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THE MILTON S. EISENHOWER RESEARCH CENTER: ITS OBJECTIVES AND ACTIVITIES

The dedication of the Research Center to Milton Stover Eisenhower on September 19, 1979 provides an occasion for reexamining the role of the Research Center in the Applied Physics Laboratory; its historical evolution; the rationale for its existence; its contributions to basic and applied science and to the Laboratory; and a summary of present activities, with a view toward the future.

PREFACE

The Research Center is a relatively small, scholarly component of APL, but its roots are deeply entwined with the Laboratory's history. Now in its thirty-third year, the Research Center is APL's oldest major organizational unit. In spite of many changes, the Research Center retains its vigor.

What sustains the Research Center? This question provides a focal theme that goes beyond the Center itself to provide insight into APL and its vitality. The reader who wishes to probe this question may profitably begin with several papers[1–4] by R. E. Gibson, Director Emeritus. Our intent here is to develop an intuitive feeling for three aspects that seem especially significant:

1. Why APL is engaged in fundamental research,
2. Why the Research Center is a separate administrative unit, and
3. How its fundamental research program relates to the Laboratory as a whole.

Perspective demands attention to what has gone before, but while there is much that is historical, this is not a history. Indeed, many highly significant achievements of the Research Center are not discussed because they do not relate specifically to present activities; for example, the contribution to the early development of the "big bang" theory of the universe. We deeply regret that brevity requires sketchy attention to or even neglect of past and ongoing activities of importance and that each present and past member of the Center cannot receive the individual recognition merited.

BACKGROUND

The characteristic common to all institutions which have remained great is their success in carefully formulating and clearly expressing a guiding purpose—a purpose which is not simply a wisp of eloquence ... but something to be continually tested and tempered by the changing times ....

Milton S. Eisenhower

from "To Chart Our Future Course," the *Johns Hopkins Magazine* **XVI**, No. 5, p. 21 (1965)

The purpose of the Applied Physics Laboratory has been summarized as follows:[5] "The general purpose of The Johns Hopkins University can be stated as public service through education, research, and the application of knowledge to human affairs. As part of the University, the Applied Physics Laboratory shares this purpose through the application of advanced science and technology to the enhancement of the security of the United States of America and basic research to which its facilities can make an especially favorable contribution."

The Laboratory is devoted primarily to solving technological problems rather than basic research. But much new technology grows from basic research and much new science grows from the problems and products of technology. This symbiosis is nurtured at APL by conducting research and development in various divisions, but particularly by maintaining one division dedicated principally to basic research. This division, the Research Center, contributes a vision of the future and blazes trails for the Laboratory's technology.

The vitality of the Research Center derives from the vision of F. T. McClure and its other founders,

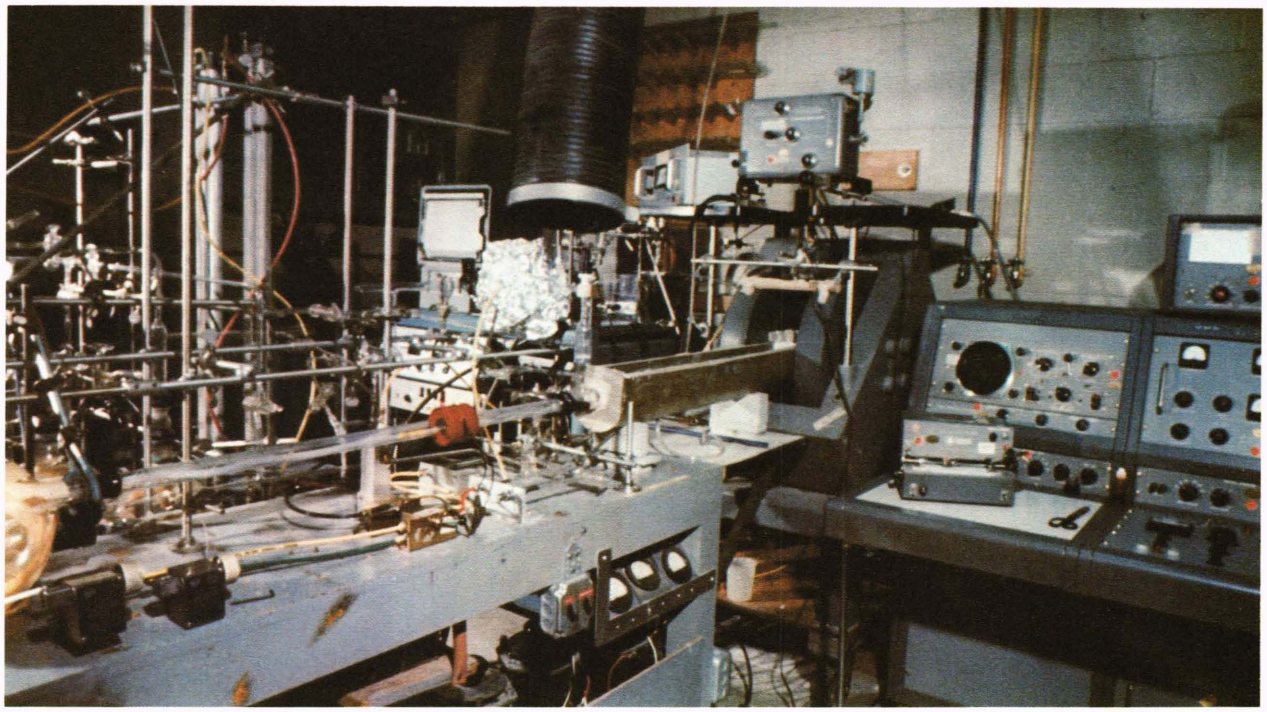

Fig. 1—Chemical Kinetics Laboratory. For their work in this laboratory, A. A. Westenberg and R. M. Fristrom received the 1966 Hillebrand Award of the Chemical Society of Washington for "brilliant...investigations...that have given new insights into...the chemistry and physics of flames..."

their concepts of what research would be expected to do, and their understanding of how to nurture it. When the Research Center was established on April 1, 1947, their concepts were formalized in several memoranda by R. E. Gibson, A. Kossiakoff, and F. T. McClure, setting forth what the Research Center would be expected to contribute to the Laboratory. The essence of those objectives, still valid today, is

1. To establish APL as a contributor to scientific knowledge and to the techniques of obtaining it,
2. To develop and provide fundamental understanding in fields presently and potentially important to the Laboratory, and
3. To enhance the professional competence of the Laboratory's staff by serving as a door to science.

The clarity of their vision is borne out by results, for over the years the Research Center has served many purposes related especially to developing new knowledge and sustaining the vigor and professional competence of the Laboratory. It quickly established APL as a contributor to fundamental science through original investigations in flame spectroscopy (R. C. Herman, S. Silverman, and others) and upper atmosphere physics (J. A. Van Allen and others). Subsequently, Research Center scientists pioneered and acquired international standing in areas such as combustion (Fig. 1), mass spectrometry (Fig. 2), free radical physics and chemistry, laser mechanisms, semiconductor physics, the structure of solids, applied mathematics, kinetic theory, physical optics, wave scattering, and biomedical science. The many contributions to science are recognized in the scientific community and sustain the reputation of the Laboratory as a center of excellence in the tradition of Johns Hopkins institutions.

How does one begin to describe the Research Center? Ideally, the first quick impression should be its scholarly quality, but this defies easy communication. The fact that Research Center scientists publish their work widely in the scientific literature suggests the presence of scientific quality (Fig. 3), but only a deeper examination will confirm its existence.

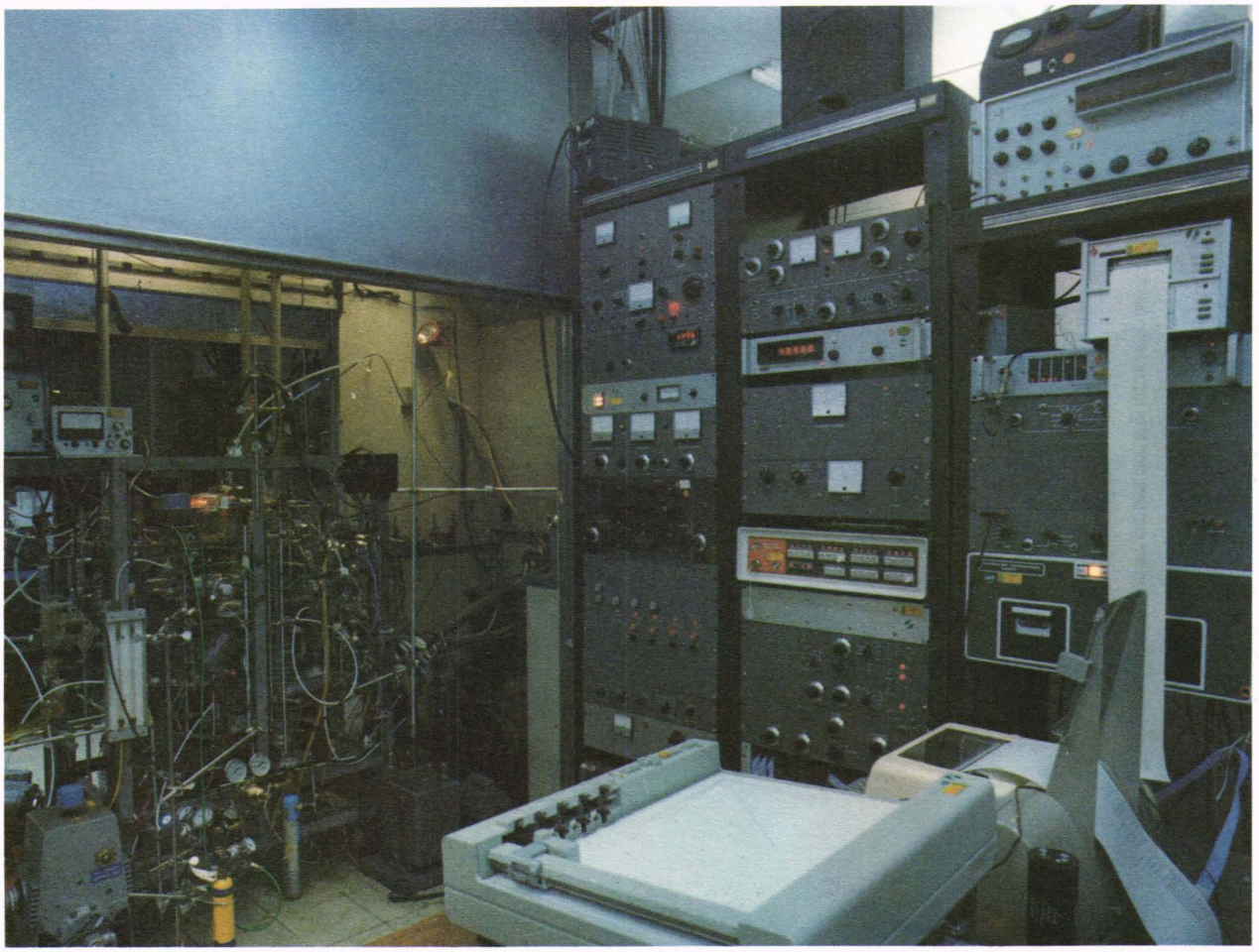

Fig. 2—Molecular beam mass spectrometer. "Two instruments, the molecular beam apparatus and its relative, the mass spectrometer... Perhaps the first really successful application of the combined system to the study of neutral atom-molecular reactions now seems to have been achieved by S. N. Foner and R. L. Hudson..." [*Nature*, **229** p. 374 (1971).]

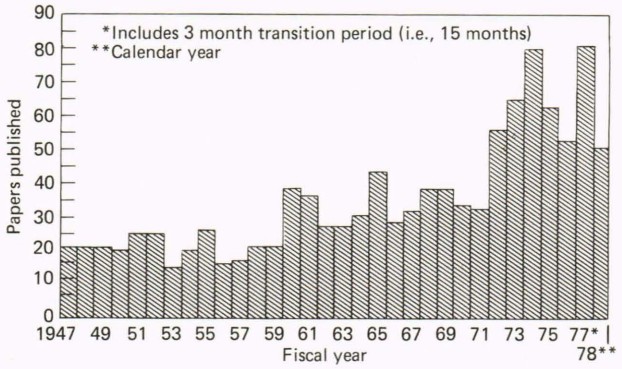

Fig. 3—The number of papers published in the professional literature by the staff of the Research Center through 1978.

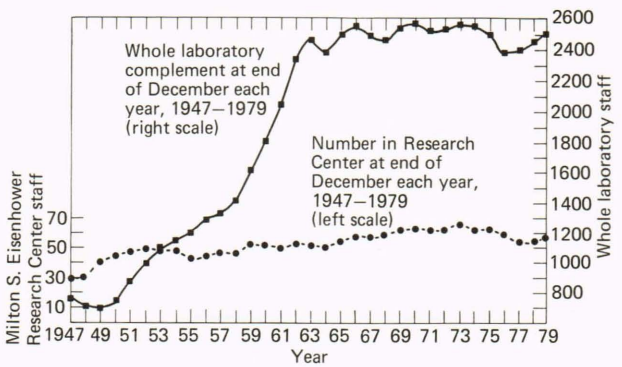

Fig. 4—Staff levels of the Research Center versus whole-Laboratory complements, 1947-1979.

In numerical terms, the Research Center employs a permanent staff of about 55 people (Fig. 4), enough to comprise complete departments of physics, chemistry, mathematics, and electrical engineering at a small university. The Research Center has 25 laboratories (Table 1), occupying about 10,000 ft^2 and equipped for research in physics and chemistry. It will be important to some to note that its programs are supported in part by contracts and grants (cf. Table 2) and in part by Laboratory Independent Research and Development (IR&D) overhead, which currently supports the work of approximately half of the Research Center's staff.

In many ways, the Research Center is larger than its permanent staff would suggest because it also encompasses researchers on temporary and part-time assignments, graduate students, postdoctoral fellows, and staff members of other units of the

Table 1

RESEARCH CENTER LABORATORIES

Auger Electron Spectroscopy Laboratory	Fluorescence Spectroscopy	Optical Spectroscopy Laboratory
Biodynamics Laboratory	Intensity Correlation Spectroscopy Laboratory	Optics Laboratory
Chemical Kinetics Laboratory	Laser Applications Laboratory	Photochemistry Laboratory
Chemistry Laboratory	Laser Chemistry Laboratory	Scanning Electron Microscopy Laboratory
Combustion Research Laboratory	Laser Measurements Laboratory	Secondary Ion Mass Spectrometry Laboratory
Computer Facilities Room	Mass Spectrometry Laboratory	Solid State Research Laboratory
Crystal Growing Laboratory	Materials Research Laboratory	Surface Science Laboratory
Electronic Instrumentation Laboratory	Mössbauer Spectroscopy Laboratory	X-Ray and Glassblowing Laboratories
	Nuclear Magnetic Resonance Spectroscopy Laboratory	

Table 2

CONTRACTS/GRANTS TO RESEARCH CENTER INVESTIGATORS DURING 1979

Title	*Sponsor*	*Principal Research Center Investigator*
High Resolution Spectroscopy of Porphyrins	NIH	B. F. Kim/J. Bohandy
Tomosynthesizer	Mellon Found.	A. B. Fraser
Holographic Stress Testing of Surgical Cornea	NIH	B. F. Hochheimer(1)
Light Scattering Aerosols	Army	R. A. Farrell
Structural Alterations in Cornea from Exposure to IR Radiation	Army	R. A. Farrell
Light Scattering of Ocular Tissues	NIH	R. A. Farrell
Ruby Laser (Glaucoma Studies)	NIH	A. B. Fraser(1)
Low Level Laser Retinal Damage	Army	B. F. Hochheimer
Polarized Light Retinal Photography	NIH	B. F. Hochheimer
Continued Studies of Angiographic Dyes	NIH	B. F. Hochheimer
Laser Spectroscopy of Lipoproteins	NIH	R. L. McCally(1)
Stenosis Hemodynamics and Endothelial Response	NIH	V. O'Brien
Rheological Effects in Liquid Breakup	Army	V. O'Brien
Ship-Wave Interaction	Navy	J. C. W. Rogers
Vacuum Deposited Polycrystalline Silicon Films	DOE & SERI	C. Feldman
Amorphous Iron Borides	Army	K. Moorjani
Infrared Extinction Phenomena in Solids	Army	T. O. Poehler
Photoeffects at Semiconductor Electrolyte Interfaces	Navy	T. O. Poehler
New Organic Conductors	NSF	T. O. Poehler(2)
Electrical Discharge Laser	Navy	T. O. Poehler/R. Turner
Li + He: A Theoretical and Experimental Study of Rotational Energy Transfer	NSF	D. M. Silver(2)
Submarine Oxygen System	Navy	D. M. Silver
Acoustic Leak Detection in Natural Gas Pipelines	GRI	J. G. Parker
Corrosion Detection in Natural Gas Pipelines	Columbia Gas	J. G. Parker(2)/J. C. Murphy(2)

(1) Co-Principal Investigator; Principal Investigator at School of Medicine.
(2) Co-Principal Investigator; Principal Investigator at Homewood campus.

Table 3

NON-RESEARCH CENTER COLLABORATORS FUNDED IN RESEARCH CENTER PROJECTS DURING 1979

Affiliation	*Investigator*	*Research Project*
APL Fleet Systems Dept.	C. H. Hoshall(1)	Heterogeneous chemistry
	J. A. Krill(2)	Scattering of electromagnetic waves
	J. A. Krill(2)	Light scattering aerosols
APL Space Dept.	D. C. Culver(3)	Gas leak and corrosion detection
	G. S. Hartong(4)	
	J. E. Ricker(5)	
APL Aeronautics Dept.	F. F. Mark(4)	Blood flow hemodynamics
APL Assessment Div.	M. S. Morris(4)	Gas leak detection
JHMI	J. Cox (6)	Light scattering in ocular tissues
	W. R. Green (7)	Structural alterations in cornea
	G. M. Hutchins (8)	Stenosis hemodynamics
	K. Sagawa (9)	
	S. D'Anna (10)	Laser retinal damage
	S. D'Anna (10)	Studies of angiographic dyes
JHU (Homewood campus)	W. Bryden (11)	New organic conductors
	R. S. Potember (11)	
	M. Hawley (11)	
	R. E. Green (12)	Gas leak detection
	S. Southwick (11)	Solid state (semiconductor) physics
	C. A. Beattie (13)	Numerical analysis of eigenvalues
Technion-Israel Inst. of Tech.	J. Stricker (1)	Heterogeneous chemistry
Univ. of Sheffield (UK)	G. Warman (14)	Photoacoustic spectroscopy

(1) Chemist
(2) Engineer
(3) Engineering assistant
(4) Physicist
(5) Technician
(6) Electron microscopist
(7) Professor, ophthalmology
(8) Associate Professor, pathology
(9) Professor, biomedical engineering
(10) Ophthalmological photographer
(11) Chemistry student
(12) Professor, mechanics and materials
(13) Mathematical sciences student
(14) Physics student

Laboratory, and because scientists at many universities and other institutions (supported by their own funds) collaborate in the Research Center's programs. A quick insight into the interaction among the Research Center, the rest of APL, and the University is provided by a list of people from elsewhere who are funded to work on Research Center projects (Table 3) and of Research Center scientists who work part-time on specific problems of other divisions of APL (Table 4). But the basic and most important interactions are more subtle and not so easily communicated.

RATIONALE FOR BASIC RESEARCH AT APL

It is most important that we be impractical (like the scientists of the 1930s who concerned themselves with the atomic nucleus) and esoteric ... and that we be intensely practical, as well.

Milton S. Eisenhower

from "We Are Involved in Mankind," the *Johns Hopkins Magazine* **X**, No. 5, p. 5 (1959).

As has already been noted, APL is devoted primarily to solving practical technological problems, but there is also a dedication to fundamental research whose practicality may be vague and whose value may lie in the indefinite future. Such research is found to be sustained only where it is institutional policy to do so, i.e., where the topmost administration has the conviction that fundamental research is necessary to the institution's future.[6] Thus, it is important to APL that its staff (from which its future leaders will be drawn) should share that conviction. Otherwise, APL might one day find itself, like the Department of Defense (DoD) of today, overdependent on technology spawned by decades-old basic science.[7]

The rationale for supporting basic research at APL, as at other institutions, lies in the need for intellectual growth to cope with changing and complex science and technology, i.e., to avoid institutional obsolescence (to which many institutions succumb).[8] Specific research needs change with time, but there are constant needs that are well summarized in a recent report expressing DoD rationale for basic research.[9] These needs, which apply equally to APL, are: to ensure that fields of direct

Table 4

JHU/APL ADMINISTRATIVE UNITS UTILIZING RESEARCH CENTER SCIENTISTS DURING 1979

Administrative Unit	*Research Center Investigator*	*Problem Area*
Aeronautics Div.	R. Benson(7)	Nonintrusive combustion instrumentation
	R. Murphy(2)	
	R. Turner(1)	
	S. Favin(3)	Computer programming
Biomedical Programs Office	O. J. Deters(3)	Laser velocimetry
	A. B. Fraser(1)	3-D X ray and other
Director's Office	M. Linevsky(1)	Laser applications
	E. P. Gray(1)	Colloquium chairman
Engineering Facilities Div.	B. F. Hochheimer(1)	Oil spill detection (spectroscopy)
		LANDSAT Satellite (optics)
	C. B. Bargeron(1)	Scanning electron microscopy
	R. B. Givens(4)	
Fire Program Office	O. J. Deters(3)	Data gathering and analysis
	S. Favin(3)	Computer programming
	C. B. Bargeron(1)	Scanning electron microscopy
	R. B. Givens(4)	
Fleet Systems Dept.	M. R. Feinstein(5)	Electromagnetic scattering theory
JHU (Homewood campus)	R. L. McCally(1)	Parsons Fellow, 1979-80
	V. G. Sigillito(3)	Parsons Visiting Professor, 1978-79, and Lecturer in mathematical sciences
	D. W. Fox(3)	Lecturer in mathematical sciences
	L. Monchick(7)	Lecturer in mathematical sciences
	J. G. Parker(1)	Gas line leak and corrosion detection
	J. C. Murphy(1)	
	T. O. Poehler(6)	Visiting Professor and Lecturer in electrical engineering
	V. O'Brien(1)	Lecturer in mechanical engineering
	D. M. Silver(7)	Theoretical chemistry
JHMI	R. L. McCally(1)	Laser spectroscopy of lipoproteins
	B. F. Hochheimer(1)	Instructor in ophthalmology
	B. F. Hochheimer(1)	Holographic stress testing of cornea
F. T. McClure Computing Center	L. W. Ehrlich(3)	Advanced computer programming
Space Dept.	J. F. Bird(1)	Electromagnetic theory
	C. B. Bargeron(1)	Scanning electron microscopy
	R. B. Givens(4)	
	S. Favin(3)	Computer programming
	R. L. Hudson(6)	DISCOS satellite charge measurements
	R. B. Givens(4)	
Strategic Systems Dept.	B. F. Hochheimer(1)	Optical systems technology
	A. B. Fraser(1)	Laser instruments and data handling technology
	H. A. Kues(2)	Dye tracer technology
	S. Favin(3)	Computer programming
Submarine Technology Div.	H. A. Kues(2)	Dye tracers (and chemical support)
	C. D. Mitchell(4)	
	B. F. Hochheimer(1)	Fluorometer design
	A. B. Fraser(1)	Project scientist
	N. Blum(1)	Electromagnetic theory
	V. O'Brien(1)	Hydrodynamic theory

(1) Physicist
(2) Engineering staff associate
(3) Mathematician
(4) Engineering assistant
(5) Physicist (postdoctoral)
(6) Engineer
(7) Chemist

importance are not neglected, to encourage direct access by technical personnel to scientists, to acquaint researchers with pressing technical problems so as to stimulate new research directions, to attract highly qualified personnel, and to create a pool of research scientists in relevant fields who are acquainted with technical problems and are potentially available to help.

For a deeper understanding of the rationale, consider the inception and evolution of basic research at APL. In the beginning, basic research arose more from the interests of the staff than from their conviction that such research was necessary to APL's vitality. (The February 1952 issue of *Physics Today* contains a perceptive account of the inception and early years of the Research Center;[10] see also "Reflections on the Origin and Early History of the Applied Physics Laboratory", by R.E. Gibson.[11]) Most of the founders had been teaching and conducting research at universities before the Second World War. Through their wartime experiences with the development of the proximity fuze, the radar gun director, and guided missiles, they had felt excitement and satisfaction in applying new scientific techniques—developed in universities—to practical problems. Moreover, it was recognized that the future of the Laboratory would require scientific as well as technological minds, and that it would be difficult to hire and retain scholarly scientists to work exclusively on applied tasks. These and other considerations (some will be discussed later) led to the consolidation of basic research activities in a single organizational unit called the Research Center.

Although the Research Center's value to APL tends to be diffuse, there are distinctive patterns. In its scholarly activities, the Center provides APL staff members with access to science through seminars, consultations, and conjoint research activities. The roots of the APL Reference Library, Colloquia, and Evening College lie in the Research Center. It also contributes importantly to the leadership of the Laboratory; many of APL's top leaders were at one time members of the Center. The Center's staff is prominent on the faculty of the JHU Evening College Center at APL, and many have part-time appointments at The Johns Hopkins University, at its School of Medicine, and at other nearby universities.

Conspicuous among Research Center contributions to APL is the genesis of new units of the Laboratory and of new programs that are being carried on in other units of the Laboratory. These include the genesis of the Space Department, the program on causes, prevention, and control of unwanted fires, and the biomedical research program now under the aegis of the Biomedical Programs Office. These (and an environmental safety program) illustrate different ways in which the Center enhances the vigor of the Laboratory.

ORIGIN OF THE SPACE DEPARTMENT

The origin of the Space Department illustrates that the pursuit of "unprogrammed" intellectual curiosity can lead to unforeseen applications, for it stemmed directly from the Research Center Project D-54, which was approved by the Director (Dr. Gibson) on November 8, 1957, to study "orbits of artificial satellites and radiation from them." The project was initiated by three Research Center scientists: W. H. Guier and G. C. Weiffenbach, who were encouraged to indulge their desire to understand radio emissions from the first artificial earth satellite, and Dr. McClure, who was then concerned with Navy problems to which that understanding turned out to be applicable. Their work led to the Transit Navy Satellite Program under R. B. Kershner and, thereby, to a major field of endeavor for the Laboratory and important contributions to the nation.

ORIGIN OF THE APL FIRE PROGRAM

The genesis of the fire program illustrates how the "programmed" pursuit of scientific stature can lead to unanticipated new endeavors for the Laboratory. Stemming from APL's pioneer involvement with supersonic ramjets and problems of burning fuel-air mixtures that invariably have flame speeds that are very small compared with the speed of sound, Research Center scientists (most notably R. M. Fristrom and A. A. Westenberg) carried out fundamental research and gained international stature in the field of combustion. (See the article on pp. 33-35.) In 1971, the National Science Foundation requested W. G. Berl and R. M. Fristrom to investigate unwanted fires. This led to an APL fire program under their leadership.

THE BIOMEDICAL PROGRAM

The biomedical research program illustrates a "programmed" effort to develop a new field of expertise for the Laboratory. In 1965, the Laboratory began a concerted effort to increase the scope of its activities in civilian fields. Leaders of the Laboratory recognized that biomedicine could benefit from APL's technological expertise and that, as a member of the Johns Hopkins family, APL was in a unique position to interact with the biomedical community.

With the enthusiastic interest of Milton S. Eisenhower, then President of The Johns Hopkins University, it became APL policy to develop a program in biomedical engineering in collaboration with the Johns Hopkins Medical Institutions (JHMI). The effort was spearheaded at APL by F. T. McClure. He was assisted by many others, but especially by A. G. Schulz and J. T. Massey, two other Research Center investigators, and by Dr. R. J. Johns at the School of Medicine. As it has grown, the program has come to be recognized as unique in the extent of its collaboration between medical and physical researchers.

Important for obtaining the funding to support any program is professional standing; the responsibility for developing professional standing in biomedical science naturally fell to the Research Center. Its scientists worked closely with colleagues at the School of Medicine and succeeded to the extent that several of them (most notably R. A. Farrell, B. F. Kim, M. H. Friedman, B. F. Hochheimer, R. W. Flower, and J. T. Massey) are now recognized experts in their chosen new fields. For example, in collaboration with M. E. Langham and others of the Wilmer Institute, light scattering studies by R. A. Farrell, R. W. Hart, and other Research Center physicists dispelled previous misconceptions and developed new understanding of how the transparency of the cornea depends on its structure (Fig. 5). Other studies that involved M. H. Friedman, then a chemical engineer in the Center, used innovative experiments and thermodynamic theory to explain how the thickness of the cornea is regulated and how it depends on corneal structure. Other results of collaboration, especially between B. F. Hochheimer (an optical physicist in the Center) and A. Patz (of the Wilmer Institute) led to the development of fluorescent dyes, dye techniques, and optical instrumentation and their use to understand blood circulation in the eye (Fig. 6). The first prototype argon laser photocoagulator also was developed.

By 1972, the collaboration had grown to involve people from all the major divisions of the Laboratory; the APL Biomedical Program Office was established under Dr. Massey, a physicist transferred from the Research Center. There, he had been supervisor of the Excitation Mechanisms Group, actively assisting in the development of collaborative projects between APL and JHMI. Dr. Friedman, supervisor of the Research Center's Theoretical Problems Group, subsequently transferred out of the Center to become Dr. Massey's deputy. Messrs. Massey, Friedman, Hart, Flower, and Hochheimer now hold joint appointments in the School of Medicine.

In 1975, a notable milestone that marked the growth of APL's stature in biomedical science was achieved when two Research Center physicists, B. F. Kim and J. Bohandy, were awarded the first National Institutes of Health (NIH) grant to APL for biomedical work that did not involve a collaborator in JHMI. These two physicists, with backgrounds in optical and microwave spectroscopy, applied their talents to the study of porphyrins. They developed experimental techniques to achieve high resolution spectra that advance basic understanding in areas such as oxygen transport in blood (involving iron porphyrin) and photosynthesis (involving especially magnesium porphyrin).

University and Laboratory policy is aimed at increasing APL's effort and stature in biomedical areas. The Research Center continues to play a central role in the program.

PROGRAM IN ENVIRONMENTAL SAFETY

Finally, we recognize a program in an area of environmental safety that is now being nurtured at the Laboratory. It began in 1975 when J. G.

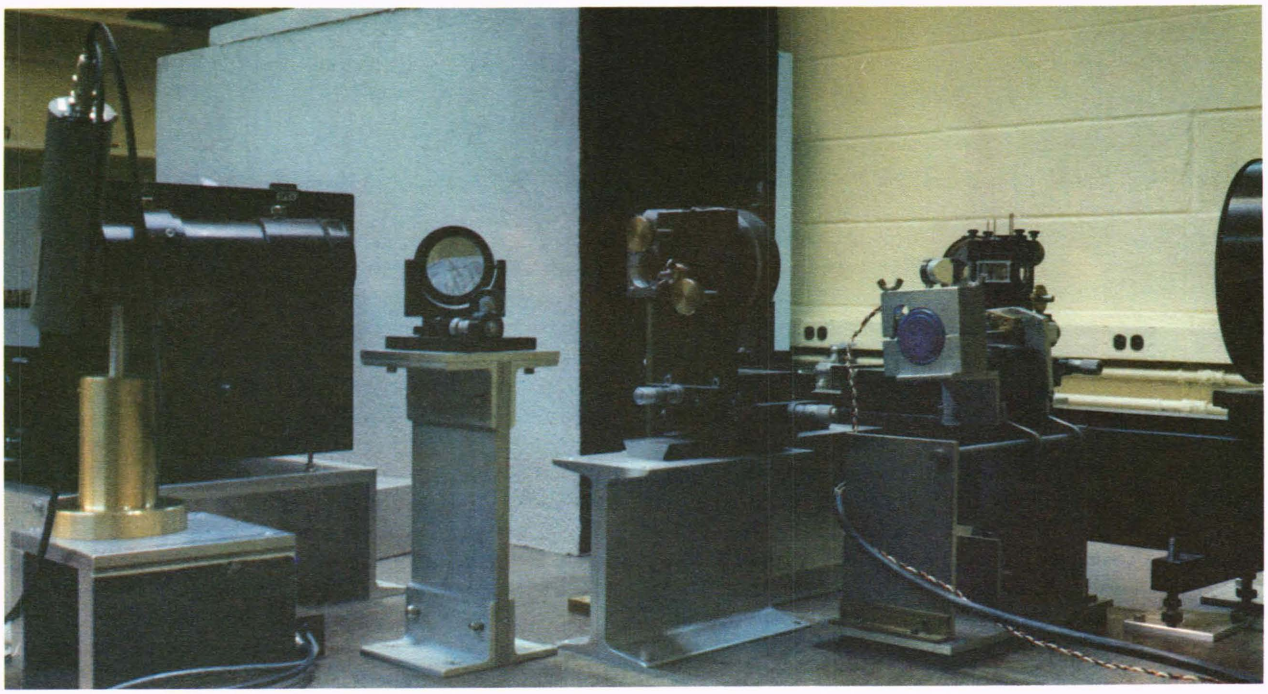

Fig. 5—Cornea light scattering apparatus. "When the cornea of the eye becomes swollen, the collagen fibrils of which its stroma is composed become disrupted and this results in loss of transparency... The Hopkins investigators showed that corneal transparency was a consequence of the semi-ordered arrangement of the fibrils..." [*Medical World News* **13**, No. 16, p. 4011 (1972).]

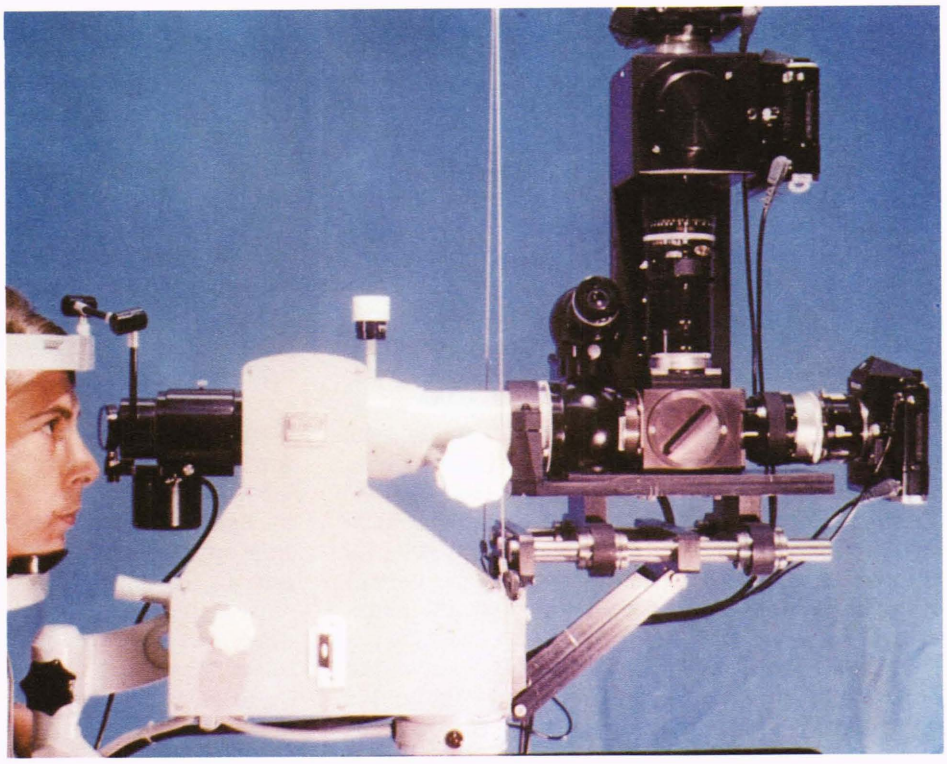

Fig. 6—Fundus camera. A special camera for simultaneous study of choroidal and retinal circulation in the eye "by a new technique teaming indocyanine green dye with infrared radiation. The technique, developed at The Johns Hopkins University Applied Physics Laboratory, makes it possible to examine the usually veiled choroid." [*Chemical and Engineering News*, Oct. 1, 1973, p. 20).]

Parker, a Research Center scientist well known for his basic studies of sound propagation in gases (including methane), was asked by the American Gas Association to investigate basic problems in the acoustic detection and localization of leaks in gas mains. Under the primary aegis of the Gas Research Institute and in collaboration with other APL and JHU investigators, this work is currently being broadened in scope to encompass other aspects of gas pipeline safety.

COMMENTS

The above activities (and many others) testify to the practical value of pioneering research in areas relevant to the Laboratory's needs. However, while it is easy to recognize this value in principle, it is difficult in practice to resist many day-to-day pressures that tend to discourage such activities. Short-term financial considerations, for example, inhibit pioneering research, regardless of whether APL's major sponsors are pressing the Laboratory to take on additional work or whether APL needs new sponsors to enable it to solve important new problems. In the first case, the pressure is to divert people from the pioneering research in order to satisfy present sponsors; in the second case, the pressure is to divert people into activities to secure new sponsorship. Sustaining a firm commitment to long-term research under these conditions is not easy for either individuals or institutions, and demands enlightened institutional policy and discipline.[6] One particularly important aspect is that of maintaining a fertile research environment, as is discussed in the next section.

THE RESEARCH ENVIRONMENT

Our strength cannot be in numbers. It must be in excellence. Here must be a community of scholars who, in an environment of courageous freedom, are constantly pushing back the walls of the unknown.

Milton S. Eisenhower

from "The Future of Johns Hopkins," the *Johns Hopkins Magazine* **VIII** No. 7, p. 8, (1957).

Post-World War II history teaches that basic research is difficult to sustain, especially outside the shelter of a university, and that the institutional research environment is of critical importance. In particular, basic research tends to die if it is dispersed in technologically oriented institutions.[6] An atmosphere of scholarship and responsible freedom to explore is essential to excellence in basic research, and the Research Center is maintained to provide it. For APL to thrive in the future, its staff (and especially APL's future leaders) should understand why this environment is necessary.

Peer pressure is undoubtedly at the root of why basic research tends to die when it is dispersed. Joseph Henry, in his first presidential address to the Philosophical Society of Washington,[12] noted that "Man is a sympathetic being, and no incentive to mental exertion is more powerful than that which springs from a desire for the approbation of his fellow men." With this observation in mind, it becomes clear that a basic research program cannot

be reliably sustained if freedom to explore is assigned only to selected research scientists dispersed throughout an institution: the research scientist's associates (and especially his supervisor), concerned mainly with current technology, tend to look askance at fundamental studies whose practical payoffs (if any) lie far in the uncertain future. And even engineering colleagues who applaud the principle of basic research exert more or less subtle pressure to redirect the research into areas they view more favorably. (Many people seem to think that a basic scientist changes fields as readily as a suit of clothes.) Relatively few basic researchers can accommodate to an atmosphere in which implementing an application is of prime importance to the immediate peer community. Indeed, pioneering scientists, like frontiersmen, tend to be misfits in a too settled environment where their spirits often clash with those of their near neighbors.

The early origins of the Research Center illustrate the significance of this principle at APL. The Center was established in April 1947. Its professional staff was initially comprised of a Research Council constituted from many of the best qualified and most highly motivated scientists at the Laboratory. They defined and carried out a program of fundamental research reflecting the difficulties and opportunities uncovered by their work on applied tasks. Since the research problems grew from ongoing task problems, conflicting peer pressures were minimal and basic studies flourished.

This early state changed rapidly, however. Soon some investigators, who had intended to carry on part-time basic research, found their technological activities pressing and discontinued their basic research. Others, who had intended to carry on their technological activities part-time, found basic research irresistible and discontinued their technological work. Thus occurred the initial separation between "settlers" and "frontiersmen".

Predictably, since fundamental research tends to raise more questions than it answers and since the "frontiersmen" cannot long resist exploring new terrain, the basic researchers in various parts of APL began to lose close intellectual touch with their more technologically occupied colleagues. In short, the researchers found that they had more in common with each other than with their parent groups. It was seen to be time to consolidate physically the basic research activities. This was done in September 1948 when a wing of the Laboratory's Silver Spring building was assigned to the Research Center.

Dr. McClure was appointed the first full-time chairman of the Research Center on April 12, 1948, when it had a complement of 38 people. He continued to lead the Center as its chairman until 1972, when he elected to devote himself fully to the office of Deputy Director of APL. At that time, the complement of the Center had grown to 62. Dr. Hart, who was appointed to succeed him, has served since as chairman of the Center and more recently also as the Laboratory's Assistant Director for Exploratory Development.

Perhaps the most idyllic appeal of academia is the principle of freedom to pursue research of one's own choosing; attention was devoted to ensuring that the administration of the Research Center followed academic practices to nurture this freedom. Accordingly, the Center was initially organized along horizontal lines: independent investigators, with their assistants, worked singly or in collaboration on research problems initiated by themselves and were responsible for managing their own laboratories. The chairman of the Center supplied necessary administrative arrangements and, supported by a "Committee on Research," provided critical judgment, provoked self-criticism, and fought for funds and facilities.

Subsequently, groups were formed whose leaders took over the role of the Committee on Research and assumed many of the duties of technical administration. Each researcher recognized that his interests should be related to the applied science activities of the Laboratory. It was decided as a matter of policy that the fields to be encouraged initially would be aerodynamics, molecular physics, electromagnetics, and high-altitude research.

Later, many new areas of research were pursued. This rare support of individual initiative led inevitably to an extraordinary diversity of expertise in the Research Center.

RESPONSIBLE RESEARCH FREEDOM

However, this degree of research freedom was not maintained totally, partly because of federally imposed restrictions on funding, partly because size limitations constrained work to subcritical mass levels of effort, but especially because such research freedom tends to lead researchers too far away from consciousness of Laboratory concerns. Such concerns are essential to the Research Center because its life depends ultimately on APL's perception of its value. (Many research centers elsewhere died as soon as they were perceived to be liabilities by the organizations that supported them.) The Center has always been regarded as valuable to APL; this perception must be maintained by continuing to foster ties to other units of the Laboratory and to their problems.

On the other hand (as has been discussed), basic research also dies when tied too closely to technology, so it is necessary to guard with sensitivity the coupling between the Research Center and the other units of the Laboratory. Thus, the chairman and group leaders of the Center tactfully stimulate consciousness of APL concerns so that explorations are channeled into areas of value to the Laboratory, while at the same time preserving responsible freedom of choice. This is facilitated by the fact that the Research Center's chairman is a member of the Director's Program Review Board, of the

Advisory Board, and of other committees; by seminars; and by fostering interactions at the working level between Research Center scientists and scientists and engineers throughout the Laboratory. One measure of success is that this year almost all of the professional staff of the Center are spending some part of their time working with other divisions of APL or with the University.

PROGRAM AND PLANS

And we must be prepared, always, to enter new fields of scholarship, for nothing is so inevitable as change; we cannot know into what areas of research and education the needs of tomorrow may lead us.

Milton S. Eisenhower

from "The Future of Johns Hopkins," the *Johns Hopkins Magazine* **VIII**, No. 7, p. 10, (1957)

The previous sections sketched the emergence of the Research Center, discussed some of the reasons that the Center is maintained, and illustrated in a rather general way the nature of some of its activities. The central purpose of this section is to outline from a more technical viewpoint the ongoing research program and to show how its elements relate to the Laboratory and its future.

The focus of every program element relates broadly to well-documented Navy or other DoD research requirements, because APL tasks are primarily in such areas and because IR&D funds from those sources can only be used to support such work. Nevertheless, there is extensive overlap at the basic level between DoD and civil needs, and each program element is also important to topical concerns in energy, environment, or health.

The Center's activities are organized into eight groups, each having an IR&D core-area project and, in addition, ancillary projects for sponsoring agencies or other divisions of the Laboratory. The present focal areas of the groups are indicated in Fig. 7, along with relationships to several of the directly funded projects that have already been noted (cf. Tables 2 and 4). However, intergroup boundaries are very permeable. Intergroup activities are the rule rather than the exception; the research horizon for the individual scientist is much broader than the compartments of the organization chart suggest. Each group is strengthened by others and thus approaches the critical mass levels of effort that are thought necessary to have scientific impact.

THE PHYSICS OF WAVES

Because of the small size of the Theoretical Physics Group, its research is necessarily confined to only a few areas. The current focus is on theo-

THEORETICAL PHYSICS (RTP)	QUANTUM ELECTRONICS (RQE)	APPLIED MATHEMATICS (RAM)
New methods in wave physics	**Materials science**	**New methods in partial differential equations**
• Variational-stochastic scattering theory (IR&D) • Scattering in cornea (NIH) • Light beating spectroscopy (NIH) • Scattering & absorption of chaff (Army)	• Transition metal oxides (IR&D) • 1-dimensional conductors (NSF) • Electrolyte interfaces (ONR) • Ternary oxides (OSR)	• Fundamental solutions for stratified fluids (IR&D) • Stratified fluid, initial value, free boundary problems (ONR) • Channel flows (NIH)
CHEMICAL PHYSICS (RCP)	**SOLID STATE PHYSICS (RSS)**	**MICROWAVE PHYSICS (RMP)**
Heterogeneous chemistry	**Disordered semiconductors (vacuum-deposited films)**	**Radiation chemistry, Photochemistry, & Spectroscopy**
• Fundamental mechanisms in gas-solid chemistry (IR&D) • Many-body perturbation theory (NSF) • Gas leak detection (GRI)	• Fundamental mechanisms in disordered semiconductors (IR&D) • Amorphous silicon solar cells (DOE)	• Fundamental mechanisms of radiation effects on membranes & thin films (IR&D) • High resolution spectroscopy of porphyrins (NIH)
EXCITATION MECHANISMS (REM)		**ELECTRONIC PHYSICS (REP)**
Optical physics Laser applications, ophthalmic optics		**Surface science atomic, molecular & electronic physics**
• Retinal laser damage mechanisms (Army) • Ocular photography research (National Eye Institute, NEI) • Heterogeneous chemical laser mechanisms (IR&D) • Holographic stress testing of surgical cornea (NEI) • Ruby laser (glaucoma studies) (NEI)		• Fundamental mechanisms of physical & chemical processes at surfaces & interfaces (IR&D) • Corrosion, erosion, ablation & catalysis (IR&D)

Fig. 7—Selected activities of the Milton S. Eisenhower Research Center.

retical techniques for dealing statistically with the scattering and propagation of electromagnetic, acoustic, and hydrodynamic waves. This field is basic to many APL activities, but it is currently most strongly coupled to activities of the Fleet Systems Department (which sponsors one postdoctoral research associate and one of whose researchers works half time on the Research Center project) and to the Biomedical Programs Office (members of the group are principal investigators of four medical contracts or grants).

The Research Center's involvement with wave problems dates back to the so-called low-angle beamriding missile problem in 1951, when a Research Center task study group was assembled to explain effects on guidance of the scattering of radar waves from the ocean surface. From that study stemmed the Research Center's Theoretical Physics Group, whose direction changed with time, especially when Drs. Guier and Weiffenbach transferred to satellite activities to pursue their pioneering investigations of satellite Doppler tracking.

By 1957, the importance of solid propellant rockets for military and space applications was becoming evident. Combustion instability became a matter of great concern because its underlying principles were not well understood and because its effects were often catastrophic. Dr. McClure led a DoD panel to develop the needed understanding, and the group participated with him in the work of the panel. Drs. McClure and Hart, with the support of other members of the group, succeeded in developing the basic theory of the coupling between acoustic waves and propellant combustion.[13] The results were of notable value both practically and scientifically. The major practical result was a method of testing the stability (or instability) of potential rocket propellants; after 1964, only propellants that passed this test were used for large-scale development. The major scientific result was a comprehensive theory that explains how and why the dynamic pressure dependence of solid propellant combustion can amplify acoustic (pressure) waves in a rocket chamber and thereby lead to combustion instability. The work was recognized by the presentation of the Hillebrand Award of the Chemical Society of Washington to McClure in 1961 and of the Distinguished Young Scientist Award of the Maryland Academy of Science to J. F. Bird (of the group) in 1963.

Subsequently, the basic theory of the scattering of light in the cornea was developed to explain how corneal transparency depends on the spatial distribution of its collagen fibrils.[14] More recently, the group has pioneered in developing new techniques to treat the propagation and scattering of electromagnetic and acoustic waves.[15]

The core of the current wave physics activities of the Research Center lies in developing variational techniques and in verifying their value through proof-of-principle application.[16] The Army's Research Office and Chemical Systems Laboratory will support a substantial fraction of this work over the next few years.

The work's scientific significance lies in developing improved methods to understand how waves are affected when they are incident on surfaces or clouds of particles. For example, the complex configuration of the ocean surface disperses radar beams incident from above and sonar beams incident from below. Since the amplitudes, phases, and directions of propagation of the ocean surface waves are not ordinarily known, it is necessary to use statistical methods to predict and understand their effects. Many of these are complex and difficult to unravel by either experiment or theory.

From the theoretical standpoint, all except the most trivial problems require approximation methods; previously developed methods suffer from important deficiencies that generally limit their use to scattering elements that are either very large or very small compared to the wavelength of the incident wave. There is, therefore, a large and important gap.

Variational methods offer an approach to closing this gap, but as previously developed they are intractable in evaluating statistical averages. The group has made considerable progress in formulating a variational method that is statistically tractable. Although the method is mathematically complex, its variational aspects are both interesting and readily understood.

The generic scattering problem is to determine how a plane wave is dispersed by a rough surface. The answer can be formulated in terms of a sum of scattering contributions from points on the surface, but the scattering from each depends on the local field. Expressing this field exactly is not ordinarily feasible even for nonstatistical surfaces. The error in the desired scattered field depends, in general, on the first power of the error in approximating the surface field. The central idea of the variational method is to improve accuracy by recasting the answer in such a way that all first-power errors cancel.

Figure 8 suggests the efficacy of the variational method by comparing the exact solution for a simple (nonstatistical) rough surface with that obtained using the conventional long wavelength perturbation approximation (for the surface field) and with the variational solution using the same approximate surface field. The nominal limit of validity of the conventional long wave approximation corresponds to $2\pi a/\lambda \lesssim \pi/10$. For the upper left-hand plot, $2\pi a/\lambda = 0.4$, the result is clearly in error, whereas the variational solution is evidently indistinguishable from the exact solution. The other two plots indicate that the variational method significantly extends the useful range of the surface field approximation and makes it readily possible to predict and interpret scattering from con-

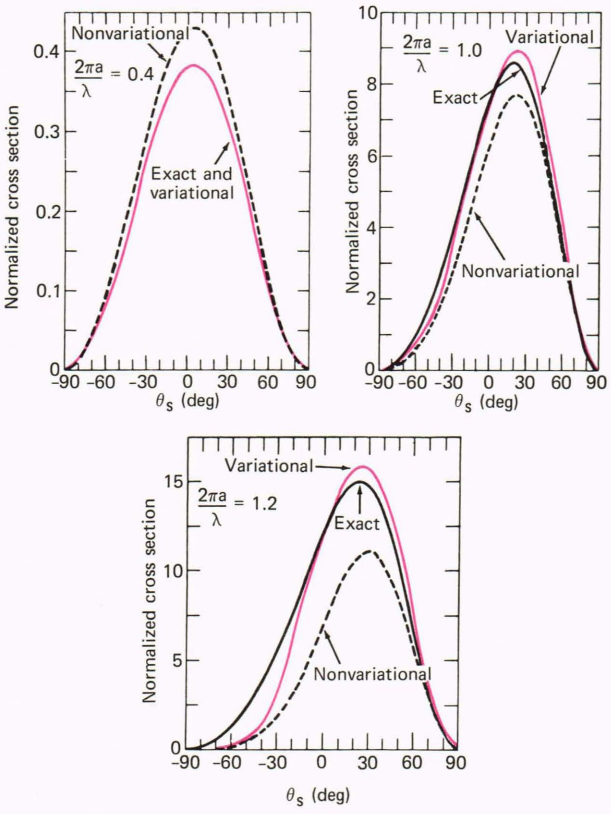

Fig. 8—Scattering cross section versus angle of scattering (θ_s) for a plane wave incident at 45° on a rough surface consisting of one hemicylinder of radius a on a perfectly conducting plane. As indicated, the three figures show the results for three wavelengths (λ) corresponding to $2\pi a/\lambda = 0.4$, 1.0, and 1.2. Scattering of waves from a hemicylinder on a plane is of interest for testing approximate theories because it is one of the few rough-surface problems that can readily be solved exactly. Illustrated here is the efficacy of using variational invariance to extend the range of validity of conventional first-order perturbation theory.

siderably rougher surfaces than has heretofore been possible.

The mathematical development by which the group has recast the conventional variational method so that necessary statistical averages can be carried out is highly technical. One of the significant early results is that even for very long wavelengths, where the first order perturbational result is usually thought to be correct, it differs from the variational result. The source of this discrepancy is that the first-order perturbative result does not include multiple scattering whereas the variational result does. (This has been confirmed in detail through an exact analysis that has recently been carried out for the case of two statistically distributed hemicylinders.) Multiple scattering is notoriously difficult to treat, so the fact that the variational method approximates its effect is of considerable interest.

In summary, the long-range objective is better understanding of wave scattering and absorption by random rough surfaces or from randomly dispersed objects, to form a basis for improved radar, sonar, altimeters, and communications systems. Initially, the approach is to apply our statistical variational method to scattering problems whose solutions have been approximated by other methods in order to extend ranges of validity and develop new insights.

Other current activities of the group are related to the Biomedical Program Office, to the Submarine Technology Division, and to the Space Department. It should also be acknowledged that other Research Center groups assist in the biomedical projects and that waves are also involved in such projects of other Research Center groups as the mathematical theory of hydrodynamic waves, photoacoustic spectroscopy, microwave effects in membranes, and the propagation of viscoelastic waves.

SURFACE SCIENCE

The central research area of the Electronic Physics Group is surface science and, in particular, the study of the physical and chemical processes occurring at surfaces and interfaces. At the high temperatures and in the reactive environments encountered by missiles, rockets, and reentry vehicles in high-speed flight, materials are subjected not only to a variety of corrosion mechanisms, but also to the actions of erosion and ablation. There is an increasingly important need for fundamental understanding of the physics and chemistry underlying these phenomena, especially in connection with components of future hypersonic air-breathing missiles of concern to both the Aeronautics Division and the Fleet Systems Department (e.g., radomes, windows, nozzles, and combustion chamber liners) and in connection with a variety of reentry problems of concern to the Strategic Systems and Space Departments.

Historically, the group had its origin in 1947 in one of the first programs undertaken in the Research Center, "Kinetic Studies with the Mass Spectrometer," which reflected APL concerns with missile propulsion and guidance and, especially, with understanding the detailed chemistry of combustion processes. The group, under the supervision of S. N. Foner, was subsequently designated the Mass Spectrometry Group in 1948 and became involved in studies of ionization by electron impact, detection of free radicals, and reaction kinetics. A modulated molecular beam mass spectrometer with a collision-free sampling system was invented and constructed to permit the study of highly reactive transient species. The hydroperoxo (HO_2) radical was one of many free radicals first detected and characterized here;[17] the definitive research that followed has received international recognition. For pioneering research on the mass spectrometry of flame constituents, particularly the HO_2 free radical, Dr. Foner was awarded the 1954

Physical Sciences Award of the Washington Academy of Sciences. (See the article on pp. 35-37.)

A significant extension in the core area of the group occurred in 1955 when it was decided to explore the technique of electron spin resonance (ESR) for studying free radicals trapped in solid matrices at low temperatures. The idea was that highly reactive atomic or molecular free radicals, which ordinarily have short lifetimes (milliseconds), could be deposited and immobilized in a nonreactive molecular matrix at low temperatures, such as that of liquid helium (4.2 K), so that they could be studied at leisure. In collaboration with C. K. Jen, who was then supervisor of the Microwave Physics Group, a number of critical experimental problems were overcome, and the technique became a very effective means for identifying free radicals and determining their properties.

Among the group's first successes was the trapping of hydrogen atoms in a molecular hydrogen matrix at 4.2 K. This evoked considerable technological interest because it was generally recognized that, if a large enough concentration of hydrogen could be stored in a molecular hydrogen matrix, the subsequent energy release on recombination of the atoms would make it into an ultrahigh energy fuel for rocket propulsion. Although major attempts were made at several laboratories to obtain high concentrations of stored atomic hydrogen, the ESR measurements at APL clearly established that the then-available techniques for hydrogen atom stabilization would be unable to produce satisfactory yields for propellant applications. A large variety of atomic and molecular free radicals have since been investigated at APL by ESR, giving important information on the magnetic hyperfine interactions in the free radicals, the molecular geometry of the free radicals, and the forces that the matrix environment exerts on the trapped radicals.

Recently, mass spectrometric measurements were made[18] to redetermine the heat of formation of diimide (N_2H_2) in response to renewed attention to it at other institutions. Diimide, the first member of the azo compounds, is a short lived and highly endothermic compound whose existence was established in experiments at APL two decades ago. Because diimide is an important intermediate in many chemical reactions, considerable attention has recently been focused on its chemical, spectroscopic, structural, and thermodynamic properties. The heat of formation of a compound is one of its most important thermodynamic properties because it appears in the energy balance equation that determines whether a reaction can occur. Theoretical calculations of the heat of formation of diimide have ranged from 10 to 70 kcal/mole. In the original experiments that identified the molecule, the heat of formation was found to be 48.7 ± 5 kcal/mole. Although very few direct measurements have been made, a recent experimental study elsewhere yielded a value of 36 ± 2 kcal/mole. This prompted a reinvestigation with greater precision than was previously available.

The method used for determining the heat of formation of diimide involves measuring the ionization potential of N_2H_2 produced by an electrical discharge in a high-speed stream of gaseous hydrazine (N_2H_4), and the appearance potential of the $N_2H_2^+$ ion in the reaction $N_2H_4 + e \rightarrow N_2H_2^+ + H_2 + 2e$. From these two measurements and the known heat of formation of hydrazine, it is a straightforward procedure to obtain the heat of formation of diimide.

Figure 9 shows the ion intensities of $N_2H_2^+$ from N_2H_2 and of $N_2H_2^+$ from N_2H_4 as a function of electron energy, after deconvolution to remove the effects of thermal energy spread in the electron beam. The measured ionization potential of N_2H_2 is 9.65 ± 0.08 eV, in good agreement with the most recent photoelectron spectroscopic value, 9.59 eV, which lends confidence in the experiment. The appearance potential of $N_2H_2^+$ from N_2H_4 is 10.75 ± 0.08 eV. These measurements lead to a value for the heat of formation of diimide at 298 K of 50.7 ± 2 kcal/mole, which is in excellent agreement with the results of our earlier study and in good agreement with recent theoretical calculations.

In recent years, there has been a reorientation of the core research area of the group toward surface science. This has resulted largely from two factors: (a) a recognition that, while the properties of surfaces play dominant roles in the use of materials, our knowledge about the fundamental processes taking place at surfaces is limited; and (b) the influx of new experimental methods, such as scanning electron spectroscopy, Auger electron spectroscopy, and secondary ion mass spectrometry, coupled with ultrahigh-vacuum techniques, permits definitive experiments to be carried out. An ultrahigh-vacuum scanning electron microscope with an energy-dispersive X-ray analyzer for ele-

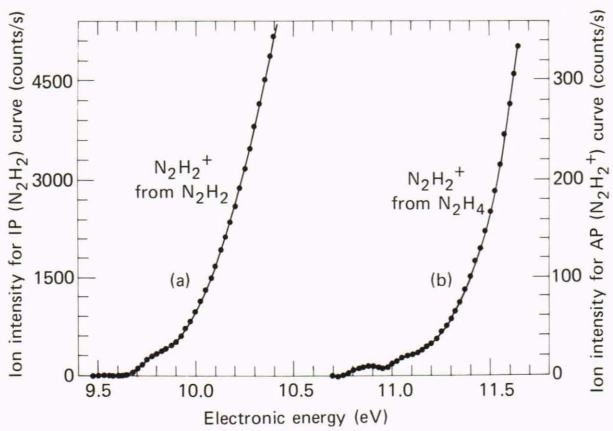

Fig. 9—Initial portions of (a) the ionization curve for N_2H_2 and (b) the appearance potential curve for $N_2H_2^+$ from N_2H_4. The electron energy scale has been standardized using argon.

mental analysis was placed in service in 1975. In addition to carrying out research for the group, the instrumentation is now widely used for analysis by other divisions of the Laboratory (as well as by other groups in the Research Center). Among the first published results using the scanning electron microscope were studies on localized corrosion in aluminum[19] in which a hitherto unknown step in pitting corrosion of aluminum was reported. To study the outer few atomic layers of a surface, an Auger electron spectrometer with a low-energy electron diffraction accessory was acquired in 1978. With other instrumentation already in service or available, the Research Center is now well equipped for fundamental studies of surface physics and chemistry.

The overall objective of the research program is to understand the physical and chemical processes that occur at surfaces and interfaces, with the aim of acquiring a more rational basis for enhancing the use of existing materials and the development of new materials with superior properties. The major thrust of the program involves experimental and theoretical studies of corrosion, erosion, ablation, catalysis, and molecular beam reaction and scattering from surfaces. Techniques that have been effectively applied at APL to study excited state molecules and other unstable intermediates in gas phase reactions will be used to study the reactions of atoms and molecules with surfaces.

Other activities (and sponsors) of the group include theoretical support for the acoustic detection of leaks in underground natural gas distribution networks (Gas Research Institute), experimental support for cornea damage (Army), research on the correlation of arterial hemodynamics and morphology (NIH), and SEM/X-ray microanalysis studies for many other divisions of the Laboratory.

RADIATION CHEMISTRY

The central research area of the Microwave Physics Group is the study of electromagnetic field interactions with matter. Although many such interactions are basic to much of the Laboratory's technology, the small size of this group requires that its research be focused on a small area. The current emphasis is on understanding basic mechanisms underlying the biological effects of electromagnetic fields. Since much of the Laboratory's work is rooted in microwave engineering, it is to be expected that the Research Center would carry out research in microwave physics and, as other parts of the spectrum become increasingly important to Laboratory programs, in infrared and optical physics as well. Many scientific contributions have been made to the understanding of the interactions of radiation with materials. These contributions are important to generating, propagating, and detecting radiation, and also, since radiation may be viewed as a probe, to understanding atomic and molecular structure. A few of these contributions are mentioned below.

Microwave research began in the Research Center in 1949 with experimental studies of interactions of microwaves with solids (dielectric constant and magnetic permeability studies) and with gases (Stark and Zeeman effects). Numerous significant early discoveries were made. For example, in illuminating the isotopic origin of numerous spectral lines, more than 100 lines of the spectrum of deuterated hydrogen peroxide were observed in 1953.

Subsequently, emphasis shifted to microwave interactions in solids and in particular to the so-called "color centers" of alkali-halide crystals. A microwave resonance study of potassium chloride F-centers confirmed the results of earlier work, but results for F-centers in lithium fluoride differed greatly. Controversy persisted for several years until the APL results became generally accepted through corroboration by several other workers. Subsequently, the experimental research was extended to other alkali-halides, and a comprehensive theory was developed that is now a standard reference in the field.[20]

More recently, the research has emphasized photochemistry, particularly the structure of noble gas monohalides (of interest with respect to tunable ultraviolet lasers, for example) and the spectroscopy of porphyrins[21] (of interest with respect to oxygen transport in blood and in photosynthesis, for example). It has led to numerous contributions to the scientific literature. Recent effort also has been devoted to chemically induced magnetic polarization, with particularly notable results.

Chemically induced magnetic polarization (CIMP) is the name given to the phenomenon in which chemical reactions produce nonequilibrium distributions of nuclear spin states of the diamagnetic products and reactants and of electron spin states of the free radical intermediates. Electron spin polarizations are extremely important to chemical reactions because only oppositely polarized electrons can form chemical bonds; nuclear spins are important because of their interactions with the electron spins. Thus, the magnetic interactions between the spins are intimately involved in chemical reactions. Nuclear spin states are often relatively long lived and readily observable by microwave resonance techniques. Accordingly, CIMP provides a tool for studying very rapid reaction steps that are not otherwise accessible. Among the most intriguing of these are the as yet unknown steps in photosynthesis. Since 1970, F. J. Adrian, supervisor of the group, has played a prominent role in developing the theory. The status of the field is described in his recent comprehensive review articles prepared and published in conjunction with invited lectures at the 1977 NATO Advanced Study Institute on chemically induced magnetic polarization.[22]

For quite some time, it was generally believed that the so-called radical pair mechanism was solely responsible for the abnormal polarization. (The radical pair mechanism describes the interplay between electron-spin-dependent chemical bonding interactions between two radicals.) However, it became clear that a number of photolytic reactions could not be explained satisfactorily by the radical pair mechanism, so a new theory was developed. This theory, the triplet mechanism, begins with electron-spin-selective singlet-triplet intersystem crossing of a photoexcited molecule. Whether or not the initially excited singlet state transfers most of its energy to a lower-lying triplet state can be very important because radiation deexcitation to the singlet ground states is forbidden. Thus, triplet states tend to be long lived and can be responsible for reactions that would otherwise have little opportunity to occur. Subsequent reaction of the triplet yields a pair of electron-spin-polarized radicals; their electron spin polarization is subsequently transferred to their nuclear spins by electron-nuclear cross relaxation.

The triplet mechanism is illustrated here for a simple case analogous to various photochemical processes, including photosynthesis: the photochemical reaction of tetrafluoro 1, 4-benzoquinone with the corresponding hydroquinone yielding semiquinone radicals that react further to ultimately regenerate the original quinone. The triplet mechanism as described by the steady-state solution of the rate equations corresponding to these reactions agrees rather well with experimental data (Fig. 10), whereas the radical pair mechanism does not.

The new core project having to do with electromagnetic effects on membranes and thin films derives mainly from three considerations:

1. The increasing concern about the biological effects of microwaves and the consensus that the effects must be understood at the level of membranes,
2. The paucity of effort being devoted to the problem elsewhere and the fact that it is a very difficult and multidisciplinary challenge that relatively few investigators are properly equipped to accept, and

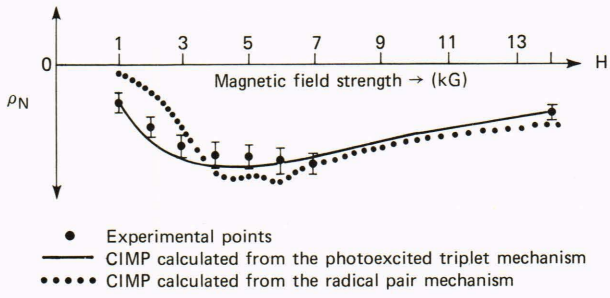

Fig. 10—Field-dependent CIMP intensity (ρ_N) of tetrafluoro, 1, 4-benzoquinone photoreacting with the corresponding hydroquinone.

3. The varied experience and interest that Research Center scientists have in elucidating the interactions of radiation with fundamental structures.

The proposed research is directed toward improved understanding of absorption and dissipation of electromagnetic radiation in complex molecular systems, with emphasis on the relationships with molecular structure and the nonthermal effects of nonionizing radiation. The initial approach is to apply electron spin resonance, nuclear spin resonance, and optical spectroscopy to study the effects on synthetic model membranes and thin films selected for their systematic resemblance to important biological/chemical systems. These techniques, combined with spin labeling and theory, can study effects that have been implicated by previous studies elsewhere, e.g., on membrane permeability and on molecular structure and stimulated charge transfer.

Other group activities include the continuation of an NIH-sponsored project on spectroscopy of porphyrins that began in 1975 and collaboration on directly funded projects of the Chemical Physics and Quantum Electronics Groups.

HETEROGENEOUS CHEMISTRY

The central responsibility of the Chemical Physics Group is the development of basic understanding in areas of chemical physics that are of concern to present and future tasks of the Laboratory. The new core project in heterogeneous chemistry is aimed toward the fundamental physical and chemical mechanisms that govern behavior at the interface between flowing gases and solids. Its genesis lies primarily in a recent series of discussions with leaders in other divisions of APL, discussions that looked at long-term problem areas and how the available talents and facilities for basic research in chemical physics could be most helpful.

From these discussions (and from reference to numerous DoD planning documents), it became apparent that a most exciting challenge, and one that impacted on several Laboratory divisions, stemmed from increasing concern with effects (such as ablation) caused by hypersonic gas flows over surfaces. It also appeared that, whereas an impressive array of technological talent and facilities would be devoted to the problem by other institutions, relatively little attention to this aspect of surface science was in evidence on the part of basic scientists. Since Research Center scientists have a record of achievement in closely related disciplines, and since the chemical physics of surfaces is a most active scientific frontier, the decision was made to move in this new direction.

Since its early days, APL has been intimately involved with supersonic missiles and with chemical physics. This involvement first began with rockets. Rocket propulsion was largely a new field in this

country, and there was much interest in its problems and potential on the part of APL chemists. Technology moved rapidly, however. By the time the Research Center was established, scientific interest had definitely shifted to supersonic ramjets and the means of reconciling efficient combustion with high-velocity flow fields. Accordingly, projects in mass spectrometry, flame spectroscopy, and chemical kinetics were among the first to be included in the Research Center's program. These three projects went separate ways, mass spectrometry developing mainly in the Electronic Physics Group and optical and infrared spectroscopy in the Excitation Mechanisms Group. The Chemical Physics Group, with a focus in chemical kinetics, was established in 1963 under Dr. Westenberg's supervision. This short glimpse into history must unavoidably overlook many well recognized contributions made to science through published researches and through service on numerous committees and editorial boards. But it will be recalled in passing that Drs. Westenberg and Fristrom pioneered in developing accurate methods for quantitative analysis of combustion processes and determination of chemical kinetic rate constants. Among notable milestones are their book, "Flame Structure",[23] and the Hillebrand Award of the Chemical Society of Washington that they received in 1966.

When Dr. Westenberg retired in 1977, D. M. Silver was appointed supervisor of the group. Since joining the Research Center in 1970, he made notable contributions (with collaborators here and at several other institutions) to understanding chemical reactivities in terms of underlying molecular structure and mechanism by incorporating electron-electron interactions into a rigorous quantum mechanical framework and by using the framework to establish new physical insight. First, a new approach to the problem of electron correlation was developed by expressing the total electronic wave function in terms of a product of pair functions, each giving a correlated description of the interaction between different pairs of electrons. Later, after original studies illuminating the hydrogen-deuterium exchange reaction, methods of group theory were explored to examine symmetry effects on chemical reaction and to provide a firm theoretical and conceptual basis for well-known symmetry rules of organic chemistry.[24]

Beginning in 1974, an extensive theoretical program was initiated (with colleagues at several other institutions and with National Science Foundation support) in the application of many-body perturbation theory to determine the electronic structure of atomic and molecular species and to develop understanding of their properties and reactions.[25] The work has resulted in more than a score of publications during the past three years. They demonstrate very high accuracy in the calculation of correlation energies, the importance of taking proper account of three- and four-body electron interactions, the concept of universal atomic orbital basis sets, and the extension of the perturbative approach to chemical reactions.[26] The program has also led to important new computer techniques that make the evaluation of electron correlation effects readily obtainable for certain classes of systems. Dr. Silver has recently been elected to membership on the first executive committee of the User Association of the National Resources for Computation in Chemistry.

Other recent activities of the group include quantum mechanical calculations that yield new understanding of the dynamics and corresponding cross sections of atom-diatom (e.g., helium-carbon monoxide) collisions,[27] including, for example, rotational state depolarization cross sections, which are important to laser operation. Other scattering calculations, including *ab initio* prediction of transport properties of hydrogen at low temperature, are being carried out in collaboration with the Max-Planck Institut für Physik und Astrophysik.

Another significant recent project of the group is a study of the collisional deactivation of singlet excited molecular oxygen in which J. Stricker, here on sabbatical from the Technion-Israel Institute of Technology, assisted.

The core research objective is to develop and verify a detailed description of the kinetics of oxygen/graphite surfaces, which involves a unified theoretical and experimental attack. The theoretical task, which is to create a general model that allows for gas flow, reaction, absorption, energy transfer, and radiative excitation, will be approached using interaction potential, molecular scattering, statistical, mechanical, and fluid mechanical procedures. Experimental projects are designed to guide and verify critical elements of the model.

Further activities of the group include the leak detection project[28] sponsored by the Gas Research Institute, with assistance from the Microwave Physics and Electronic Physics Groups as well as other units of APL and JHU, and computer programming assistance to other Research Center groups and to other divisions of APL.

SOLID STATE PHYSICS

The core research of the Solid State Physics Group is in semiconductor physics, with emphasis on vacuum-deposited crystalline and noncrystalline materials. Work in several areas of solid state physics was initiated in the Research Center immediately after it was established, as has been noted in the discussions of several other activities. Here, however, attention is directed specifically to semiconductor physics.

It will be recalled that, in the early 1950's, transistors emerged abruptly into a world of practicing engineers who had been trained in vacuum tube technology. The shift of semiconductors out of the scientific area into engineering practice challenged the ability of establishments like APL to make the

transition. This accommodation was facilitated by several Research Center activities. At that time, the Research Center carried out investigations of transistor reliability and circuit applications. By 1953, the significance of the new devices was apparent, and courses were given by the Research Center to selected members of the APL staff. A comprehensive manual was prepared.

The concern with noncrystalline semiconductors derived primarily from the possibility of using them for high-temperature, radiation-resistant devices. APL scientists were among the first to recognize the potential significance of noncrystalline semiconductors; a pioneering project that began in 1968 was incorporated into the Research Center in 1972 when the present Solid State Physics Group was established under the supervision of C. Feldman. The work has been particularly noteworthy in establishing the importance of very high purity and of measuring and controlling it (Fig. 11). A significant milestone was attained in 1973 with the first demonstration of a technique for successfully processing amorphous silicon films on fused substrates into practical crystalline devices.[29]

Recently, semiconductor research has turned to studies of (a) amorphous boron films, (b) polycrystalline titanium diboride films, (c) the energy distribution of secondary ions generated by ion beam sputtering, (d) somewhat less fundamental studies to develop optical methods for characterizing the electronic structure and degree of crystallization of vacuum-deposited thin films, and (e) a project funded by the U.S. Department of Energy to develop thin film techniques for silicon solar cells. Vacuum deposition of amorphous boron-iron compositions and examination of their magnetic properties (the Mössbauer effect) are being conducted in conjunction with the Quantum Electronics Group. Significant progress has been made in each of these areas.

For example, prior to the group's studies on carbon in boron and to the work elsewhere on hydrogenated silicon, it was generally believed that the electronic properties of amorphous semiconductors could not be controlled by impurity doping (because the amorphous matrix would be able to accommodate the introduction of large amounts of impurities without significant electronic structure effects). However, it was recently shown that the electrical resistivity and the optical properties of

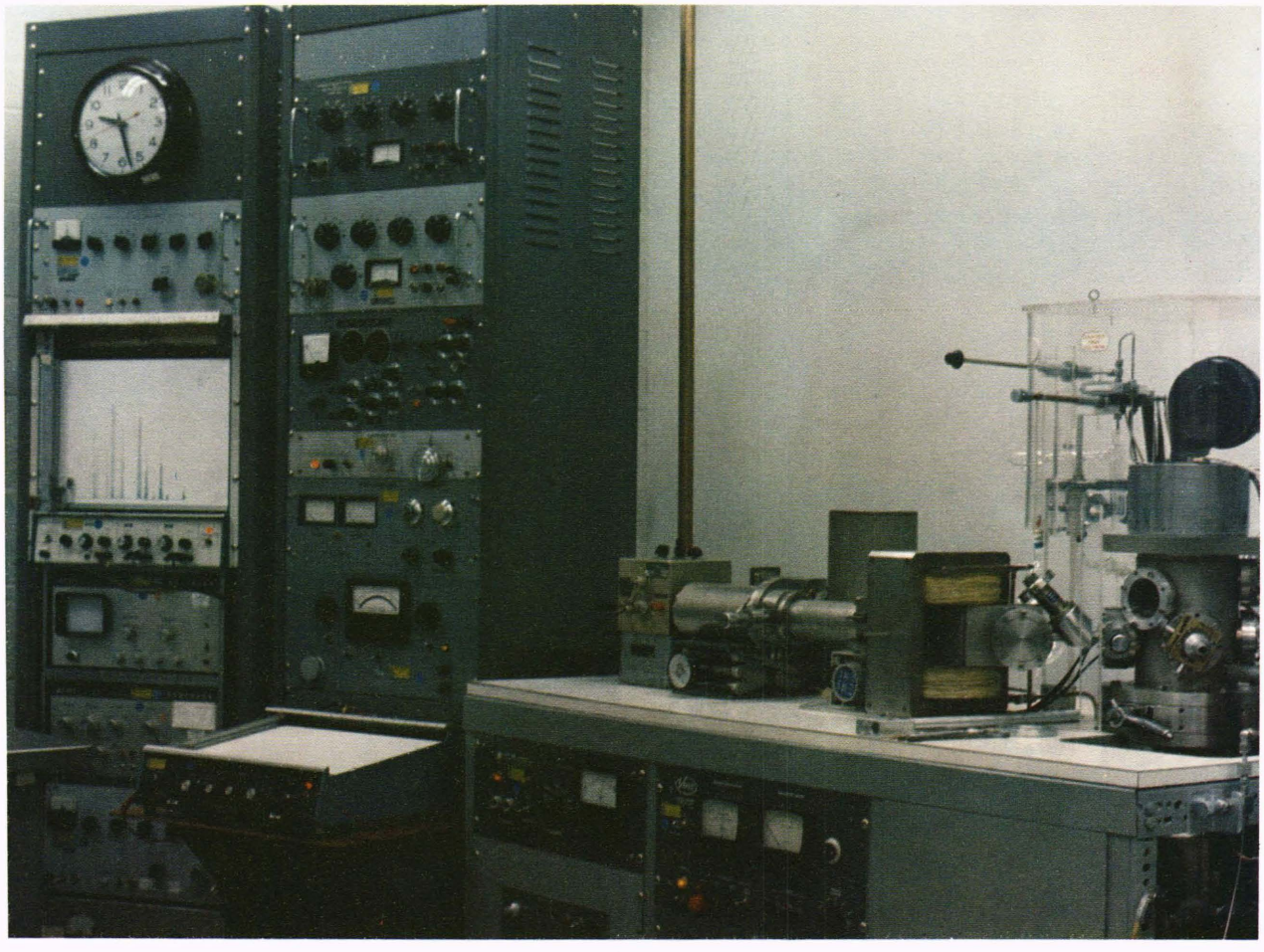

Fig. 11—Secondary ion mass spectrometer. This spectrometer is the key instrument for profiling composition and controlling purity. It can measure in the parts-per-million range, and its unusual "energy window" feature makes it particularly valuable.

amorphous boron thin films can be reproducibly controlled by small amounts of carbon and hydrogen (Fig. 12) introduced during deposition.[30] In conjunction with previous electron spin resonance data showing a decrease in spin density with increasing content of hydrogen (but not carbon), these data have led to a model for amorphous boron that shows a high density of localized levels in the energy gap. The carbon and hydrogen appear to bond to the icosahedral atom groups of the boron matrix in different ways, with the carbon replacing intericosahedral bonds and the hydrogen accommodating dangling bonds on the icosahedra. In both cases, valence electrons tend to be localized so that the resistivity is increased.

The solar cell project addresses the goal of low-cost and efficient solar cells by silicon vacuum deposition techniques. The vacuum deposition approach is particularly attractive because it lends itself to automated mass production methods. There are formidable problems, however, especially with regard to stable and adhesive bottom electrode/substrate combinations and with achieving crystallite grains large enough to yield acceptable efficiency. In this work, solar cells are formed by successive deposition onto a substrate, in vacuum, of a bottom electrode, a silicon layer, and a top electrode (Fig. 13). The cells are evaluated and studied by a variety of techniques including secondary ion mass spectrometry, scanning electron microscopy, and optical and X-ray spectrometry. Recent results indicate that alumina substrates with a titanium diboride electrode will be satisfactory; average silicon grain diameters of 27 μm size have already been achieved, approximating the size that is believed to be necessary for good voltaic efficiency.[31]

The present core project is a continuation of the previous effort to investigate and develop understanding of electronic/structural phenomena in vacuum-deposited thin films. It is conducted with collaboration from the Microelectronics Group of the Engineering Facilities Division, thereby providing a bridge between APL's semiconductor scientists and technologists. Emphasis continues to be placed on new techniques for achieving larger silicon grains. Emphasis is also placed on boron, which does not react with silicon, because of its promise for semiconductor devices able to withstand high temperatures (e.g., titanium diboride melts at about 2900°C), and because little if any work on noncrystalline boron is being pursued elsewhere in this country. Also, further data are being acquired on the energy distribution of secondary ions generated by ion beam sputtering with the ultimate objective of understanding the sputter process and interpreting these data.

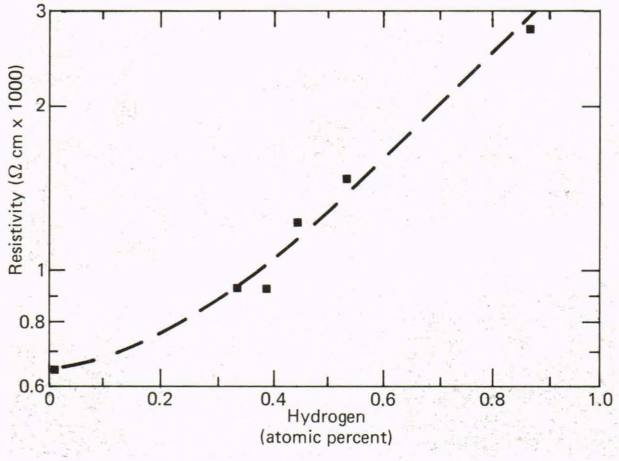

Fig. 12—Resistivity versus hydrogen content in vacuum-deposited amorphous boron film.

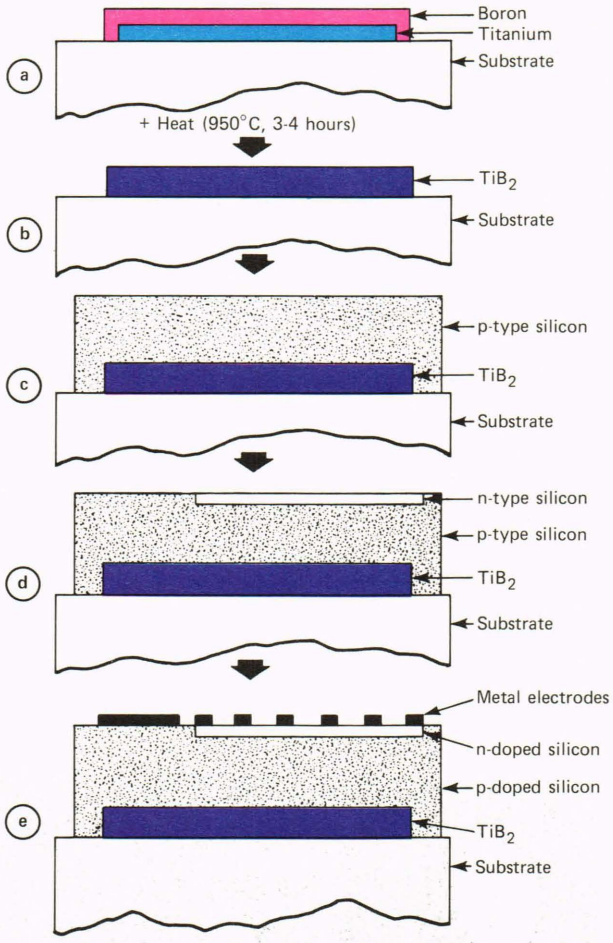

Fig. 13—Vacuum-deposited polycrystalline silicon solar cell. (a) Formation begins with layers of boron (B) and overlying titanium (Ti) on a substrate of alumina. (b) Heating in vacuum reacts the Ti and B to form TiB_2 for the bottom electrode. (c) p-type silicon is then overlaid by co-deposition of silicon and boron at a substrate temperature of ~1000°C. (d) Subsequently, phosphorus is diffused into the upper surface to create an n-p junction. (e) Finally, metal electrodes are deposited to complete the cell. At present, contact to the TiB_2 electrode is made through the p-type silicon layer.

OPTICAL PHYSICS

The central research area of the Excitation

Mechanism Group is optical science. Optical methods have played an important role in solving engineering problems at APL since its beginning; they have become increasingly pervasive with the recent rapid pace of the transfer of optical science to engineering technology. Recent examples include fluorescent tracer techniques in the Submarine Technology Division, in the Biomedical Program, and in the Power Plant Siting Program; optical tracking techniques in the Fleet Systems Department; and laser diagnostic techniques in the Aeronautics Division.

In the early years of the Research Center, optical methods, particularly emission and absorption spectroscopies, were components of numerous projects (e.g., the study of free radicals in flames). However, formation of a group devoted specifically to optical science dates to 1956 when the present group was established. The group's activities emphasized excitation mechanisms of electrical discharges in gases and provided a firm scientific foothold for quick entry into the laser field shortly after lasing was demonstrated elsewhere. Initially, the group made basic contributions in helium-neon laser physics. That work led both to laser applications (e.g., one of the first prototypes of argon laser photocoagulator systems, now widely used in ophthalmology) and to new concepts of chemical reaction pumping. These led to the first demonstration of an efficient deuterium fluoride–carbon dioxide pulsed chemical laser[32] operating at pressures up to one atmosphere (Fig. 14), and later to the first purely chemical laser that operated on relatively safe reactants and products by using sodium-catalyzed combustion of carbon monoxide and nitrous oxide to yield nitrogen and carbon dioxide. Sodium was obtained by thermal decomposition of sodium azide, an approach that matured into the present research in laser-induced reactions at surfaces.

Recently, significant progress has been made in three areas, one relating to the Laboratory's Biomedical Program, another to laser-induced heterogeneous reactions of potential importance to high-energy chemical lasers, and a third to viewing submerged bodies from above the ocean surface.

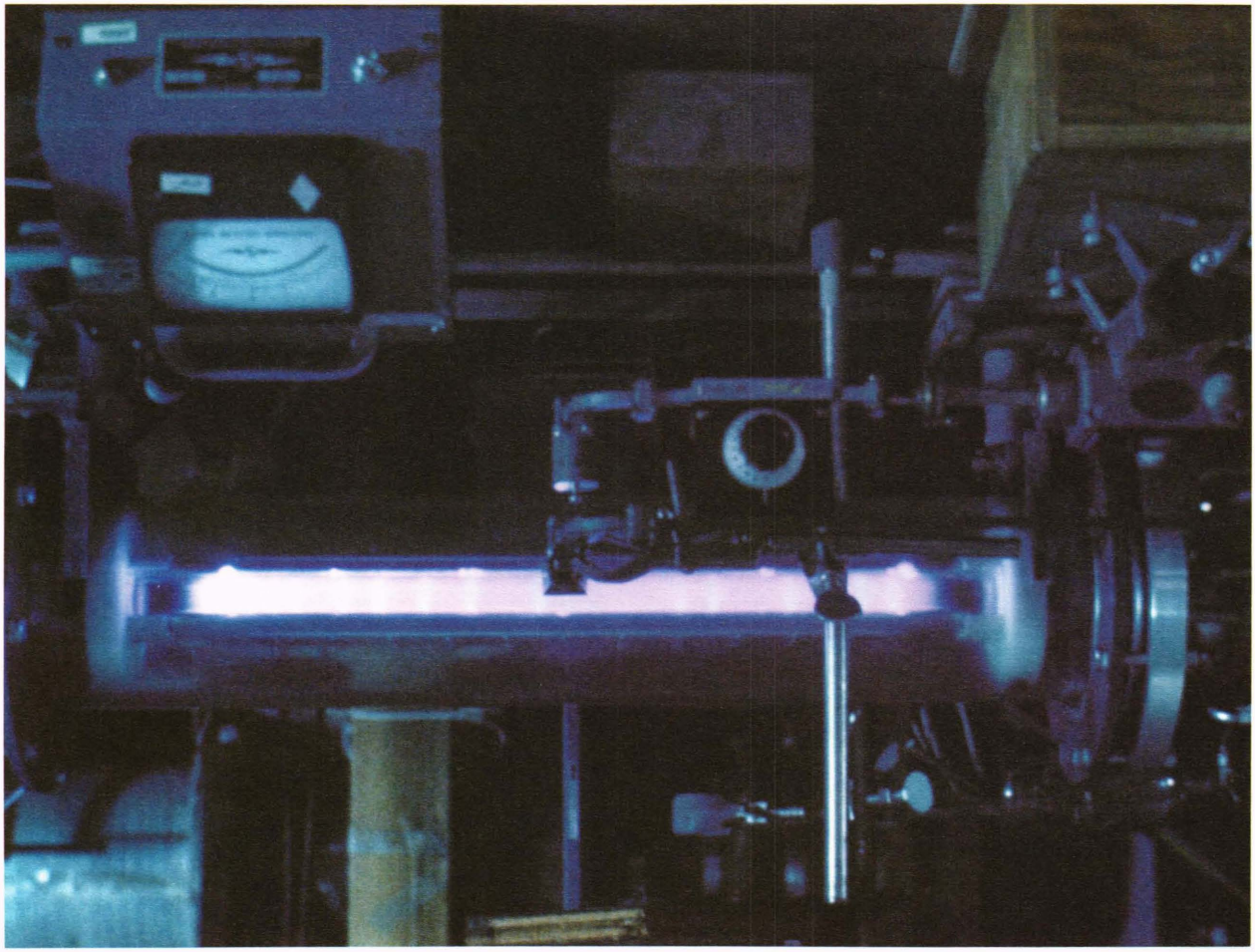

Fig. 14—Pulsed chemical laser. The deuterium fluoride—carbon dioxide pulsed chemical laser has excited wide interest because of its potential for high power. "... Of particular interest are the measurements reported by Poehler et al of The Johns Hopkins Applied Physics Laboratory... These authors have worked with mixtures of D_2:F_2:CO_2:He at pressures up to 1 atm." [T. A. Cool, *IEEE J. Quantum Electronics*, **QE9**, p. 81 (1973).]

Some of the new developments in the first two areas will be sketched below.

The recent biomedical activities of the group are primarily collaborative with JHMI and are NIH- and Army-supported efforts involving optical techniques in the study of the eye. Emphasis is placed on visualizing retinal and choroidal blood circulation by fluorescence methods and on improved photographic and angiographic techniques to document phototoxic retinal damage (damage that can be induced by long exposures to ophthalmic instruments and low-level laser radiation). Among the recent significant technological results are improvements to a Zeiss fundus camera that include a factor-of-two improvement in resolution, as illustrated by Fig. 15.

With respect to the study of laser-induced heterogeneous chemical reactions, scientists of the group recently proposed a new approach to a supersonic flow chemical laser that avoids an important conventional aerothermodynamic problem. In the conventional design, gaseous reactants are introduced separately, rapid mixing is achieved by using supersonic injectors, and the laser cavity is operated at low pressure (10^{-2} atm) in order to achieve satisfactorily short mixing times. But at altitudes below about 10 km, supersonic diffusers cannot achieve atmospheric pressure recovery so that additional pumping is required; this decreases the overall efficiency of the system and increases its weight and size. The new concept avoids the need to operate at low pressure by dispersing a suitable, thermally decomposable powder in a premixed (and unreacting) fuel-oxidizer mixture and by initiating the reaction by radiant heating that decomposes the powder and provides the necessary free radical chain carriers. In work funded primarily by the Naval Sea Systems Command, spectroscopic and gas analysis methods have been used to study the thermal decompostion of several powder-fuel-oxidizer systems including silver difluoride in mixtures of fluorine, hydrogen, and oxygen and also in mixtures of nitrogen trifluoride and hydrogen. In the latter case, for example, radiative decomposition of silver difluoride produces atomic fluorine, which then initiates reactions involving nitrogen trifluoride and hydrogen. Spontaneous emission was observed from vibrationally excited hydrogen fluoride molecules formed during the reaction, indicating that the approach meets the preliminary requirements for a high-pressure laser. The basic mechanisms involved in such reactions are not yet understood in detail and are under study.

The present core activity of the group is an extension of the earlier research in elucidating the fundamental mechanisms of laser-induced reaction and phototoxic retinal damage. The approach to laser-induced reactions primarily involves straightforward techniques of mass spectrometry, gas chromatography, or absorption spectroscopy, measurement of emission spectra (using a multichannel analyzer), and, ultimately, other new and more advanced optical methods. Results are expected to be of value in many applications, such as combustion, chemical lasers, laser-induced damage to materials, and heterogeneous catalysis, and will complement other Research Center activities in surface science and heterogeneous chemistry. Optical techniques, usable in principle at essentially all pressures, ultimately should provide the needed bridge between the conventional low-pressure techniques of surface physics and the conventional higher pressure techniques of chemical kinetics. The approach to phototoxic retinal damage is less well defined because the phenomena are still obscure. However,

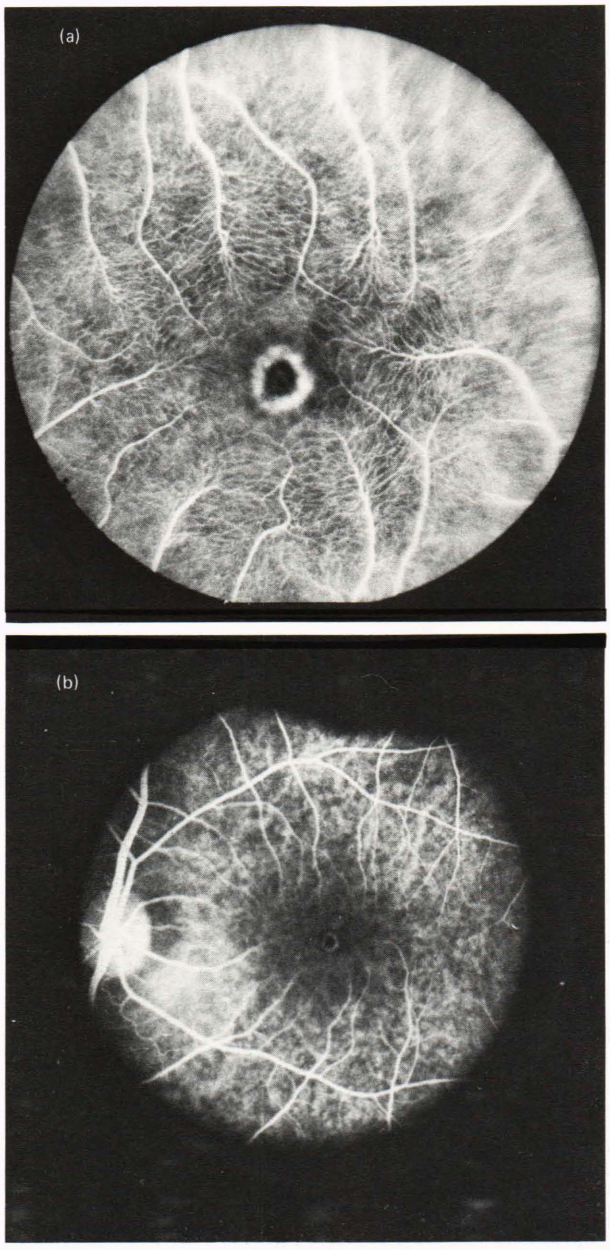

Fig. 15—Photographs showing retinal and choroidal blood circulation as obtained by (a) the high resolution APL-modified Zeiss fundus camera and (b) the conventional camera.

several mechanisms have been postulated, and experiments have been outlined to test a number of them.

Other group activities include sponsored angiographic and retinal projects (Table 2) with collaborators at JHMI and optical technology assistance to other divisions of APL. Other aspects of optical science are involved elsewhere in the Research Center including, for example, the wave physics core project and the NIH-supported porphyrin spectroscopy project.

APPLIED MATHEMATICS

Technology is rapidly becoming increasingly dependent on analytical and numerical techniques for the efficient design, control, and evaluation of engineering systems. The central responsibility of the Applied Mathematics Group is to maintain a strong Laboratory capability in modern applied mathematics.

In the early years of the Laboratory, its mathematical needs were accommodated individually in the various task-oriented divisions. Over the years, however, the pace of mathematics and related APL needs quickened. Simultaneously, an active nucleus of innovative mathematicians developed in the Aeronautics Division. But in that task-oriented environment, stresses developed between these frontier explorers and their Laboratory peers. So it became evident that if APL's newly developing expertise in mathematics were to be nurtured, a more research-oriented environment would have to be provided. Thus, in 1966, the mathematical nucleus was transferred to the Research Center and the Applied Mathematics Group was established under the supervision of D. W. Fox.

Both analytical and numerical studies are pursued. The initial analytical studies were conducted primarily in areas that had arisen in connection with task problems and that for the most part related to heat conduction and vibrational modes of mechanical structures, problems involving spectral analysis and approximation, and *a priori* inequalities for parabolic and elliptic equations.

Initial numerical studies derived from similar problems and were primarily concerned with zero-finding methods for polynomials, matrix eigenvalue and eigenvector algorithms (e.g., describing resonance frequencies of vibrations of mechanical structures), and computational methods for biharmonic boundary value problems (e.g., in fluid flows). Research in most of these areas has continued and has led to many publications in the mathematical literature, including a book by V. G. Sigillito, "A Priori Inequalities with Applications to Boundary Value Problems."[33]

The group has established itself internationally. For example, its recent advances in bounding the energy levels of atoms and ions[34] have stimulated similar research by many other researchers in Europe as well as in this country. The group is a valuable resource to APL through sustained collaborations with the F. T. McClure Computing Center and through transient collaborations with many other divisions of the Laboratory. In connection with the Biomedical Program (and the Theoretical Physics Group), for example, advanced computational methods have been developed to solve the hydrodynamic equations describing steady and pulsatile fluid flow through normal and atherosclerotic arteries,[35] a topic of considerable current interest because of ways in which blood flow is implicated in atherosclerosis.

Recently, much of the group's activity has turned to stratified flows because of their relevance to submarine detectability and because of difficult conceptual and mathematical challenges. One area of particular interest with respect to linear problems has been utilization of the "fundamental solution" by techniques that generally have proved helpful but that have been little used for buoyant flows. In this connection, the group has developed the methods for three-dimensional buoyant flows and has obtained an integration theory for initial value problems with essentially arbitrary initial velocities and densities.

One of the most elegant analytical developments in hydrodynamics research concerns the behavior of two-dimensional models of wake collapse in the linear theory of buoyant flow. Previous work on this problem elsewhere had, through certain limiting arguments, led to an unexplained, persistent, oscillating-jump discontinuity at the wake boundary, whose existence cast serious doubt on the basic approach. However, by obtaining a solution in tractable integral form, it was possible to expose the nature of the discontinuity, to show its correspondence to other discontinuities that are accepted in linear hydrodynamic theory, and thereby to validate the basic approach. One of the most impressive continuing numerical studies in the group is a project sponsored by the Office of Naval Research (ONR) in which computational algorithms of proved convergence are developed to solve previously intractable problems of hyperbolic and elliptic equations with free boundaries[36] (e.g., the ocean surface). Some appreciation of the power of the approach can be glimpsed from the fact that it can solve the problem of two water jets that meet head-on.

Although some effort continues to be devoted to eigenvalue estimation and *a priori* bounds for approximating solutions of partial differential equations, the major area of current activity is fluid mechanics. Analytical studies primarily involve linear buoyant flow theory. They are concerned with applications of the fundamental solution to obtain explicit solutions of initial value problems, asymptotic decay estimates, and integral equations for a class of initial-boundary-value problems for moving bodies. Numerical studies emphasize nonlinear sur-

face and internal wave phenomena and are directed mainly toward obtaining further results on stability and uniqueness of solutions, more efficient computational algorithms, and greater generality (including, for example, variable fluid density).

MATERIALS RESEARCH

The steadily growing demand for materials having improved electrical, optical, magnetic, and thermal properties makes the technology of materials increasingly important to the Laboratory's tasks. The present central responsibility of the Quantum Electronics Group is to provide a bridge to the rapidly developing science of new materials with unusual properties. The research program includes preparing and characterizing organic conductors (for NSF), materials with unusual infrared and magnetic properties (for the Army), and new photoelectrode materials (for ONR). The IR&D core project, which is directed toward discovering fundamental principles for designing new materials, relates to problems of concern to several Laboratory divisions, including the Submarine Technology Division and the Power Plant Siting Program (electrode processes and the detection of trace substances), the Fleet Systems Department (infrared and radar chaff), and to other divisions through complementary Research Center projects (e.g., in surface science, heterogeneous chemistry, and solid state physics).

The Research Center's materials program evolved through the Laboratory's Plasma Physics Group, which was established in the early sixties (and was subsequently disbanded in the early seventies after it became evident that the field of controlled thermonuclear fusion demanded research on a scale that APL could not support). A notable achievement of the Plasma Physics Group was the development of a far infrared (337 μm) HCN (hydrogen cyanide) laser and the pioneering of its use to measure high density (10^{13} to $10^{16}/cm^3$) plasmas and, by Faraday rotation techniques, to measure internal field strengths and density gradients.[37] These plasma diagnostic methods have now been widely adopted elsewhere.

However, as the great difficulties of achieving controlled thermonuclear fusion became generally recognized, the group's activities shifted toward research in areas where significant contributions could continue to be made within the constraints imposed by the Laboratory's resources. While emphasis turned partially toward characterizing mechanisms that limit pulse repetition rates of the electrically excited HCN laser, the work was focused even more strongly on semiconductor studies because, with respect to their electronic behavior, semiconductors are essentially solid state plasmas. This fact, together with experience in preparing thin films and the far infrared detectors used in the laser diagnostics of plasmas, led to numerous investigations. Measurements of photoconductive properties, band structure, impurity effects, and electron transport properties were carried out and published, especially for III-V compound semiconductors of potential interest for infrared detectors, solid state lasers, and other active devices, but also for organic conductors. Some were made in collaboration with other Research Center groups and with chemists at the University's Homewood campus who were synthesizing organic conductors but were not well equipped to characterize their electronic properties (Fig. 16). Thus, when the plasma physics project was terminated in 1973, this basic research activity was transferred to the Research Center to become the Quantum Electronics Group under T. O. Poehler.

At first, the activities of the Quantum Electronics Group were continuations of the plasma physics projects cited above. However, interest in designing new materials with unusual properties has grown, and facilities for preparing and characterizing materials have been greatly enhanced (Table 1). Organic conductor research continues to be of great interest because of the potential for unique electrical and magnetic properties (including, perhaps, superconductivity near room temperature). Research in this area (in collaboration with A. N. Bloch, D. O. Cowan, and other chemists at Homewood) has been particularly fruitful for insights that guide the design and preparation of organic materials with desired electrical and magnetic properties.[38] For example, a new type of magnetic insulator has been found, the nature of TTF-TCNQ (the salt of tetrathiofulvalene and 7,7,8,8-tetracyanoquinodimethane) below its metal-insulator transition has been elucidated, and high-resolution conductivity measurements have provided new understanding of the nature of phase transitions in several organic conductors.[39]

The group's research on effects at semiconductor-electrolyte interfaces is relatively new. Of great technological interest are photo effects (e.g., as an alternate approach to solar cells for utilizing solar energy) and chemical effects (e.g., in connection with designing needed materials such as fast-response ion-specific electrodes for contaminant/tracer detection). Early experiments elsewhere established titanium dioxide as a dissolution-resistant electrode material for use in photo-assisted electrolysis, but it is not efficient for solar energy because its band gap is so large ($\sim$3.3 eV) that only the high-energy part of the solar spectrum is used. However, the group's theoretical considerations suggested that a lower band gap could be achieved without sacrificing resistance to dissolution by making electrodes of a titanium-vanadium-dioxide alloy, $Ti_{(1-x)}V_xO_2$, with $x \sim 1/4$. Indeed, the experiments (now supported by ONR) show very promising results using both ceramic and single crystal specimens. Figure 17 illustrates the photoresponses for titanium dioxide and the new alloy $Ti_{0.75}V_{0.25}O_2$ and shows that the edge of the photoelectric spec-

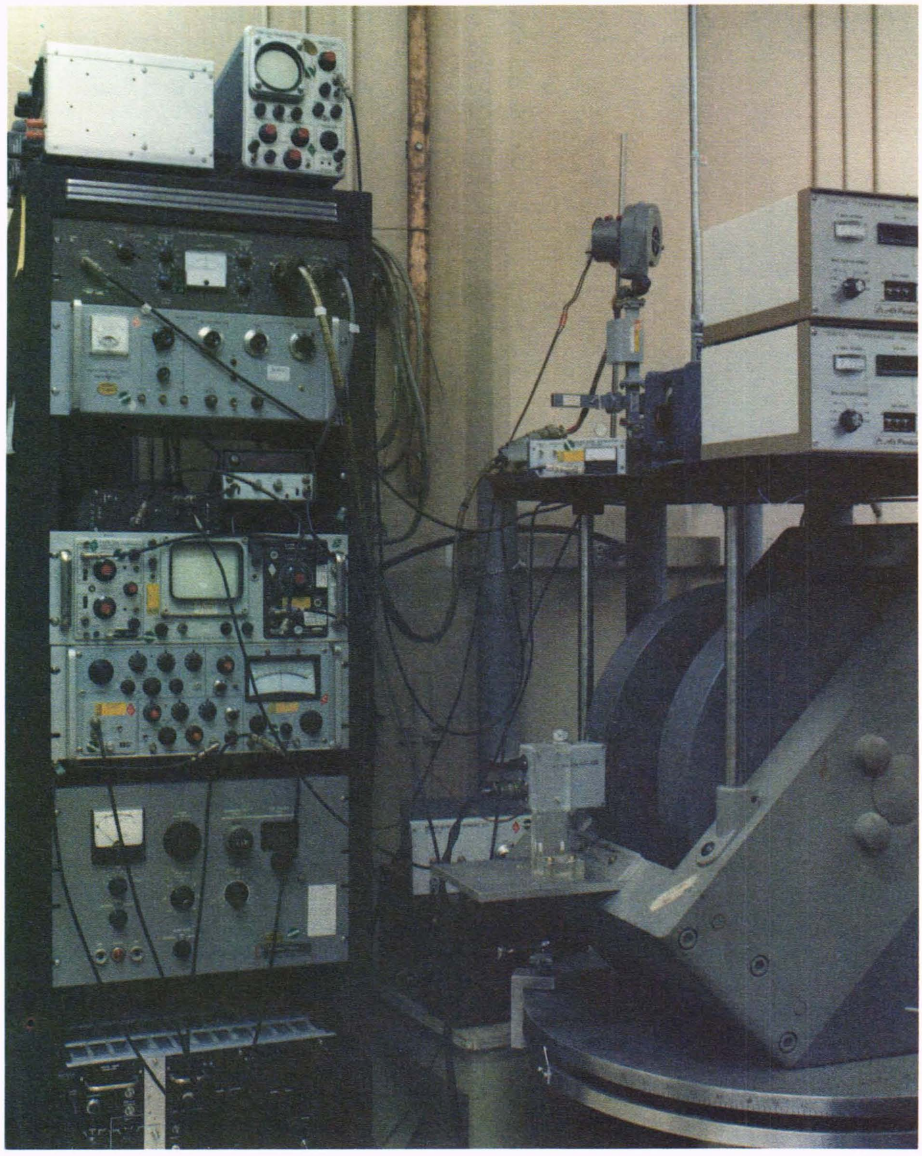

Fig. 16—Electron spin resonance spectrometer. "The researchers at Johns Hopkins have found a new organic charge transfer salt which has the highest room temperature conductivity of any known organic substance... Work by the Johns Hopkins group has shown that HMTSF-TCNQ behaves electrically as a metal in the temperature range from 1.1 K to 300 K..." [*Science*, **190**, p. 451 (1975).]

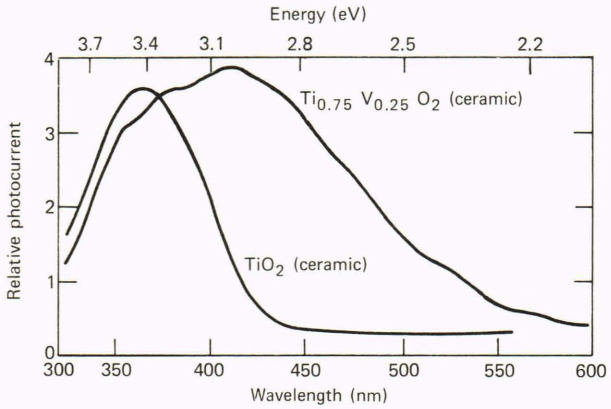

Fig. 17—Photoresponse of TiO_2-VO_2 alloy. Replacing one out of four titanium atoms with vanadium extends the photoresponse well into the visible and permits greater utilization of the solar spectrum.

trum has been lowered to about 2.2 eV, a value close to but still somewhat higher than optimum.

A recent finding of potentially exciting technological importance is the discovery of stable and reproducible current-controlled, bistable, fast ($\sim 10^{-9}$s) electrical switching and memory phenomena in polycrystalline, organic, semiconducting films.[40] Figure 18 illustrates the threshold switching behavior of copper-TCNQ film (thickness ~ 10 μm, area $\sim 1/4$ cm^2) sandwiched between one copper and one aluminum electrode. The upper trace of Fig. 18a shows a single 5 V (subthreshold) pulse of 10 μs duration applied to the device; Fig. 18b shows that the voltage has been increased slightly and that the device has abruptly switched from the high impedance (~ 2 MΩ) state to the low impedance (~ 200 Ω) state.

The long-range objective of the materials science research program is to discover the fundamental principles essential to the development of technologically important new materials and to achieve a thorough understanding of their electronic, optical,

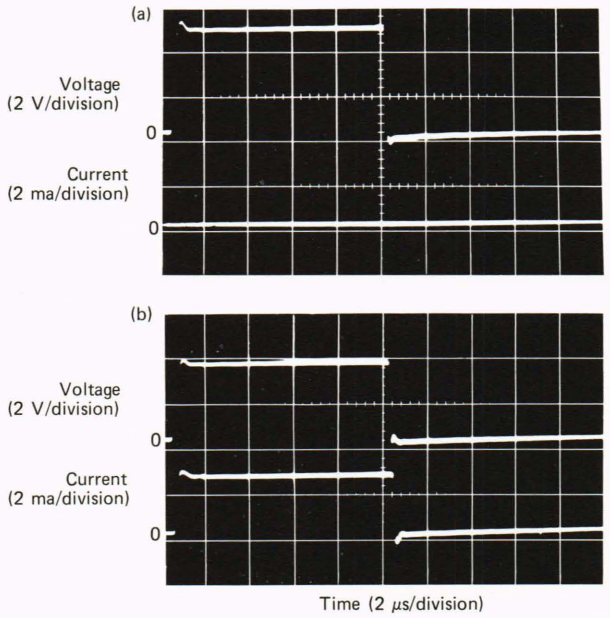

Fig. 18—Threshold switching behavior of Cu-TCNQ film. In Fig. 18(a) the upper trace shows a subthreshold voltage pulse applied to the film; the lower (current) trace shows that the resistance of the film remains high throughout the pulse. In Fig. 18(b), the voltage pulse is above threshold (upper trace) and the current trace shows that the resistance of the film switches almost instantaneously.

magnetic, and structural properties. Principal short-term objectives include further development and characterization of materials having band gaps matched to the solar spectrum (with emphasis on $Ti_{(1-x)}V_xO_2$ alloys and on titanates of the form $MTiO_3$), of organic conductors with increased two-dimensional character, and of transition metal-metalloid alloys (initially of iron and boron, Fe_xB_{1-x}).

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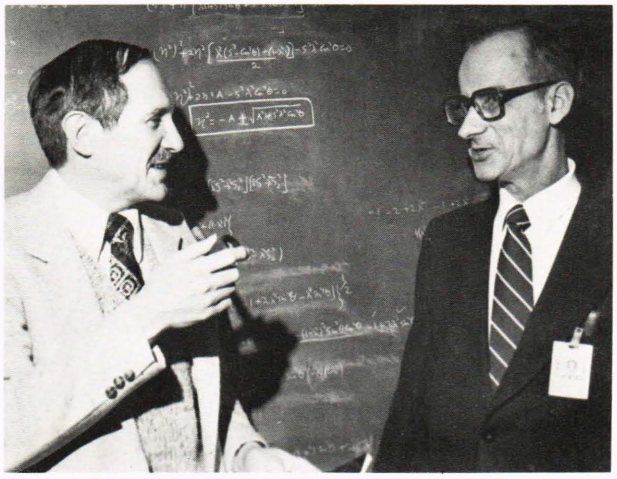

Robert W. Hart (left) and Samuel N. Foner

SAMUEL N. FONER is Vice-Chairman of the Milton S. Eisenhower Research Center and Supervisor of its Electronic Physics Group. Born in New York City (1920), he studied physics and mathematics at what is now the Carnegie-Mellon University, where he received his D.Sc. degree in physics in 1945. He was employed as an instructor in the Physics Department and later as a research associate of the Manhattan Project, working in the laboratory of the Nobelist Otto Stern who instilled in him the use of conceptually simple experiments to answer complex questions.

Dr. Foner joined APL in 1945 and became associated with the Research Center as Supervisor of the Mass Spectrometry Group (1947-52) and the Electronic Physics Group (1953-present). He has made many noteworthy contributions to the mass spectrometry of free radicals and reaction intermediates, to the detection of free radicals stabilized at very low temperatures, and to the ionization of substances by electron impact.

He has served as a member of the NAS/NRC Advisory Committee for the Army Research Office and an Advisor to NATO's Scientific Affairs Division. In 1954, Dr. Foner received the Physical Sciences Award of the Washington Academy of Sciences for work in free radical chemistry and physics. He is a member of the Combustion Institute, the Philosophical Society of Washington, and a Fellow of the AAAS, the American Physical Society, and the Washington Academy of Sciences.

ROBERT W. HART is Chairman of the Milton S. Eisenhower Research Center and Assistant Director of APL for Exploratory Development. Born in Yankton, SD, in 1922, he studied at the University of Iowa and received his Ph.D. degree in physics from the University of Pittsburgh in 1949. After a year of teaching at the Catholic University in Washington, he joined APL in 1950. He has been a member of the Research Center ever since.

During the 1960s, Dr. Hart developed a detailed theory of the complex combustion behavior of solid propellants in rockets in collaboration with the late Frank T. McClure and as member of the Joint Armed Services Committee on Combustion Instability. As Supervisor of the Special Problems Research Group (1954-1975), his interests covered theoretical aspects of wave scattering, the structure of the eye, and other physical and biophysical topics.

Dr. Hart is a member of the American Physical Society and of the Combustion Institute. Outside of professional activities, he is interested in the origin and evolution of civilization and science.

RESEARCH RETROSPECTIVES

THE STRUCTURE OF FLAMES

Flames have been the most important source of heat, light, and power since the earliest days of civilization. At present, the combustion of fuels is, by far, the largest chemical operation under human control. Yet, until quite recently, detailed knowledge of what goes on within a flame did not exist. Although the complexity of combustion is not entirely understood, even today, what was virtually *terra incognita* has been opened up during the past 25 years by the classic studies at APL by Robert M. Fristrom, Arthur A. Westenberg, and their colleagues.

What does one need to know about a flame? Chemists want a detailed accounting of the steps by which fuels (such as oil, natural gas, or coal) and oxidizers (such as air) are converted into products of combustion (water, oxides of carbon, soots, and ash) as well as the intermediate reaction paths that are involved in this transformation. They want to understand why and how inhibitors can extinguish flames or prevent engine "knock" and know how rapidly these transformations can take place. Physicists, on the other hand, are interested in temperature effects, radiation, the flow fields set up by the gases moving into and out of the flames, and countless other physical properties.

What sets flames apart from more conventional chemical transformations is that one is dealing with a very intricate situation in which chemical reactions are closely coupled with the physical flow of substances into and out of a reaction zone, accompanied by a steep rise in temperature, abrupt changes in composition, and numerous optical and electrical phenomena that may be important under specific circumstances. In a distance of less than 1 mm, temperatures can change by thousands of