing to the Graduate Field Representative, Sibley School of Mechanical Engineering, Upson Hall, Cornell University, Ithaca, New York 14850.

Requests for further information on the Master of Engineering (Mechanical) degree program should be addressed to the Director, Sibley School of Mechanical Engineering, Upson Hall, Cornell University, Ithaca, New York 14850.

Nuclear Science and Engineering

The study of nuclear science and engineering is concerned with the understanding, development, and application of the science of nuclear reactions and radiations. The graduate programs at Cornell allow specialization in basic nuclear science, in applied nuclear engineering, or in a combination of the two. Minors may be chosen in a wide variety of other engineering or science fields. Three graduate degrees are granted. The Master of Engineering (Nuclear) is intended primarily as a terminal professional degree. The Master of Science and Doctor of Philosophy degrees are intended for those students who plan to pursue research or teaching careers. About twenty graduate students are concentrating in nuclear science and engineering at the present time.

The nuclear engineering courses cover the basic principles of nuclear reactor systems with a major emphasis on reactor safety and radiation protection and control. There is a growing market for engineers who have a thorough knowledge of these safety provisions and who are able to apply it effectively in the design, supervision, and regulation of reactor plants and environmental monitoring systems. The close working relationship between the faculties in nuclear engineering and in radiation biology illustrates the strength and interdisciplinary breadth of the graduate student's opportunities in nuclear engineering at Cornell. Students have entered the program with undergraduate degrees in a variety of engineering or science areas. The expansion that is currently underway in the size and number of nuclear electric power plants is increasing the job opportunities with reactor manufacturers, consulting firms, and governmental agencies.

The Master of Engineering (Nuclear) degree, which is described in the *Announcement of the College of Engineering,* is a two-semester curriculum degree which also emphasizes reactor safety and radiation protection. It is primarily a terminal degree program requiring a design project but no thesis. It can, however, also be used as preparation for doctoral study in nuclear engineering.

The TRIGA reactor, a source of neutrons and gamma rays, is used in graduate research projects in nuclear science and engineering.

Thesis research areas in nuclear engineering include experimental and analytical reactor physics, nuclear environmental engineering, reactor plant dynamics and safety, radiation protection and control, radiation effects on materials, energy conversion, radiation chemistry, and neutron transport theory.

Nuclear science is the other major specialization in the graduate Field of Nuclear Science and Engineering. Basic courses are chosen from offerings in both the College of Engineering and the College of Arts and Sciences. Thesis research areas include low-energy nuclear structure physics, interactions between nuclear and atomic processes, nuclear geochemistry and cosmochemistry, nuclear astrophysics (experimental), and activation analysis.

Facilities

The Ward Laboratory of Nuclear Engineering is the major facility at Cornell for graduate research and teaching. It is the center for study of reactor physics and engineering, low energy nuclear structure physics, and nuclear and radiation chemistry. The following is a list of primary facilities housed in the Laboratory and a description of their functions.

A TRIGA reactor has a steady state power of 100 kilowatts and a pulsing capability of up to 250 megawatts. The reactor is a source of neutrons and gamma rays for activation analysis and research in nuclear physics. In addition to standard pneumatic and mechanical transfer systems, the reactor has a 40-millisecond rapid transfer mechanism which allows study and use of radionuclides having a relatively short half-life.

A critical facility or "zero power reactor" of versatile design, unique to Cornell, is used for basic studies in reactor physics and dynamics. Auxiliary equipment includes a pulsed 14 MeV neutron generator used for studies of transients.

A shielded gamma cell with a 5,000 curie Co^{60} gamma ray source is used for studies of radiation chemistry and radiation damage. Experimental versatility is obtained by a viewing window and remote manipulators.

A 3 MV Dynamitron or positive-ion accelerator of high current capability is used for studies of nuclear structure and high intensity radiation damage. A lithium target capable of power dissipation approaching 10,000 watts per square centimeter has been developed for use in controlled energy neutron production.

A digital computer for routine on-line or off-line data reduction is equipped with an oscilloscope display system with light-pen for manipulating stored nuclear spectra.

Areas of Research

The Cornell Energy Project

This is an interdisciplinary research project sponsored by a division of the National Science Foundation called Research Applied to National Needs (RANN). An important part of this research is developing optimum strategies for meeting the energy needs of the United States over the next fifty years. The economics of determining optimum strategies requires the evaluation of the total costs (economic, biological, and sociological) of meeting these energy demands.

The Energy Project is composed of a group of faculty members, research associates, and graduate students in radiation biology, physical biology, epidemiology, political science, sociology, economics, thermal engineering, and nuclear engineering. The project maintains a library of unpublished working papers and documents concerning energy and the environment and a meeting place for the researchers.

An example of this research is the development of strategies for meeting electrical energy demand by an "optimum mix" of base-loaded nuclear plants, intermediate-loaded fossil plants, and peak-loaded pumped storage and gas turbine plants. Considerations of the various discharges—gaseous oxide, particulate and radioactive—from these plants affects the optimum strategies. The development of models and their application to specific regions of the country is being pursued.

Nuclear Safety Engineering

Safety research in light water reactors and fast breeder reactors is important in the development and use of these reactor plant systems. A current research topic is the development of probabilistic models for determining optimum testing frequencies, testing methods, and replacement schedules for the maintenance and operation of plant safety systems. A second example is the development of complete reactor plant models and computer codes for nuclear plant transients and accidents.

Nuclear Environmental Engineering

The Calvert Cliffs decision by the United States Court of Appeals in July, 1971 requires the Atomic Energy Commission (and the nuclear industry) to carry out total-environmental-impact reviews of proposed nuclear power plant sites in accordance with the National Environmental Policy Act of 1969. These reviews require cost/benefit analyses of alternative radiological and thermal discharge control systems. An example of research in this rapidly growing field being undertaken by the Cornell Energy Project is the development of models for following and summing the routine radiological waste discharges from nuclear plants over the exposure pathways to the dose-receiving population. Similarly, models of accidental discharges using a spectrum of accident probabilities and consequences predict expected exposures to the population.

A recent publication which gives a good idea of the research in this area is:

Franco, J. A., and Cady, K. B. 1971. *A review and analysis of radwaste management at light water reactors,* Cornell Energy Project report, October 1971. Ithaca: Cornell University.

Fusion Reactor Technology

Under the auspices of the Laboratory of Plasma Studies and the engineering faculty, research programs on several aspects of fusion reactor technology are planned. Included will be problems of materials, energy conversion, and superconducting magnet technology for prototype fusion reactors. Among the areas being investigated are (*a*) Lithium blanket design, including materials problems of corrosion and radiation damage, and problems of pressure drops and power requirements to pump liquid metal coolants across magnetic field lines; (*b*) Neutron transport problems affecting the tritium breeding ratio, structural heat loading, induced radioactivity, and heating of the cryogenic magnets; (*c*) Vacuum wall design as affected by heat loading, sputtering, and radiation damage; (*d*) Energy conversion systems: direct conversion as well as advanced thermal cycles such as helium gas turbines, two-phase liquid metal MHD, and binary liquid metal steam cycles.

Fission Reactor Physics

Basic research in the kinetics of the neutron chain reaction is carried out in conjunction with the reactor plant dynamics work discussed above. The main experimental facility for basic reactor physics is the Cornell critical facility. One example of research is the measurement of neutron importance functions, and another is the measurement and understanding of neutron density waves propagating through multiplying media. The critical facility is of very flexible design and a large variety of cores of different shape, size, and water-to-fuel ratios can be investigated. It forms a unique educational tool for the operational understanding of nuclear reactor cores.

Professor Cady is directing research in this area. An example of recent publications is:

Greenspan, E., and Cady, K. B. 1970. The measurement of neutron importance functions. *Journal of Nuclear Energy* 24:529.

Low-Energy Nuclear Physics

Among projects now under way in this area is an experimental study of isomeric (metastable) states in nuclei. This work provides valuable information on high-spin excited states of nuclei. The energies, spins, parities, life-times, and other parameters of these levels obtained in such studies can be compared with predictions from various theoretical models and thus provide checks on the validity of these models. Several such isomers have been discovered at Cornell with use of the TRIGA reactor and the fast transfer system.

Isomeric states frequently decay by internal conversion, producing vacancies in the inner electron shells of the atom, and this results in x-ray emission. A new method for determining properties of isomeric levels by observation solely of these x rays has been conceived and developed in the course of research on Ta-182; the method will also be applicable to other nuclides.

The discovery of spontaneously fissioning isomers and recent theoretical research at various laboratories have led to the hypothesis of a new type of isomerism called "shape isomerism." The phenomenon, which is widespread among elements of atomic number 92 and higher, is due to a double-hump in the fission barrier. Nuclei in the isomeric state are stretched into a cigar-like shape with the polar axis almost twice the equatorial diameter. Experiments designed to measure the degree of "stretch" and other properties such as the expected decay of the isomer by modes other than fission are under way with use of neutrons from the TRIGA reactor. Experiments using higher energy neutrons from the Dynamitron are also planned.

Professors Clark and Kostroun are directing research in these areas of low-energy nuclear physics.

Theoretical and experimental spectroscopic studies of nuclear structure are also being pursued. Of particular interest are precision experiments relating to isobaric-spin symmetries in light nuclei. Such studies attempt to relate states with identical nuclear properties in different nuclides. Specialized detectors and angular correlation and other techniques are used. Professor McPherson is in charge of these studies.

Examples of recent publications in the area of low-energy nuclear physics are:

Clark, D. D. 1971. Shape isomerism and the double-humped fission barrier. To be published in *Physics Today* (December).

Taylor, H. W., Singh, B., Prato, F. S., and McPherson, R. 1971. A tabulation of gamma-gamma directional-correlation coefficients. *Nuclear Data* A9:1.

Interaction of Nuclear and Atomic Processes

Luminescence in gases caused by x rays in the 2 to 10 keV range is being investigated in order to clarify the mechanism of light emission following the absorption of ionizing radiation. The Cornell 3 MV Dynamitron charged-particle accelerator is utilized to produce characteristic x rays in the energy range of interest by proton bombardment of various targets. The resulting x ray-excited optical spectra of various gases, together with data on the pressure dependence of luminescence, provide information about the mechanisms of light emission and permit determination of the manner in which the x-ray energy is deposited in the gas. Such information is useful in the study of radiation-induced plasmas. It is also of value in the investigation of the possibility of laser pumping utilizing nuclear reactors as a source of a variety of ionizing radiation. Professors Kostroun and Clark are directing this research.

Following the creation of vacancies in inner shells of atoms by such processes as the photoeffect, beta decay, electron capture, or internal conversion, the excited states of atoms decay either by radiative or nonradiative processes. Calculations dealing with three or more vacancies in the final state are being undertaken to investigate the contribution of these processes to the production of highly ionized atoms following the creation of a single vacancy in the 1*s*, 2*s*, or 2*p* shell. Professor Kostroun is directing this study. An example of the recent publications in connection with this research is:

Kostroun, V. O., Chen, M. H., and Crasemann, B. 1971. Atomic radiationless transition probabilities to the 1*s* state and theoretical K-shell fluorescence yields. *Physical Review* 3A:533.

Nuclear Geochemistry and Activation Analysis

Research in multielement trace analysis of geological, metallurgial, and biological materials by neutron activation techniques is carried out with the TRIGA reactor. Other analytical techniques such as spark source mass spectroscopy are also employed. The following is an example of the recent papers resulting from this research, which is under the direction of Professor Morrison.

Morrison, G. H., Gerard, J. T., Potter, N. M., Gangadharam, E. V., Rothenberg, A. M., and Burdo, R. A. 1971. Elemental abundances of lunar soil and rocks from Apollo 12. In *Proceedings of the second lunar science conference* 2:1169. Boston: M.I.T. Press.

Faculty Members and Their Research Interests

Members of the Field of Nuclear Science and Engineering hold appointments as professors of applied and engineering physics, mechanical, chemical, environmental, and electrical engineering, chemistry, and physics. These men and their specialities related to nuclear science and engineering are listed below.

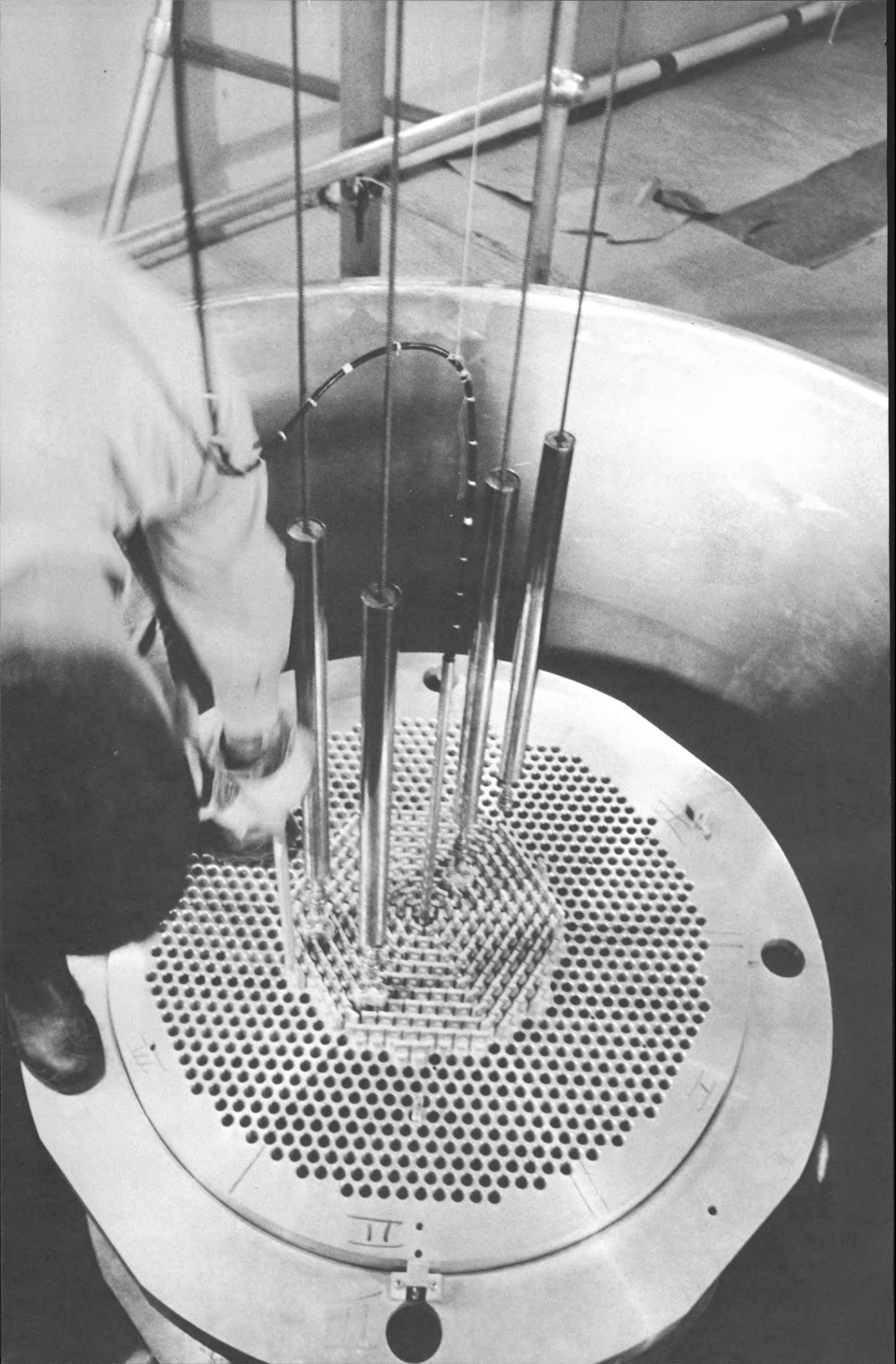
K. Bingham Cady, Ph.D. (M.I.T.): *nuclear engineering, nuclear environmental engineering, reactor physics*

David D. Clark, Ph.D. (California at Berkeley): *nuclear structure physics, nuclear instrumentation*

Trevor R. Cuykendall, Ph.D. (Cornell): *nuclear engineering*

David Dropkin, Ph.D. (Cornell): *heat transfer, energy conversion*

Charles D. Gates, M.S. (Harvard): *nuclear environmental engineering*



Vaclav O. Kostroun, Ph.D. (Oregon): *nuclear structure physics, interaction of nuclear and atomic processes*

Simpson Linke, M.E.E. (Cornell): *energy conversion and transmission*

Raphael M. Littauer, Ph.D. (Cambridge, England): *nuclear pulse electronics*

Ross McPherson, Ph.D. (McGill): *nuclear structure physics*

George H. Morrison, Ph.D., (Princeton): *nuclear geochemistry and cosmochemistry*

Mark S. Nelkin, Ph.D. (Cornell): *neutron scattering and transport*

Robert L. Von Berg, Sc.D. (M.I.T.): *radiation chemistry*

Further Information

Further information about the M.S. and Ph.D. degree programs may be obtained by writing to the Graduate Field Representative, Nuclear Science and Engineering, Ward Laboratory of Nuclear Engineering, Cornell University, Ithaca, New York 14850.

Requests for further information about the M.Eng. (Nuclear) degree program should be addressed to the Master of Engineering (Nuclear) Representative at the above address.

Unique to Cornell University is a critical facility or "zero power reactor" used for research in reactor physics and dynamics.

Operations Research

The graduate Field of Operations Research offers doctoral programs in four major subjects: operations research, applied probability and statistics, systems analysis and design, and industrial engineering. Master of Science programs are offered in all these subjects, and in information processing as well. Also offered by the School of Industrial Engineering and Operations Research is a program leading to the degree of Master of Engineering (Industrial).

More than eighty full-time graduate students, including thirty-three from foreign countries, are currently registered in these programs. Approximately one-third of the students had undergraduate degrees in mathematics, while the others majored in engineering or other sciences.

Major Subject Areas

A general description of the five subject areas in the Field of Operations Research is given below.

Operations Research

The problem areas and techniques of operations research are approached from a highly analytical viewpoint. Emphasis is placed on constructing appropriate mathematical models to represent various real-life operational systems, and on developing techniques for analyzing the performance of these models. In this way procedures with desirable properties for dealing with such systems are developed. Queuing, inventory, reliability, replacement, and scheduling theories and simulation are employed. Optimization techniques such as mathematical programming (linear, nonlinear, and probabilistic), network flows, combinatorics, and dynamic programming are also used extensively, as are the various techniques of the mathematical theory of games.

The operations research student pursues a course of study and research that emphasizes the use of the mathematical, probabilistic, statistical, and computational sciences in the development of the techniques of operations research. His ultimate goal may range from making a fundamental contribution to the techniques of operations research to applying these techniques to problems in diverse professional fields.

Most projects in operations research make use of the University's extensive computing facilities.

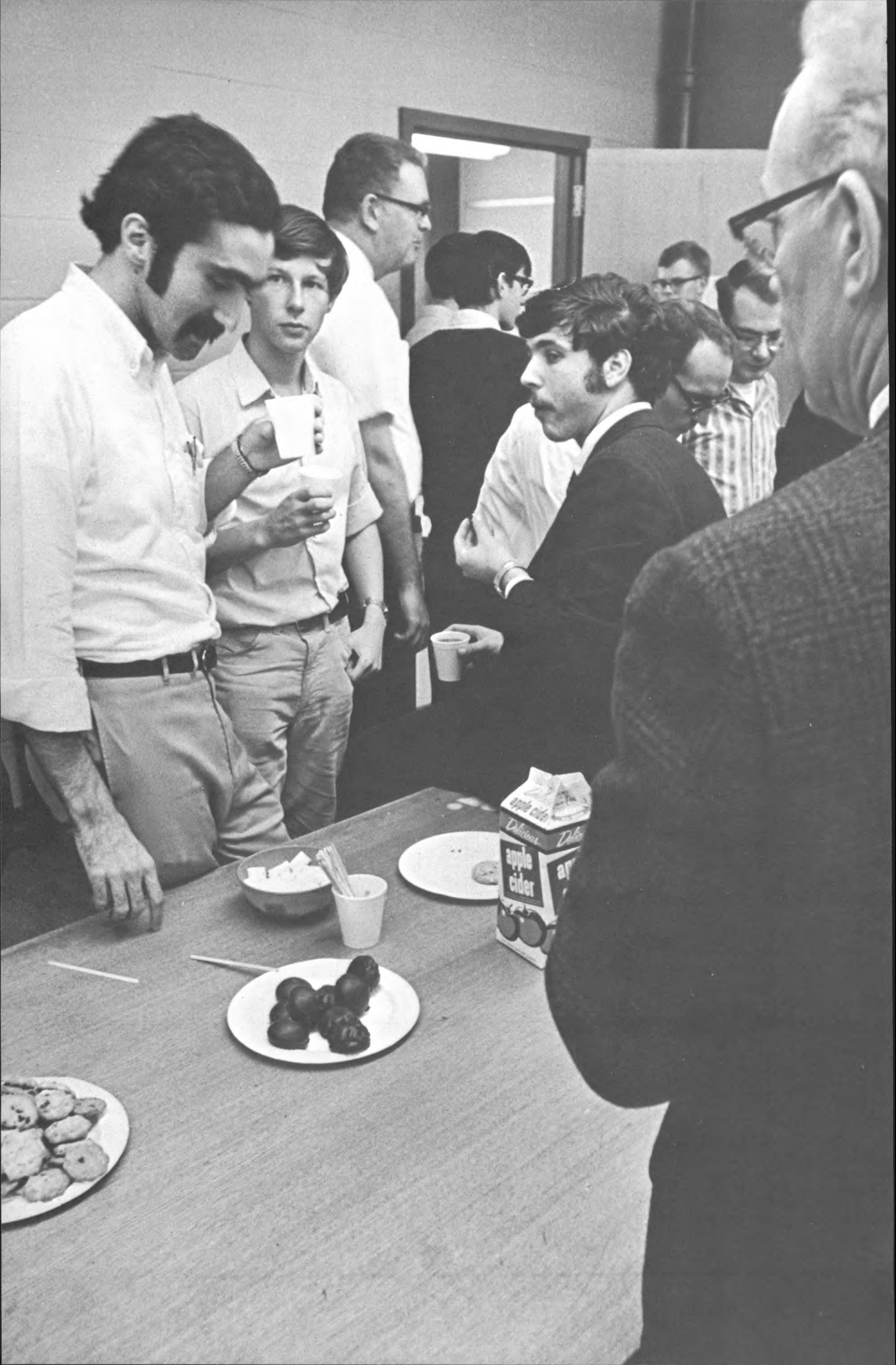
Applied Probability and Statistics

This subject of study and research is designed for students having primary interests in the techniques and associated underlying theory of probability and statistics, particularly as they are applied to problems arising in science and engineering. The techniques emphasized are those associated with applied stochastic processes (for example, queuing theory, traffic theory, inventory theory, and time-series analysis) and statistics (including statistical decision theory; the statistical aspects of the design, analysis, and interpretation of experiments, and of ranking and selection theory; reliability theory; statistical quality control; sampling inspection; and acceptance sampling).

Students who elect work in this area are expected to acquire considerable knowledge of the theory of probability and statistics. All students who major in applied probability and statistics are required to minor in mathematics.

Systems Analysis and Design

Although the solution of systems problems requires knowledge of underlying theory, the inherent practical limitations of the problem must be understood. Analysis of a system alone is insufficient; alternative solutions must be generated before selection of the one which can best be integrated with other elements of the system. Modeling concepts are equally important, but only when they can produce workable systems. Illustrations of the design of integrated systems can be found in industry, the environment, commerce, and government. A good example is the design of urban traffic control systems. Research activity may involve the development of new methodology or the synthesizing of new combinations from what is already known. The goal is to improve the understanding of systems or to develop new decision criteria for systems.


Delicious
apple
cider

Industrial Engineering

Studies of the analysis and design of the complex operational systems that occur in industry, particularly in manufacturing, are included in this subject. Plant design, cost analysis and control, and production planning are some of the major topics. A student is expected to have considerable facility in the modern analytical techniques associated with rational decision making and the establishment of valid design criteria. These techniques are drawn from among inventory theory, queuing theory, mathematical programming, quality control, and computer simulation.

Because the design and operation of modern engineering systems apply to areas other than manufacturing, the use of the word "industrial" should not be considered restrictive. Industrial engineers frequently are employed as systems specialists in commerce, banking, distribution, merchandising, and hospital management.

Information Processing

Information processing deals with the analysis and design of systems which record, transmit, store, and process information. Emphasis is on the application and integration of equipment rather than on the design of machines. Areas of interest include systems for information retrieval, manufacturing control, and traffic control. This subject also includes such underlying theoretical topics as data structure, operating system organization, and computing language structure.

The principal campus computing facility is an IBM 360/65, with on-line operation from many campus locations. A satellite 360/20, directly connected to the 360/65, is located in Upson Hall, where the Department of Operations Research is housed. Teletypewriter terminals are also in use.

Minor Subject Areas

In addition to choosing a major subject, candidates for the M.S. and Ph.D. degrees choose minors, which may be selected from the five areas described, or may be offered by another unit of the University. Appropriate minors that have been chosen most frequently in recent years, and the departments or schools which offer such courses of study are: applied mathematics (Applied Mathematics), computer science (Computer Science), econometrics and economic statistics (Economics), public systems planning and analysis (Civil and Environmental Engineering), managerial economics (Business and Public Administration), mathematics (Mathematics), and planning theory and systems analysis (City and Regional Planning).

Informal seminars are a regular feature of graduate study in Operations Research, as in all graduate Fields.

Areas of Research

A research project is an important part of the program for all M.S. and Ph.D. degree candidates. Because the research is begun at an early stage, candidates who plan to seek the doctorate are encouraged to apply for a Ph.D. program at the outset.

The range of research opportunities is suggested by the projects currently being directed by members of the faculty. Topics of these research projects are:

Statistical Engineering (sponsored by the United States Office of Naval Research)

Analytical Methodology and Optimal Control in Urban Traffic Networks (sponsored by the United States Department of Transportation)

Dynamic Stability and Combinatorial Structure of n-Person Cooperative Games (sponsored by the National Science Foundation)

Convergence of Stochastic Integrals (sponsored by the National Science Foundation)

Algebraic Approach to Duality in Mathematical Programming (sponsored by the National Science Foundation)

Multiple Decision Selection and Ranking Procedures (sponsored by the United States Army Research Office at Durham)

The Cooperative Theory of Behavior and its Applications (sponsored by the National Science Foundation)

Applied Stochastic Processes (sponsored by the National Science Foundation)

New Compiler for a General Purpose Computing Language, PL/I (industrially sponsored)

Markov Sequential Decision Processes (sponsored by the National Science Foundation)

Applications of the Asymptotic Indistinguishability of Sequences of Distributions (sponsored by the National Science Foundation)

Some books and recent research papers by faculty members and graduate students are the following.

Bechhofer, R. E., Kiefer, J., and Sobel, M. 1968. *Sequential identification and ranking procedures.* Chicago: University of Chicago Press.

Billera, L. J. 1971. Some recent results in n-person game theory. To be published in *Mathematical Programming* 1.

Brown, M. 1971. Statistical analysis of non-homogeneous Poisson processes. In *Proceedings of the international conference on stochastic point processes,* New York: Wiley, forthcoming.

Conway, R. W., Maxwell, W. L., and Miller, L. W. 1972. *Theory of scheduling.* Reading, Mass.: Addison-Wesley.

Eisner, M. J. (with Kaplan, R., and Soden, J. V.) 1971. Admissible decision rules for the E-model of chance constrained programming. *Management Science* 17(5):337.

Emmons, H. 1972. The optimal admission policy to a multiserver queue with finite horizon. To be published in *Journal of Applied Probability.*

Fulkerson, D. R., and Ford, L. R., Jr. 1962. *Flows in networks.* Princeton: Princeton University Press.

Goode, H. P. 1965. *Factors and procedures for applying MIL-STD-105D sampling plans to life and reliability testing.* Quality and Reliability Assurance Technical Report TR 7, U.S. Government Printing Office.

Lucas, W. F. 1971. Some recent developments in n-person game theory. *SIAM Review* 13(4):491.

Morgan, H. L. 1970. Spelling correction in systems programs. *Communications of the ACM* 13(2):90.

Nemhauser, G. L. 1966. *Introduction to dynamic programming.* New York: Wiley.

Prabhu, N. U. 1965. *Queues and inventories.* New York: Wiley.

Saunders, B. W. 1971. Facilities design: A problem of systems analysis. *International Journal of Production Research* 9(1):3.

Spitzer, F. L. 1964. *Principles of random walk.* Princeton: Van Nostrand.

Stidham, S., Jr. 1970. On the optimality of single-server queuing systems. *Operations Research* 18:708.

Taylor, H. M. (with Costell, W. G.) 1971. Population growth models. To be published in *American Mathematical Monthly.*

Weiss, L. 1961. *Statistical decision theory.* New York: McGraw-Hill.

An idea of the specific research conducted by Ph.D. candidates, and also of the kind of jobs they assume after receiving their degrees, may be obtained from the following list of thesis topics in the past two years and the present position of each candidate.

Asymptotically Optimal Ranking and Selection Procedures (Bell Telephone Laboratories, Holmdel, New Jersey)

On Duality in Infinite-Player Games and Sequential Chance-Constrained Programming (Assistant Professor, Department of Operations Research, Cornell)

Foundations of Deterministic Optimization Theory (Professor, Escuela de Economia, Concepcion, Chile)

Some Limit Theorems for Priority Queues (Bell Telephone Laboratories, Whippany, New Jersey)

On the Asymptotic Behavior of Regenerative Processes and Functionals of Regenerative Processes (Assistant Professor, Department of Statistics, University of Missouri)

Asymptotic Efficiency of the Maximum Likelihood Estimators for the Parameters of Certain Stochastic Processes (Mobil Francaise, Paris)

On Classification Theory in Mathematical Programming and Applications (Assistant Professor, Department of Business Administration, University of Illinois, Champaign)

Sequential Decision Making Under Uncertainty in Chance-Constrained Programming and Bid-Pricing Environments (McKinsey and Company, Inc., Los Angeles)

Solution Concepts of n-Person Cooperative Games as Points in the Game Space (Assistant Professor, Department of Business Administration, University of Colorado, Boulder)

Bounds and Optimal Strategies for Stochastic Systems (Acting Assistant Professor of Statistics, Department of Statistics and the Division of Biostatistics, Stanford Medical School)

Faculty Members and Their Research Interests

Robert E. Bechhofer, Ph.D. (Columbia): *engineering statistics, design of experiments, ranking and selection procedures*

Louis J. Billera, Ph.D. (City University of New York): *game theory, combinatorial analysis, graph theory*

Mark Brown, Ph.D. (Stanford): *stochastic processes, time-series analysis*

Richard W. Conway, Ph.D. (Cornell): *information-processing systems, computer science*

Mark J. Eisner, Ph.D. (Cornell): *mathematical programming, game theory*

Hamilton Emmons, Ph.D. (Johns Hopkins): *operations research, inventory theory*

D. Ray Fulkerson, Ph.D. (Wisconsin): *mathematical programming, network flow theory*

Henry P. Goode, M.S. (Kansas): *manufacturing engineering, industrial statistics, sampling inspection*

Jack C. Kiefer, Ph.D. (Columbia): *statistical decision theory, optimum experimental design, sequential analysis*

William F. Lucas, Ph.D. (Michigan): *game theory, combinatorial analysis, graph theory*

Walter R. Lynn, Ph.D. (Northwestern): *environmental systems*

William L. Maxwell, Ph.D. (Cornell): *information-processing systems, production control, systems simulation*

Howard L. Morgan, Ph.D. (Cornell): *management information systems, information processing*

George L. Nemhauser, Ph.D. (Northwestern): *mathematical programming, operations research*

Narahari U. Prabhu, M.Sc. (Manchester, England): *stochastic processes, queuing theory, storage theory*

Sidney Saltzman, Ph.D. (Cornell): *information-processing systems, operations research, econometrics*

Byron W. Saunders, M.S. (Stevens Institute of Technology): *facility design, materials handling, manufacturing design*

Andrew Schultz, Jr., Ph.D. (Cornell): *operations research, systems analysis*

Frank L. Spitzer, Ph.D. (Michigan): *probability theory*

Shaler Stidham, Jr., Ph.D. (Stanford): *queuing theory, transportation systems*

Howard M. Taylor, III, Ph.D. (Stanford): *applied probability*

Lionel I. Weiss, Ph.D. (Columbia): *statistical decision theory, sequential analysis, nonparametric statistics*

Associated Faculty

There are many faculty members in other units of the University whose fields of interest are closely related to operations research. Through the courses they teach and their service on Special Committees they give diversity to graduate programs in the Field of Operations Research. The following listing illustrates the faculty resources in several allied areas.

From other areas of engineering: Toby Berger: *information and coding theory;* Henry D. Block: *applied mathematics, automata theory;* John E. Dennis, Jr.: *numerical analysis;* Terrence L. Fine: *information and detection theory;* Richard H. Gallagher: *optimal structural design;* Juris Hartmanis: *theory of computation;* John E. Hopcroft: *theory of computation;* Frederick Jelinek: *network theory, information theory;* Daniel P. Loucks: *design and operation of environmental systems;* Christopher Pottle: *computer engineering, control systems;* and Gerard Salton: *information retrieval.*

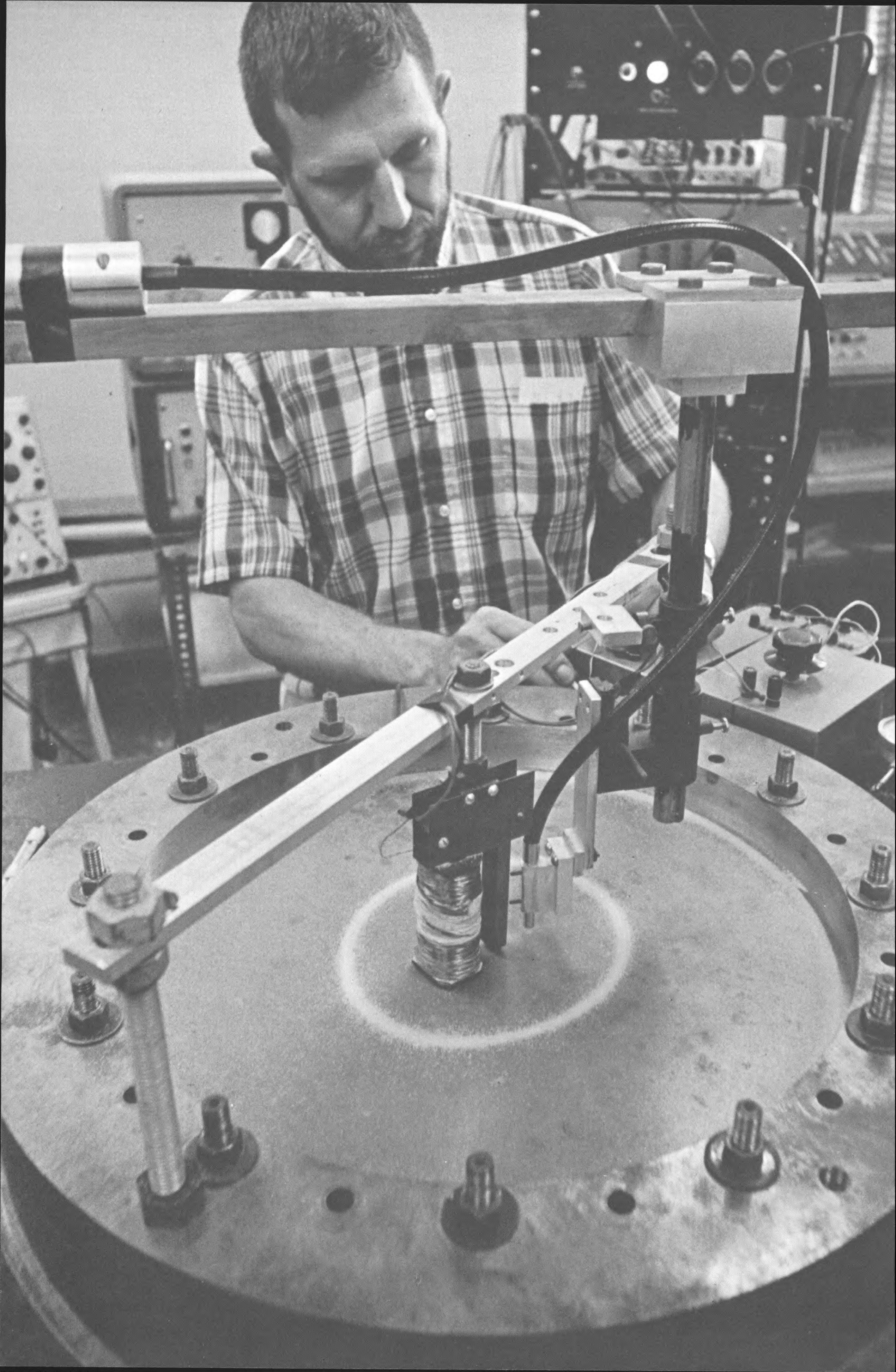
From the Department of Mathematics: Lawrence D. Brown: *statistical theory;* Roger H. Farrell: *statistical theory;* Harry Kesten: *probability theory, analysis;* Anil Nerode: *logic;* and Robert J. Walker: *numerical and computational methods.*

From the Graduate School of Business and Public Administration: Harold Bierman, Jr.: *managerial economics, accounting;* Thomas R. Dyckman: *accounting, quantitative analysis;* Norman R. Lyons: *management information systems;* Seymor Smidt: *managerial economics;* L. Joseph Thomas: *production, quantitative analysis;* and Richard Schramm: *economics, finance.*

From other University units: Edwin T. Burton, III, of the Department of Economics: *mathematical economics;* Barclay G. Jones of the Department of City and Regional Planning: *regional and city planning;* Ta-Chung Liu of the Department of Economics: *econometrics;* and Philip J. McCarthy of the School of Industrial and Labor Relations: *sampling theory.*

Further Information

Inquiries about graduate programs in the Field of Operations Research may be addressed to the Graduate Field Representative, Operations Research, Upson Hall, Cornell University, Ithaca, New York 14850.



Theoretical and Applied Mechanics

Mechanics is the study, by mathematical analysis and experimental observation, of the motion and deformation of solids and fluids. It is basic to many fields of modern technology, such as structural analysis, vehicular dynamics and control, aerodynamics, bioengineering, and space dynamics.

It is the intent of the graduate Field of Theoretical and Applied Mechanics to provide the student with a broad fundamental training in the discipline, to give him an opportunity to pursue basic and meaningful research, and to provide him with basic preparation for work in one of several different technical areas. Emphasis is placed on the basic analytical and experimental nature of the discipline, although research work is directed to specific and sometimes applied goals.

The principal areas of teaching and research are solid mechanics, fluid mechanics, space mechanics, the mechanics of materials, and biomechanics. However, there is significant overlap with other graduate Fields, since the fundamental nature of the study of mechanics lends itself to adoption by a variety of other engineering and nonengineering fields where quantitative models for specific processes are sought. It is expected that research in geological applications, biomechanics, and the study of inelastic behavior of composite materials will continue to be prominent among the research topics.

The approximately twenty-five graduate students in the Field of Theoretical and Applied Mechanics come from a variety of academic and national backgrounds. Most are studying for the Ph.D., but a few come for the Master of Science degree program. A newly instituted program leading to the professionally oriented degree of Master of Engineering (Engineering Mechanics) has been offered since June, 1971.

A majority of the graduate students in the Field are supported by Cornell University fellowships or by research or teaching assistantships. Teaching assistants help in courses in mechanics and applied mathematics that are offered by the Department of Theoretical and Applied Mechanics; research assistants are supported through grants and contracts with industrial and governmental agencies.

The Field is seeking primarily to attract prospective students who show deep interest in basic studies in mechanics and who have a strong aptitude for analysis or fundamental experimental work. Typically, a student with analytical interests pursues theoretical studies, with recourse to published experimental results. A student more interested in physical phenomena and their measurement may concentrate on a program of study and research in some aspect of experimental science; the subject of mechanics of materials provides ample opportunity for such laboratory study. The range of distribution of effort which lies between the purely abstract and the purely experimental is large enough so that it is possible for many students to attempt both aspects of study. Indeed, all are encouraged to combine sound theory with searching experiment, for it is felt that through a balanced effort of this type the best preparation for relevant contribution to science and technology will be achieved.

The nonlinear vibrations of an elastic plate are studied in a research project in theoretical and applied mechanics.

Facilities

The Department of Theoretical and Applied Mechanics has well-equipped laboratories for experimental stress analysis and photoelasticity experiments, for work with vibrations and wave propagation, and for research in the dynamics of rigid bodies. The mechanical testing laboratory of the Department of Materials Science and Engineering is available to students who are interested in the mechanics of materials. The University's computer facilities are important in many projects.

Areas of Research

As examples of the research effort in the Field, projects in the areas of solid mechanics, space mechanics, magnetohydrodynamics, and bionics are described briefly below. In addition to this research, interdisciplinary studies are being actively pursued in cooperation with other Fields of the Graduate School. These are in the areas of mechanics and agricultural engineering (the dynamics of fruit harvesting), mechanics and animal sciences (quantitative measurements of animal health), mechanics and materials science (the mechanics of fiber-reinforced materials), mechanics and biological sciences (the mathematical structure of self-reproducing systems), and mechanics and astronomy (space and satellite mechanics).

It may be noted that Professors Block, Dunn, and Ludford are also members of the Field of Applied Mathematics, and some of their research studies constitute contributions to that discipline as well as to theoretical mechanics.

Solid Mechanics

Research in a wide variety of newly developing aspects of solid mechanics is being conducted. Several members of the faculty are contributing to fundamental studies of the behavior of composite materials. Professor Boley, internationally known for his work on thermoelasticity, conducts research in the effects of thermal gradients in composite materials. Professors Lance and Robinson are concerned with the plastic behavior of composites made of ductile materials. The microscopic aspects of fibers embedded in an elastic matrix are being studied theoretically by Professor Conway and experimentally by Professor Sachse. Professor Pao, whose special interest is stress waves in solids, is conducting studies of the feasibility of determining the elastic constants of an anisotropic solid by measuring the dynamic response of such a material.

Pertinent recent publications in this area include:

Boley, B. A., and Testa, R. B. 1969. Thermal stresses in composite beams. *International Journal of Solids and Structures* 5:1153.

Conway, H. D., and Chu, W. L. 1969. Bond stresses in composites with overlapping fibers. *International Journal of Mechanical Sciences* 12:761.

Lance, R. H., and Robinson, D. N. 1971. A maximum shear stress theory of plastic failure of fiber-reinforced materials. *Journal of Mechanics and Physics of Solids* 19:49.

Sachse, W. H., and Green, R. E., Jr. 1970. Deformation rate effects on the attenuation during loading, unloading, and reloading of aluminum crystals. *Journal of Physics and Chemistry of Solids* 31:1955.

Space Mechanics

Problems in space flight mechanics and the mechanics of the solar system gain additional significance in light of recent achievements in the national space program. Professors Alfriend and Rand are studying special aspects of three-body problems in order to better understand the motion of artificial satellites as they travel in the earth-moon gravitational system. Professors Alfriend and Dunn are actively concerned with optimum trajectories—trajectories which minimize, for example, an astronaut's exposure to weightlessness.

Among recent publications in this area are:

Alfriend, K. T., and Rand, R. H. 1968. *The stability of the triangular points in the elliptic restricted problem of three bodies.* AAS paper no. 68–090 of the AAS-AIAA astrodynamics specialist conference in Jackson, Wyoming.

Alfriend, K. T. 1970. The stability of the triangular Lagrangian points for commensurability of order two. *Celestial Mechanics* 1:351.

Dunn, J. C. 1967. Final value optimal stochastic control problem with bounded controller. *AIAA Journal* 5(8):1432.

Magnetohydrodynamics

Cornell's reputation as a center for basic research in magnetohydrodynamics is due partly to the outstanding work of Professor Ludford, a well-known specialist in fluid dynamics and MHD. Current studies of flow of conducting fluids in ducts may lead to efficient and clean new methods of power generation. An example of the contributions of Professor Ludford and his students in the literature of the field is:

Ludford, G. S. S., and Hunt, J. C. R. 1968. Three-dimensional MHD duct flow with strong transverse magnetic fields. I. Obstacles in a constant area channel. *Journal of Fluid Mechanics* 33(4):693.

Bionics and Robots

A review of interests and special skills in the Field would be incomplete without a description of the work being carried on in bionics and robots under the principal direction of Professor Block. His particular goal in this aspect of theoretical mechanics is to attempt to study biological systems and their organization in order to devise better engineering systems. Professors Dunn and Rand, who assist him in his graduate course on the subject, contribute to this nonclassical subject as well. Recent publications include:

Block, H. D., and Ginsburg, H. 1968. The psychology of robots. *Psychology Today* 1(11):50. Reprinted 1969 in *Readings in psychology today,* p. 36, Delmar, California: CRM Books and 1970 in *Readings in experimental psychology today,* p. 11, Delmar, California: CRM Books.

Faculty Members and Their Research Interests

Kyle T. Alfriend, Ph.D. (Virginia Polytechnic Institute): *dynamics of rigid bodies, space mechanics*

Henry D. Block, Ph.D. (Iowa State): *applied mathematics, nonlinear mechanics, bionics and robots*

Bruno A. Boley, Sc.D. (Polytechnic Institute of Brooklyn): *elasticity and inelasticity, thermal stresses, aerospace structures*

Joseph A. Burns, Ph.D. (Cornell): *astrophysics, space mechanics*

Harry D. Conway, Ph.D., D.Sc. (London): *isotropic and anisotropic elasticity, plates and shells*

Edmund T. Cranch, Ph.D. (Cornell): *dynamics of shells, wave propagation in solids*

Joseph C. Dunn, Ph.D. (Adelphi): *applied mathematics, mechanics of artificial satellites*

Herbert H. Johnson, Ph.D. (Case-Western Reserve): *fracture, dislocation mechanics, fatigue*

Richard H. Lance, Ph.D. (Brown): *engineering plasticity, numerical analysis*

Geoffrey S. S. Ludford, Ph.D., Sc.D. (Cambridge): *applied mathematics, fluid mechanics, magnetohydrodynamics*

Yih-Hsing Pao, Ph.D. (Columbia): *elasticity, vibrations and wave propagation in solids, magnetoelasticity*

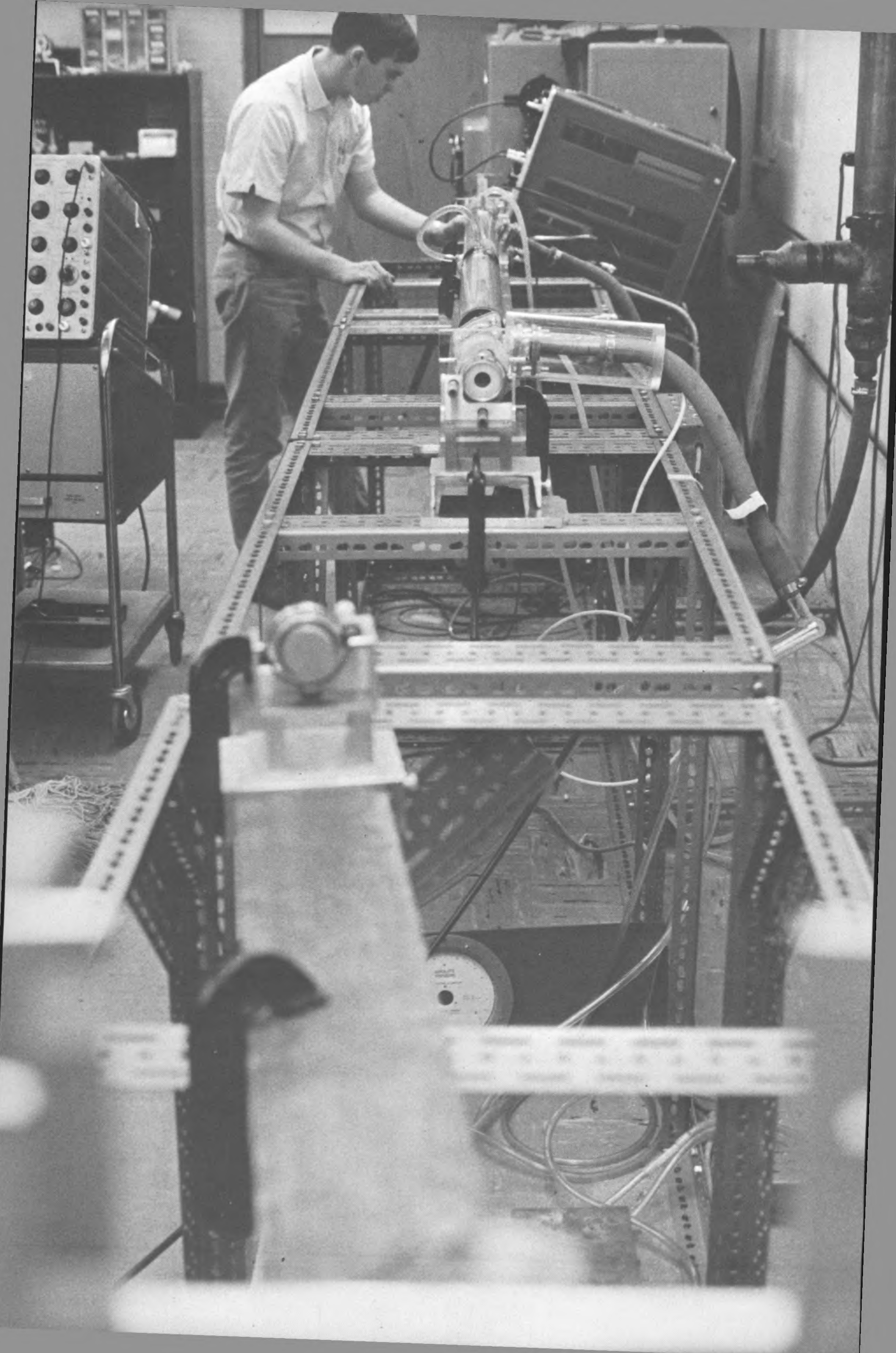
Richard H. Rand, Engr. Sc.D. (Columbia): *nonlinear vibrations, dynamics of particles*

David N. Robinson, Ph.D. (Brown): *viscoelasticity, dynamical plasticity, experimental stress analysis*

Wolfgang H. Sachse, Ph.D. (Johns Hopkins): *crystal mechanics*

Further Information

Further information may be obtained by writing to the Graduate Field Representative, Theoretical and Applied Mechanics, Thurston Hall, Cornell University, Ithaca, New York 14850.



Interdisciplinary Centers at Cornell

Cornell University maintains several interdisciplinary research centers that are of great significance in many applied science and engineering projects. These are of interest to prospective students in the various graduate Fields in that their research efforts might be closely identified with those of a center, or their research activities might be conducted in the associated laboratories. These centers do not formally admit graduate students; those interested in the areas encompassed by an interdisciplinary center should apply for graduate admission through a related graduate Field and work with the center through their supervising professors.

Center for Environmental Quality Management

This Center provides an interdisciplinary research and graduate training focus for those interested in issues pertaining to the control of the environment. It has become increasingly apparent that approaches which concentrate on limited objectives are insufficient to cope with the complexities of contemporary and anticipated problems involving the environment, and this Center is designed to facilitate broad approaches involving many disciplines.

The scientific aspect of environmental quality management involves the biological, physical, and social sciences and serves to provide information that will enhance the development of optimal public policy decisions. The methods of the management sciences, such as systems analysis, operations research, computer science, and statistical inference, provide an initial base of quantitative methods for analysis of problems with an important bearing on environmental quality.

The Center functions primarily as an organizational mechanism to encourage interactions among various disciplines. It also attempts to assist in financial and scholarly support for students who are interested in interdisciplinary studies pertaining to environmental management. Those interested in pursuing graduate work in areas of interest to the Center are advised to indicate this interest when they apply for Graduate School admission.

More detailed information may be obtained by writing to Professor Walter R. Lynn, Director of the Center for Environmental Quality Management, Hollister Hall, Cornell University, Ithaca, New York 14850.

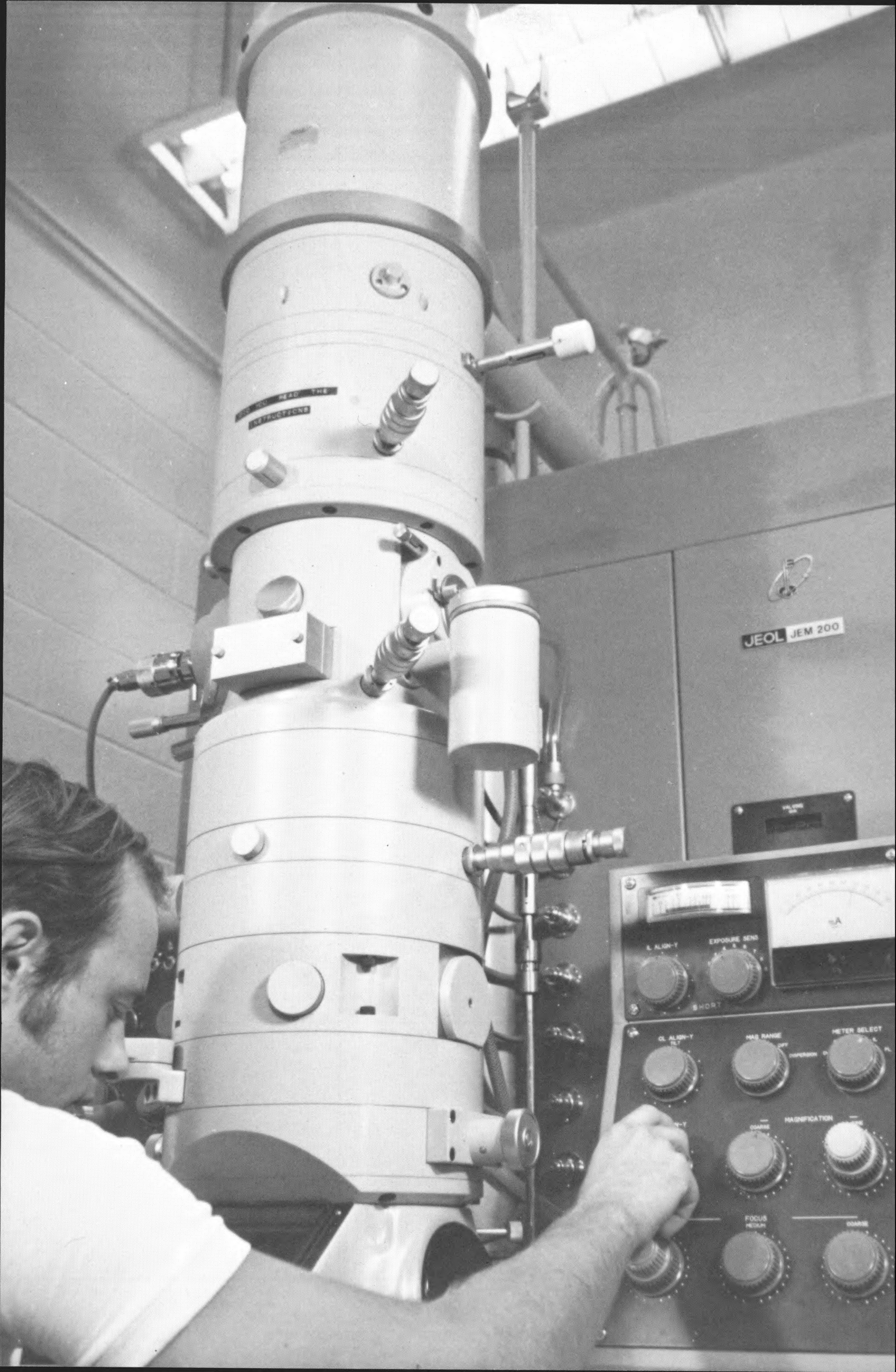
Molecular laser research is an active experimental area in the Field of Electrical Engineering and the Laboratory of Plasma Studies.

Center for Radiophysics and Space Research

This Center provides facilities for research in astronomy and the space sciences that is carried out by several departments in the University, and facilitates contact and cooperation among the various disciplines. Graduate students interested in space science research may apply for Graduate School admission through a number of graduate Fields of study. Fields of engineering and applied science that draw on the resources of the Center are Aerospace Engineering, Applied Physics, and Electrical Engineering.

The Center's facilities on the Cornell campus include an infrared laboratory, a lunar laboratory, and a laboratory for planetary studies. Large optical telescopes in the southwestern United States are available, and plans are being made for additional optical telescope facilities for a group of New York State universities, including Cornell. Facilities for research in radio-radar astronomy are available through the National Astronomy and Ionosphere Center, which is operated by Cornell in Arecibo, Puerto Rico. This Center has the world's largest radio-radar telescope, with an antenna 1,000 feet in diameter. Facilities of Sydney University in Australia are also available to Cornell students and faculty through the Cornell-Sydney University Astronomy Center, a cooperative venture of the two universities.

Further information may be obtained by writing to the Secretary, Center for Radiophysics and Space Research, Space Sciences Building, Cornell University, Ithaca, New York 14850.


JEOL JEM 200
EXPOSURE SENS
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Laboratory of Plasma Studies

This laboratory was established as an interdisciplinary center for research in plasma physics and lasers. Active areas of research include controlled fusion, intense beams of relativistic electrons, basic plasma physics, theory of high-temperature plasmas, molecular lasers, chemical lasers, and laser-produced plasmas. A variety of both large and conventional laboratory-scale facilities is provided.

Faculty members associated with the Laboratory represent several graduate Fields, among which are Aerospace Engineering, Applied Physics, Chemistry, Electrical Engineering, Mechanical Engineering, and Physics. Graduate students normally become affiliated with the Laboratory by choosing to do research with a faculty member engaged in Laboratory projects. During the Laboratory's first four years of existence, its research projects led to the completion of sixteen Ph.D. and five M.S. theses.

Financial assistance in the form of graduate research assistantships is available in limited quantity and is obtained directly from the Laboratory; fellowships are available through the normal Graduate School channels.

Further information may be obtained by writing to Professor Peter L. Auer, Director of the Laboratory of Plasma Studies, Upson Hall, Cornell University, Ithaca, New York 14850.

Materials Science Center

This Center facilitates graduate research and training in many phases of the science of materials. It provides a number of special laboratories containing highly sophisticated equipment that is made available in this way to researchers in many areas, including applied physics, chemistry, electrical engineering, materials science and engineering, mechanics, metallurgy, and physics. In some cases new equipment needed for specific thesis research projects and the assistance of technicians can be provided. The Center is also able to provide financial assistance in the form of research assistantships.

The laboratories at the Center are for materials preparation, metallography, x-ray diffraction, electron microscopy, electronics, high-pressure and low-temperature work, chemical analysis, irradiation, and nonmetallic crystal growth. Each of these laboratories is under the direction of a faculty member and staffed with trained technicians, so that researchers receive expert guidance and assistance.

In the materials preparation laboratory there are facilities for growing oriented single crystals and bicrystals ranging from semiconductors to refractory metals, and facilities for preparing special alloys and compounds. In addition to the conventional crystal-growing, zone-refining, and melting apparatus, this laboratory has two electron-beam melting units, an electron-beam evaporator, an induction plasma unit, a cold-hearth arc melting unit, a levitation melter, a vacuum induction furnace, high-temperature resistance furnaces, and vapor deposition apparatus. There is also equipment for rolling, swaging, wire drawing, and inert gas welding, and special crystal cutting apparatus such as a precision wafering machine and spark cutting units.

The analytical facility is capable of determining the composition of samples in the macro to ultratrace concentration range, with use of electron microscopy, chemical analysis, flame photometry, neutron activation analysis, optical emission spectroscopy, inert gas fusion, and spark source mass spectroscopy.

Most of the Materials Science Center facilities are located in Clark Hall of Science, the University's center for solid state and applied physics.

Additional information may be obtained by writing to the Director, Materials Science Center, 627 Clark Hall, Cornell University, Ithaca, New York 14850.

This JEM 200 kV electron microscope is among the instruments made available to graduate students by the Materials Science Center.

Water Resources and Marine Sciences Center

This Center is an interdisciplinary organization serving the entire University at the graduate study and research level. Its purpose is to promote and coordinate a comprehensive program in water resources planning, development, and management that involves faculty and graduate students in the sciences, engineering, agriculture, law, economics, government, regional planning, and public health.

As part of its responsibilities, the Center undertakes and supports water resources research involving these various fields, and it publishes the results of research. It encourages new combinations of disciplines in research and training which can be brought to bear on water resource problems, and it develops and operates central facilities.

The graduate Field of engineering that is most involved with the Center is Civil and Environmental Engineering; the Center is located in Hollister Hall, the main facility of the School of Civil and Environmental Engineering. Also, the Field of Water Resources, which offers an interdisciplinary minor program of study available to graduate students, is closely related to the Center.

Further information about the Center may be obtained by writing to Professor Leonard B. Dworsky, Director of the Water Resources and Marine Sciences Center, Hollister Hall, Cornell University, Ithaca, New York 14850.

General Information

Location of the University

Most of the schools and colleges of the University are located in Ithaca, at the southern end of the Finger Lakes region of upstate New York. The population of the greater Ithaca area, including students, is about 40,000. Public transportation to Ithaca is provided by Mohawk Airlines and the Greyhound bus lines.

The Cornell University Medical College and the Cornell University-New York Hospital School of Nursing are located in New York City. The University also operates the New York State Agricultural Experiment Station in Geneva, and the National Astronomy and Ionosphere Center in Puerto Rico.

Financial Aid and Employment Opportunities

Financial aid in the form of teaching, research, or residence hall assistantships, fellowships, scholarships, and loans is available to graduate students.

An applicant for admission to an M.S. or Ph.D. degree program will receive detailed information about available financial aid along with his application materials, and should indicate a request for aid on his application form. A prospective student in one of the M.Eng. degree programs should file a separate application for financial aid along with his admission application. Addresses for obtaining the appropriate materials are given at the end of this *Announcement.*

It may be helpful for applicants, especially those applying for fellowships and scholarships, to take the Graduate Record Examination Aptitude Test (Verbal and Quantitative) and Advanced Engineering Test and have scores sent to the Graduate School. Information about the tests may be obtained from the Educational Testing Service, Princeton, New Jersey 08540.

It may also be noted that there are fellowships and scholarships offered by state and national governmental agencies, by foundations, and by private parties. The Cornell University Career Center maintains a collection of pertinent reference materials on such sources of financial aid. A useful reference book is Norman Feingold's *Scholarships, Fellowships, and Loans.*

Opportunities for part-time employment are sometimes available to graduate students through their own departments, and a part-time employment service is maintained by the Office of Scholarships and Financial Aid. Wives of students frequently find employment at Cornell through the University's Personnel Office, or with local businesses or industries, professional offices, schools and colleges, public service agencies, and the hospital. A New York State Employment Office is located in Ithaca.

Extracurricular Activities

A wide variety of cultural events, including lectures, special programs and conferences, and music, drama, and film offerings, are available at Cornell. Ithaca residents also have the opportunity to attend theatrical and musical events at Ithaca College.

Programs in religious affairs at the University include information, counselling, and referral services as well as ministries in many religious groups. A Center for Religion, Ethics, and Social Policy is a nondenominational, educational unit which sponsors lectures, conferences, seminars, action projects, and publications.

The Sage Graduate Center supplements the three student unions at Cornell in providing opportunity for social and recreational activities. Graduate students are also welcome to join undergraduates in student activities such as intramural sports, drama, and the production of campus publications. The various University musical groups and many of the more than one hundred organizations on campus are open to graduate students. Wives of graduate students are frequently active in their own special organizations. There is also an organization for foreign students and their families.

Extensive recreational facilities, including those for swimming, ice skating, golf, bowling, and tennis, are available on campus. Graduate students are also

A popular winter sport for Cornell students is skiing, available at several nearby areas.

eligible for all intramural and informal sports at the University. Additional opportunities for outdoor sports and recreation are available in the surrounding area. Three exceptionally large and scenic state parks and a municipal park are located within a few miles of the campus, and skiing is offered at several nearby areas.

Housing

Graduate dormitory housing and apartments for married students are available on campus, and help in obtaining off-campus housing is offered. Detailed information about housing is sent along with requested application materials, and may also be obtained from the Housing Services Office, 223 Day Hall, Cornell University, Ithaca, New York 14850.

Further Information

The *Announcement of the Graduate School* and the *Announcement of General Information* are useful to prospective Cornell graduate students and should be consulted for additional information on admission, financial aid, and degree requirements. Information about facilities and programs in the various schools and departments of the College of Engineering is included in the *Announcement of the College of Engineering.* Applicants for graduate study may also request the *Announcement of the Graduate School: Course Descriptions.* Copies of these publications may be obtained by writing to Cornell University Announcements, Day Hall, Ithaca, New York 14850.

In addition, further information about specific graduate programs may be obtained by writing to the Graduate Field Representative (for M.S. or Ph.D. degree programs) or to the Master of Engineering Representative (for the M.Eng. degree programs) in the academic area of interest. Addresses are given at the end of each graduate Field section.

Application materials for the Graduate School, including financial aid information and request forms, may be obtained from the Sage Graduate Center, Cornell University, Ithaca, New York 14850. Admission and financial aid application forms for the Master of Engineering degree programs may be obtained by writing to the Graduate Professional Engineering Programs, 221 Carpenter Hall, Cornell University, Ithaca, New York 14850.