

AD-A072 299

HARVARD UNIV CAMBRIDGE MA DIV OF APPLIED SCIENCES
JOINT SERVICES ELECTRONICS PROGRAM.(U)
DEC 78

F/G 9/5

UNCLASSIFIED

N00014-75-C-0648

All

1 OF 1

AD
A072 299



END
DATE
FILMED

9-79

DDC

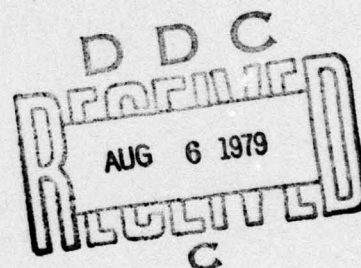
AD A 072299

col 4
LEVEL

12
A

Division of Applied Sciences
Harvard University Cambridge, Massachusetts

ANNUAL PROGRESS REPORT NO. 92



JOINT SERVICES ELECTRONICS PROGRAM

N00014-75-C-0648

Covering Period

January 1, 1978 - December 31, 1978

May 1979

This document has been approved
for public release and sale; its
distribution is unlimited.

DDC FILE COPY

79 07 11 005

6 Joint Services Electronics Program.

15 N00014-75-C-0648

9 ANNUAL PROGRESS REPORT NO. 92

1 Jan - 31 Dec 78

12 69 p.

Covering Period

January 1, 1978 - December 31, 1978

11 31 Dec 78

The research reported in this document, unless otherwise indicated, was made possible through support extended to the Division of Applied Sciences, Harvard University by the U. S. Army Research Office, the U. S. Air Force Office of Scientific Research and the U. S. Office of Naval Research under the Joint Services Electronics Program by Contract N00014-75-C-0648. Related research sponsored by the Office of Naval Research, the National Science Foundation, the National Aeronautics and Space Administration, and by the University is also reported briefly with appropriate acknowledgement.

Division of Applied Sciences

Harvard University

Cambridge, Massachusetts

410 457

mt.

ANNUAL PROGRESS REPORT NO. 92

Joint Services Contract

N00014-75-C-0648

The Steering Committee

Related Contracts

AFOSR76-3073

F19628-77-C-0146

F44620-72-C-0021

T.T. Wu

T.T. Wu

T.T. Wu

N00014-77-C-0002

N00014-76-C-0032

N00014-77-C-0085

N00014-78-C-0531

N00014-77-C-0533

N60530-78-C-0041

D. Turnbull

M. Tinkham

M. Tinkham

E. Yablonovitch

Y.C. Ho

N. Bloembergen

NSF-ENG75-14455

NSF-ENG76-11824

NSF-DMR78-10014

NSF-DMR77-10210

T.T. Wu

Y.C. Ho

W. Paul

H. Ehrenreich

NSF-DMR76-01111, and

NSF-DMR77-24295

H. Ehrenreich

W. Paul

P.S. Pershan

M. Tinkham

NSF-DMR76-11323

M. Tinkham

NSF-DMR76-15325, and

NSF-DMR78-10014

W. Paul

NSF-DMR-76-22452

P.S. Pershan

NSF-DMR-10210

H. Ehrenreich

DAAG29-77-G-0059

DAAG29-76-G-0139

DOEU78-S-02-4631-A000

W. Paul

R. Brockett

E. Yablonovitch

Accession For	
NTIS GRA&I	☒
DDC TAB	☐
Unannounced	☐
Justification	☐
By <i>[Signature]</i>	
Distribution/	
Availability Codes	
Dist.	Avail and/or special
<i>A</i>	

JOINT SERVICES ELECTRONICS PROGRAM

January 1, 1978 - December 31, 1978

ADMINISTRATIVE STAFF

Contract

N00014-75-C-0648

The Steering Committee

Prof. N. Bloembergen
Prof. R. W. Brockett
Prof. P. Caines
Prof. H. Ehrenreich
Prof. Y. C. Ho
Prof. W. Paul
Prof. P. S. Pershan
Prof. M. Tinkham
Prof. T. T. Wu
Prof. E. Yablonovitch
Dr. P. McKinney
Dr. J. Blake

RESEARCH STAFF

Dr. D.A. Anderson
Dr. S. Asher
Dr. J. deBettencourt
Dr. N. Bloembergen
Dr. A. Bogdan
Dr. R. W. Brockett
Dr. I. Burak
Dr. R.W. Burton (summer)
Dr. C. Byrnes
Dr. P. Caines
Dr. M. Dagenais
Dr. T. Dwyer
Dr. H. Ehrenreich
Dr. C.D. Gelatt
Dr. R. Goodrich
Dr. G. Woodwin
Dr. Y.C. Ho
Dr. R.W.P. King (Emeritus)

Dr. M. Krook
Dr. B. Kurtaran
Dr. H.S. Kwok
Dr. M. Octavio
Dr. M.A. Paesler
Dr. W. Paul
Dr. P.S. Pershan
Dr. Y. Prior
Dr. T.K. Sakar (until May 31)
Dr. L.C. Shen (summer)
Dr. W.J. Skocpol
Dr. L.N. Smith
Dr. M.J. Stephen
Dr. R. Suri
Dr. M. Tinkham
Dr. H. Vogt
Dr. T.T. Wu
Dr. E. Yablonovitch

CONTENTS

	<u>Page</u>
CONTRACTS.....	iii
STAFF.....	v
CONTENTS	vii
 I. <u>QUANTUM ELECTRONICS</u>	
1. Nonlinear Light Mixing Spectroscopy, Y. Prior, A. Bogdan, M. Dagenais, and N. Bloembergen.....	I- 1
2. Two-Photon Absorption in Solids and Liquids, Y. Prior and H. Vogt.....	I- 3
3. Two-Photon Absorption and Optical Damage with Picosecond Light Pulses, P.L. Liu, R. Yen, and N. Bloembergen.....	I- 4
4. Ultra Fast Quenching and Photoelectric Emission Induced by Picosecond Light Pulses, P.L. Liu, R. Yen, and N. Bloembergen.....	I- 5
5. Intramolecular Vibrational Relaxation in Polyatomic Molecules, I. Burak, H.S. Kwok, R. Sharp, J. Tsao, and E. Yablonovitch.....	I- 6
6. Multiphoton Vibrational Excitation, J.G. Black and E. Yablonovitch.....	I- 7
7. Laser Plasma Interaction, P. Kolodner and E. Yablonovitch	I- 8
 II. <u>SOLID STATE ELECTRONICS</u>	
1. Defects in Liquid Crystals, S.A. Asher, J. Collett, and P.S. Pershan.....	II- 1
2. Elastic Properties of Liquid Crystals, M. Fisch and P.S. Pershan.....	II- 2
3. Raman Scattering in Liquid Crystals, S.A. Asher and P.S. Pershan.....	II- 3

	<u>Page</u>
4. High Frequency Josephson Phenomena, D.A. Weitz, M. Octavio, W.J. Skocpol, and M. Tinkham.....	II- 3
5. Laser-Induced Disequilibrium in Superconducting Films, L.N. Smith, A.D. Smith, W.J. Skocpol, and M. Tinkham....	II- 5
6. Production and Characterization of Amorphous Semiconductors, D.A. Anderson, P. Ketchian, M.A. Paesler, and W. Paul.....	II- 7
7. Study of Doping, Schottky Barrier Formation and Solar Cell Efficiency in Amorphous $\text{Si}_{1-x}\text{H}_x$ Alloy, D.A. Anderson, G. Moddel, and W. Paul.....	II- 8
8. Study of Conditions for the Optimum Configuration of Pseudogap States in Amorphous Silicon, D.A. Anderson, R. Collins, E.C. Freeman, G. Moddel, S. Oguz, M.A. Paesler, and W. Paul.....	II- 8
9. Use of the Field Effect to Determine the Pseudogap State Density in Amorphous $\text{Si}_{1-x}\text{H}_x$ Alloys, D.A. Anderson.....	II-11
10. Photoconductivity in Amorphous $\text{Si}_{1-x}\text{H}_x$ Alloys, D.A. Anderson, G. Moddel, and W. Paul.....	II-12
Publications of the Research Reported in Sections II.6 to II.10.....	II-12
11. Vacancy Stabilization, L. Huisman, A. Carlsson, H. Ehrenreich, and C.D. Gelatt.....	II-13
12. Electronic Theory of Disordered Semiconductors, C.D. Gelatt and S. Kivelson.....	II-14
13. Interfaces, A. Carlsson and H. Ehrenreich.....	II-15
14. Electrons in a Random Potential, M.J. Stephen.....	II-16

III. INFORMATION ELECTRONICS CONTROL AND OPTIMIZATION, *and*

1. Data Base System Problems, Y.C. Ho, B. Kurtaran, and D.M. Chiu.....	III- 1
2. Teams and Organizations, Y.C. Ho and N. Papadopoulos....	III- 3
3. Buffer Storage Problem in a Production Line, Y.C. Ho and A. Eyler.....	III- 4
4. Decentralized Resource Management in Large Systems, Y.C. Ho and R. Suri.....	III- 5

	<u>Page</u>
5. Identification of Time Invariant Linear Systems from Non-Stationary Cross-Sectional Data, P.E. Caines.....	III- 6
6. Deterministic and Stochastic Adaptive Control, P.E. Caines.....	III- 8
7. Nonlinear Systems, R.W. Brockett.....	III- 9
8. Estimation Theory, R.W. Brockett.....	III-10
9. Linear Systems, R.W. Brockett.....	III-10

IV. ELECTROMAGNETIC PHENOMENA

ANTENNAS AND WAVES IN AND OVER DIELECTRIC, CONDUCTING, AND PLASMA MEDIA

1. Theoretical and Experimental Study of the Scattering from an Obstacle Above the Earth, H.-M. Lee, T.T. Wu, and L.C. Shen.....	IV- 3
2. Numerical and Analytical Determination of Electromagnetic Fields of Antennas in the Earth Near Its Interface with Air, R.W.P. King, B.H. Sandler, and L.C. Shen	IV- 5
3. Transmission and Reception with Bare and Insulated Antennas Embedded in Skin, R.W.P. King and B.H. Sandler	IV- 9
4. Theoretical and Experimental Study of Electromagnetic Fields and Antennas in Dissipative and Dielectric Cylinders, R. Bansal.....	IV-11
5. Experimental Studies of Antennas in Plasmas, M.J. Miller	IV-14
6. Antennas in Matter: Fundamentals, Theory, and Applications, R.W.P. King, G.S. Smith, M. Owens, and T.T. Wu.....	IV-15

ANTENNAS IN AIR

7. Single and Crossed Electrically Short and Thin Tubular Cylinders, R.W.P. King, D.J. Blejer, and B.H. Sandler.	IV-16
8. Surface Currents and Charges Induced on Electrically Thick Cylinders, Crossed Cylinders, and Cylinders Crossed with Horizontal Flat Plates by an Incident Plane-Wave Field, R.W.P. King, D.J. Blejer, and M. Krook.....	IV-17

	<u>Page</u>
9. Currents and Charges on Cylinders in a Parallel-Plate Transmission Line, R.W.P. King, D.J. Blejer, J.E. Baum, T.K. Sarkar, and M. Krook.....	IV-20
10. Theoretical and Experimental Study of the Ferrite Rod Antenna, D.V. Giri and R.W.P. King.....	IV-23

I. QUANTUM ELECTRONICS

Personnel

Prof. N. Bloembergen	Dr. H. Vogt
Prof. E. Yablonovitch	Mr. Jerry Black
Dr. I. Burak	Mr. P. Kolodner
Dr. A. Bogdan	Mr. P.L. Liu
Dr. M. Dagenais	Mr. R. Sharp
Dr. H.S. Kwok	Mr. J. Tsao
Dr. Y. Prior	

I.1 Nonlinear Light Mixing Spectroscopy. Y. Prior, A. Bogdan, M. Dagenais, and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 5.

The work on nonlinear four-wave mixing has been continued. The emphasis has been shifted to four-wave light mixing in sodium vapor. Several groups working on the theory of the nonlinear susceptibility, $\chi^{(3)}$, predict slightly different results for the lineshapes of CARS (Coherent Anti-Stokes Raman Scattering) and CSRS (Coherent Stokes Raman Scattering) signals. In the previous annual report the general theoretical expression obtained by us was mentioned.¹ This theoretical work was also reported² at the Sixth International Conference on Raman Spectroscopy, Bangalore, India, September 1978.

An experimental test of some of the damped resonance terms, about which some controversy still exists, has been undertaken. Atomic sodium was chosen because the energy levels are sharp and well defined, and they are connected by known matrix elements. Furthermore, the damping can be varied in a controlled manner by the partial pressure of a noble buffer gas. The experiments avoid any one-photon resonance from the populated 3S ground state of Na, but the frequencies of two incident dye laser beams are at or near resonance between the excited levels of the $3P_{1/2,3/2}$ doublet and the 4D level. The beams are generated in a double frequency dye laser of a novel design, which has been published.³ These experiments are difficult to perform due to competing effects of sodium molecules Na_2 . Four-wave mixing signals have been detected and analyzed, but no conclusive results have been reached to date. It appears that a very small (one part in a million), but nevertheless real, population exists in the 3P atomic state. Presumably this level is reached following molecular excitation of Na_2 . Further work to unravel the true $\chi^{(3)}$ four-wave mixing by the ground state population is in progress.

References

1. N. Bloembergen, H. Lotem, and R.T. Lynch, Jr., "Lineshapes in Coherent Resonant Raman Scattering," *Indian Journal of Pure and Applied Physics*, 16, 151 (1978).
2. N. Bloembergen, "Stimulated Raman Effect and Coherent Raman Scattering," Proc. of the Sixth International Conference on Raman Spectroscopy, edited by E.D. Schmid, R.S. Krishnan, W. Kiefer, and H.W. Schrotter (Heyden, Philadelphia, 1978), p. 335.
3. Y. Prior, "Double Frequency Narrow Band Grazing Incidence Pulsed Dye Laser," *Rev. Sci. Inst.*, 50, 259 (1979).

I.2 Two-Photon Absorption in Solids and Liquids. Y. Prior and H. Vogt,
Contract N00014-75-C-0648; Research Unit 5.

The work initiated by Lotem and de Araujo¹ to develop accurate methods for measuring two-photon absorption cross sections has been continued. The method of measuring TPA absolute cross sections by means of calibration relative to known Raman cross sections was developed further to enable internal calibration in Raman active liquids. The loss coefficient at ω_2 is proportional to the pump intensity $I(\omega_2)$ due to the two-photon absorption process at $\omega_1 + \omega_2$ in a crystal which is immersed in a fluid, e.g., benzene. The frequencies ω_1 and ω_2 are so chosen that $\omega_1 - \omega_2$ corresponds to a Raman resonance with a known Raman cross section in benzene. The loss due to two-photon absorption may be compared to, and compensated by, the Raman gain. Both processes are proportional to $I(\omega_1)$. The method is accurate because it is independent of mode structure, self-focusing and other distortions of the light beams. The measurements were extended to the uv part of the spectrum, and TPA coefficients were obtained for benzene and several alkali halide crystals at excitation energy of 6.7 eV.

The results were reported at the 1978 annual meeting of the Optical Society of America in San Francisco,² and are discussed in detail in a paper accepted for publication in Phys. Rev. B.³ The present method utilizes ns pulses derived from a uv dye laser pumped by the second harmonic of a ruby laser. Our results for the TPA cross sections in the uv were compared to those obtained in this laboratory previously with ps pulses.⁴ There is good agreement between the two independent methods.

References

1. C.B. de Araujo and H. Lotem, "New Measurements of the Two-Photon Absorption in GaP, CdS and ZnSe Relative to Raman Cross Sections," *Phys. Rev. B* 18, 30 (1978).
2. Y. Prior and H. Vogt, "Absolute Determination of Two-Photon Absorption Cross Sections," *J. Opt. Soc. of Amer.*, 68, 1423 (1978).
3. Y. Prior and H. Vogt, "Measurement of uv Two-Photon Absorption Relative to Known Raman Cross Sections," to be published in *Phys. Rev. B*, June 1979.
4. P. Liu, W.L. Smith, H. Lotem, J.H. Bechtel, N. Bloembergen, and R.S. Adhav, "Absolute Two-Photon Absorption Coefficients at 355 and 266 nm," *Phys. Rev. B* 17, 4620 (1978).

- I.3 Two-Photon Absorption and Optical Damage with Picosecond Light Pulses.
P.L. Liu, R. Yen, and N. Bloembergen, Contract N00014-75-C-0648 and
O.N.R. Grant N60530-78-C-0041; Research Unit 6.

Measurement of the dielectric breakdown threshold in diamond was carried out at 1.06 μm . The result suggests that the breakdown mechanism in diamond is similar to that in ionic crystals. The upper limit of the two-photon absorption coefficient of diamond was also determined at 532 nm. A cumulative damage effect at 532 nm was observed. It was a result of the accumulation of the color centers generated through two-photon absorption in laser pulses. A paper based on these measurements has been published.¹

Measurements on the two-photon absorption coefficients of ultraviolet window and coating materials were carried out. The two-photon absorption was determined in fused silica, SrF_2 , BaF_2 , MgF_2 , and LiYF_4 . The data are relevant for high power uv lasers. A paper presenting the design of an automatic data acquisition system along with the two-photon absorption coefficients was accepted for publication in *Applied Optics*.²

References

1. P. Liu, R. Yen, and N. Bloembergen, "Dielectric Breakdown Threshold, Two-Photon Absorption, and Other Optical Damage Mechanisms in Diamond," *IEEE J. Quantum Electron.* QE14, 574 (1978).
2. P. Liu, R. Yen, and N. Bloembergen, "Two-Photon Absorption Coefficients in uv Window and Coating Materials," to be published in the April 1, 1979 issue of *Applied Optics*.
This material is also contained in the Final Technical Report, Feb. 1979, of ONR Grant N60530-78-C-0041.

I.4 Ultra Fast Quenching and Photoelectric Emission Induced by Picosecond Light Pulses. P.L. Liu, R. Yen, and N. Bloembergen, Contract N00014-75-C-0648 and ONR Grant N60530-78-C-0041; Research Unit 6.

Picosecond laser pulses are used to induce heating and cooling with a rate of the order of 10^{13} °C/sec on the surface of a single crystal of silicon. Preliminary results demonstrate a crystalline to amorphous transformation induced by the short pulse. This ultra fast quenching process may lead to new phenomena on the kinetics of phase transitions. It may also find application in optical memory switching. Detailed studies of the morphology of the phase transformation are planned for the next reporting period.

The frequency and polarization dependence of the multiphoton photoelectric emission are under study. A tunable parametric oscillator has been designed and is under construction. In order to pump the parametric oscillator, we developed a mode-locked unstable Nd:YAG oscillator. The output pulse has a duration of 28 picosecond and an energy content of 8 mJ in each train. A paper presenting the result of the unstable oscillator was accepted for publication.¹

Reference

1. P. Liu and R. Yen, "Passively Mode-Locked Nd:YAG Unstable Oscillator," to be published in the March 1, 1979 issue of *Applied Optics*.

I.5 Intramolecular Vibrational Relaxation in Polyatomic Molecules.

I. Burak, H.S. Kwok, R. Sharp, J. Tsao, and E. Yablonovitch, Contracts N00014-75-C-0648 and N00014-78-C-0531; Research Unit 7.

Probably one of the most important problems in chemical physics is the concept of intramolecular vibrational relaxation. How fast will energy redistribute from one vibrational mode to the other vibrational modes of the same molecule? This question has been fraught with controversy for decades, but we now feel that the modern developments in laser technology will begin to answer those questions in the next few years.

The problem is important, for quantum electronics, statistical mechanics and physical chemistry. It is also central to infrared multi-photon excitation. In the past year we completed our initial experiments in this field.¹ Using a time resolved infrared-infrared double resonance technique, we have placed an upper limit of 30 psec for the energy redistribution time as the energy relaxes out of the initially excited ν_3 mode of SF_6 . A standard picosecond pump and probe technique was used. Dr. H.S. Kwok received the Ph.D. for this experiment and has taken a post-doctoral position at Lawrence Berkeley Laboratory. Mr. Sharp is continuing those experiments, with the initial objective of taking a full double resonance spectrum and improving the signal-to-noise ratio by computerizing the data collection.

Dr. I. Burak and Jeff Tsao are taking a different approach, and have set up an infrared-visible double resonance system based on our picosecond CO_2 laser pulses and a ruby pumped dye laser system. They have synchronized the two laser systems within 25 nsec at present and are already conducting experiments on NO_2 .

In the course of this work we have conceived an ingenious digital feedback technique for the single axial mode stabilization of CO_2 TEA lasers. This work will be published shortly² and is expected to become the standard axial mode stabilization technique in our laboratory.

References

1. H.S. Kwok and E. Yablonovitch, "Collisionless Intramolecular Vibrational Relaxation in SF_6 ," *Phys. Rev. Lett.*, 41, 745 (1978).
2. J. Tsao, R. Sharp, and E. Yablonovitch, *Rev. Sci. Instrum.*, to be published.

I.6 Multiphoton Vibrational Excitation. J. G. Black and E. Yablonovitch, Contracts N00014-75-C-0648 and N00014-78-C-0531; Research Unit 7.

One of the major questions in infrared laser induced chemical reactions is: What is the vibrational energy distribution produced by multiphoton excitation? A simplified theory and experimental results¹ for SF_6 have been published with the following conclusion: The energy distribution is bimodal with some fraction of the molecules bottlenecked among the discrete levels and the balance excited in roughly a thermal distribution.

This model for multiphoton excitation, in which energy fluence rather than peak power plays the key role, was described in a recent review article.²

During these experiments we discovered a decomposition formula for Gaussian spatially averaged experimental data.³ The true nonlinear functional dependence of a physical parameter on local light intensity can be obtained. This mathematical formula is invaluable for our energy deposition and yield experiments. These measurements are being extended to a series of molecules of different sizes. To this end, the data collection system has been computerized and tested. Measurements should be completed during the next reporting period.

References

1. M.J. Schultz and E. Yablonovitch, "A Statistical Theory for the Collisionless Multiphoton Association of SF₆," *J. Chem. Phys.*, **68**, 3007 (1978).
2. J.G. Black, P. Kolodner, M.J. Schultz, E. Yablonovitch, and N. Bloembergen, "Collisionless Multiphoton Energy Deposition and Dissociation in SF₆," *Phys. Rev. A*, February (1979).
3. N. Bloembergen and E. Yablonovitch, "Infrared Laser Induced Unimolecular Reactions," *Physics Today*, **31**, no. 5, p. 23, May (1978).
4. P. Kolodner, H.S. Kwok, J.G. Black, and E. Yablonovitch, "Exact Decomposition of a Gaussian-Averaged Nonlinear Function," *Opt. Lett.*, **4**, 38 (1979).

I.7 Laser Plasma Interaction. P. Kolodner and E. Yablonovitch, Contracts N00014-75-C-0648 and DOEU78-S-02-4631-A000; Research Unit 7.

We have continued to study the resonant acceleration of electrons in the interaction of a powerful electromagnetic wave with a plasma density gradient. This effect, which was first experimentally discovered in our laboratory, plays a major role in the absorption of laser energy by inertial confinement fusion targets.

In the resonant absorption (RA) theory of laser-plasma interaction,¹ the most important plasma parameter is the electron density scale length $L \equiv n_e |\nabla n_e|^{-1}$. Our efforts in the past year have been directed towards plasma production with reproducible L by optical breakdown on the front of a moving shock wave. Such a target has $L \sim 1$ to $10 \mu\text{m}$, exactly the range of interest in present laser interaction research.

To this end, we have constructed an electrothermal shock tube which produces waves of Mach number ~ 5 in H_2 gas at ~ 50 torr pressure. A high-speed laser schlieren-type shock-front detection system has been developed which allows the motion of the shockfront to be "frozen" with spacial resolution $\leq 100 \mu\text{m}$. Experiments have been performed in which high-power CO_2 laser pulses, triggered by this detection system, irradiate the "frozen" shock front. The spacial density profile of the shock front has at this stage manifested itself only to the lowest order; i.e., when the shock front is far from the focus of the laser pulse, resonantly accelerated electron emission is greatly reduced. We are presently involved in attempts to expose more directly the effects of the neutral-gas density profile in the shock front on the laser-plasma interaction.

Reference

1. J.P. Friedberg, R.W. Mitchell, R.L. Morse, and L.I. Rudinski, *Phys. Rev. Lett.* 28, 795 (1972).

II. SOLID STATE ELECTRONICS

Personnel

Prof. H. Ehrenreich	Mr. A. Carlsson
Asst. Prof. C.D. Gelatt	Mr. J. Collett
Prof. W. Paul	Mr. R. Collins
Assoc. Prof. W.J. Skocpol	Mr. M. Fisch
Prof. M. Tinkham	Mr. D.J. Frank
Dr. D.A. Anderson	Ms. E. Freeman
Dr. S. Asher	Mr. L. Huisman
Dr. M. Octavio	Mr. S. Kivelson
Dr. M.A. Paesler	Mr. G. Moddel
Dr. R. Pindak	Mr. S. Oguz
Dr. L.N. Smith	Mr. A.D. Smith
Dr. M.J. Stephen	Mr. D.A. Weitz
Mr. G.E. Blonder	Mr. A.E. White

II.1 Defects in Liquid Crystals. S.A. Asher, J. Collett, and P.S. Pershan, Contracts N00014-75-C-0648, NSF DMR77-24295 and NSF DMR76-22452; Research Unit 4.

The work described last year on defects in lipid water systems has been continued and the first reports on this topic are published.^{1,2} Specific features of the proposed parabolic focal conic (PFC) defect have been confirmed experimentally and several other defects have been identified. We are continuing our investigation of the rheology of the PFC defects by examining their formation and their light scattering properties upon mechanical dilation or compression of monodomain samples.

References

1. S.A. Asher and P.S. Pershan, "Parabolic Focal Conics and Polygonal Textures in Lipid Liquid Crystals," *J. de Physique*, 40, 161 (1979).
2. S.A. Asher and P.S. Pershan, "Defect Structures in Lyotropic Lipid Liquid Crystals," (to be presented at the International Colloid and Surface Science Symposium, Lolla, MO, June 1979).

II.2 Elastic Properties of Liquid Crystals. M. Fisch and P.S. Pershan, Contracts N00014-75-C-0648, NSF DMR77-24295, and NSF DMR76-22452; Research Unit 4.

Our work on the elastic properties of the smectic phases was previously based on the Brillouin technique. Although that will remain an essential part of our effort, we have investigated the feasibility of studying these same modes at lower frequencies using a surface wave technique. We have learned to make $\sim 100 \mu\text{m}$ thick smectic samples with one free surface. Alignment and optical quality of these samples are better than any others that have previously been studied. Theoretical considerations imply that MHS shear acoustic waves in the bulk of these materials form underdamped standing waves that distort the free surface and thus scatter light rather strongly. Preliminary experiments demonstrate that the theory is correct and we are currently continuing to develop them in order to make quantitative measurements of the low frequency smectic elastic constants. The acoustic-optic effects in this type of geometry have never been measured and we will evaluate them for applications purposes as well as a tool for understanding the materials. Further, these results together with Brillouin studies on the same material will give a clear measure of the importance of dispersive phenomenon on acoustic-optic effects in smectic liquid crystals.

II.3 Raman Scattering in Liquid Crystals. S.A. Asher and P.S. Pershan, Contracts N00014-75-C-0648, NSF DMR77-24295, and NSF DMR76-22452; Research Unit 4.

The construction and testing of the PDP 11/03 computer controlled Raman spectrometer has been completed. Preliminary measurements on lipid liquid crystals prepared from dipalmitoyl phosphatidyl choline and water in the $L\alpha$ phase indicate an almost isotropic hydrocarbon ordering. However, below the $L\alpha$ phase the molecular ordering appears to become anisotropic. We are attempting to prepare monodomain samples below the $L\alpha$ phase of sufficient optical quality for polarized Raman measurements.

II.4 High Frequency Josephson Phenomena. D.A. Weitz, M. Octavio, W.J. Skocpol, and M. Tinkham, Contracts N00014-75-C-0648, N00014-76-C-0032, and NSF Grant DMR76-11323; Research Unit 2.

We have completed systematic measurements¹ of the ac Josephson effect in Nb point contacts at far-infrared laser² wavelengths between 1.22 mm and 70 μ m. Detailed analysis of the observed current widths of the constant-voltage Josephson steps has allowed us to study the frequency dependence of the strength of the Josephson effect from far below to far above the superconducting energy gap frequency.^{3,4} At low frequencies the observed step widths are consistent with the predictions of the usual RSJ model, with the strength of the Josephson current set by the observed dc critical current. Near to the gap frequency, the step sizes are larger than predicted by the RSJ model in a manner qualitatively consistent with the Riedel peak in the frequency response. Beyond the gap frequency, the size of the steps rolls off steadily but remains easily observable at

2.52 THz (119 μm ; about twice the gap frequency). At the highest frequency studied (4.3 THz or 70 μm) no steps were observed, but the primary difficulty was insufficient laser output and poor coupling. The frequency dependence generally agrees with Werthamer's tunneling theory,⁵ but systematic discrepancies suggest an additional rolloff associated with the relaxation time of the order parameter, qualitatively consistent with predictions of the time-dependent Ginzburg-Landau theory applied to a metallic constriction.⁶ The data definitely excludes the need for the anomalously long relaxation times conjectured⁷ in order to explain data from indium microbridges, which we believe were affected by heating.^{8,9}

Certain features of the dc I-V curves of our point contacts, particularly the sharpness of the structure at the gap voltage, were found to correlate well with good high-frequency performance and can be used as reliable predictors of high-frequency behavior. Other features, such as the "excess supercurrent," were shown to have no relation to the Josephson effect.¹⁰

We have also investigated the noise properties of our junctions.¹¹ The high-frequency noise can be determined from the rounding of the steps induced by the laser, and we found that the results were consistent with Johnson noise enhanced because of the temperature rise of the point contacts under irradiation. Additional noise which varies like $1/f^2$ below 10 kHz was measured directly, and proved to be the limiting factor on the NEP of junctions used as incoherent detectors of low-level radiation when biased near the incipient Josephson step. Typical NEP values at 604 GHz (496 μm) were about 10^{-13} Watts/(Hz)^{1/2} with a responsivity of 10^5 Volts/Watt.

References

1. D.A. Weitz, DAS Harvard Technical Report No. 14 (Tinkham Series), 1978.
2. D.A. Weitz, W.J. Skocpol, and M. Tinkham, *Optics Lett.* 3, 13 (1978).
3. D.A. Weitz, W.J. Skocpol, and M. Tinkham, *Phys. Rev. Lett.*, 40, 253 (1978).
4. D.A. Weitz, W.J. Skocpol, and M. Tinkham, *Phys. Rev.*, B18, 3282 (1978).
5. N.R. Werthamer, *Phys. Rev.*, 147, 255 (1966).
6. B.R. Fjordboge and P.E. Lindelof, *J. Low Temp. Phys.*, 38, 83 (1978).
7. T.D. Clark and P.E. Lindelof, *Phys. Rev. Lett.*, 37, 368 (1976).
8. M. Octavio, DAS Harvard Technical Report No. 13 (Tinkham Series), (1978).
9. M. Octavio and W.J. Skocpol, to appear in *J. Appl. Phys.*
10. D.A. Weitz, W.J. Skocpol, and M. Tinkham, *J. Appl. Phys.*, 49, 4873 (1978).
11. D.A. Weitz, W.J. Skocpol, and M. Tinkham, *Infrared Phys.*, 18, 647 (1978).

II.5 Laser-Induced Disequilibrium in Superconducting Films. L.N. Smith, A.D. Smith, W.J. Skocpol, and M. Tinkham, Contract N00014-75-C-0648, and NSF Grant DMR76-11323; Research Unit 2.

We are continuing with experiments involving optical and far-infrared laser illumination of superconducting thin films, described in greater detail last year. For strong optical perturbation, the question being investigated is whether the observed smooth transition to the normal state is the result of a spatial instability involving breakup

into domains with large and small values of the superconducting energy gap.¹ Our measurements of the resistive transition have proved inconclusive because of inhomogeneities (phase-slip centers) are also caused by the strong current perturbation. Most of our recent efforts have been devoted to developing photolithographic techniques for producing small tunnel junctions which are directly sensitive to the energy gap and which will perturb the illuminated film less strongly.

We are also continuing our efforts to measure changes in the distribution function of thin films illuminated by far infrared laser radiation with photon energies comparable to the energy gap. As a probe we are now using Al/I Oxide/Pb-Bi tunnel junctions which are sensitive to the distribution function over a wider range of energy above the energy gap of aluminum. We have carefully characterized the equilibrium tunneling curves and are studying the distribution function with weak optical illumination. We have not yet succeeded in absorbing sufficient far-infrared radiation in the films to produce interesting nonthermal distributions that contain structure reflecting the photon energy.

Reference

1. L.N. Smith, *J. Low Temp. Phys.*, 28, 519 (1977).

II.6 Production and Characterization of Amorphous Semiconductors. D.A. Anderson, P. Ketchian, M.A. Paesler, and W. Paul. Contracts N00014-75-C-0648, NSF DMR78-10014, NSF DMR76-15325, NSF DMR76-01111, NSF DMR77-24295 and ARMY DAAG29-77-G-0059; Research Unit 3.

Amorphous semiconducting films of Ge, Si, $\text{Ge}_{1-x}\text{H}_x$ alloy, $\text{Si}_{1-x}\text{H}_x$ alloy, GaAs, and $(\text{GaAs})_{1-x}\text{H}_x$ alloy have been produced by r.f. sputtering of polycrystalline targets by argon onto substrates of Be, 7059 glass, crystalline Si and Al held at suitable temperatures between 0°C and 400°C. Variation of the partial pressure of Ar was done to alter the conditions in the plasma so as to change the deposition rate and the surface mobility of the depositing Si atoms. Variation of the substrate temperature permitted healing of the disordered network without inducing crystallization. Variation of the partial pressure of H both permitted studies of variable composition alloys and exploration of the possible different H-configurations incorporated. Addition of PH_3 , B_2H_6 , N_2 or O_2 to the sputtering gas permitted doping the semiconductor n or p-type, the formation of n-p junctions, or interfacing high and low resistivity material.

The films are characterized chemically, when required, by electron microprobe and sputter-ion analysis. X-ray examinations are conducted to ensure amorphicity, the density is determined by floating the sample in a liquid whose density may be varied and accurately measured, and the thickness is found using a Sloan Dektak profiling apparatus.

The films produced are used for measurements of transport, photo-transport, photoluminescence, optical absorption, electron spin resonance, electoreflectance, drift mobility and field effect. A coherent

self-consistent explanation of these data is then sought. In subsequent sections, only those measurements supported predominantly by the JSEP will be described.

- II.7 Study of Doping, Schottky Barrier Formation and Solar Cell Efficiency in Amorphous $\text{Si}_{1-x}\text{H}_x$ Alloy. D.A. Anderson, G. Moddel, and W. Paul, Contracts N00014-75-C-0648, NSF DMR76-01111, NSF DMR77-24295, and DAAG29-77-G-0059; Research Unit 3.

The study of Schottky barriers, rectification characteristics and solar cell parameters has been temporarily postponed in favor of further determination of the optimum conditions for sample preparation, which is described in Section II.8.

- II.8 Study of Conditions for the Optimum Configuration of Pseudogap States in Amorphous Silicon. D.A. Anderson, R. Collins, E.C. Freeman, G. Moddel, S. Oguz, M.A. Paesler, and W. Paul, Contracts N00014-75-C-0648, DAAG29-77-G-0059, NSF DMR76-15325, and NSF DMR78-10014; Research Unit 3.

During this report period, work has concentrated on further improvement of the basic material so as to *optimize* the functional dependence (on energy) of the density of states in the energy gap. In the past, *optimization*--whether directed at producing material which can be doped with the least addition of dopant atoms, or at producing material with the highest photoconductivity or best photoluminescence--has been equated to the maximum reduction of defect-associated states in the

semiconductor pseudogap. It now appears that this is too simplistic a view, as will be described. For this investigation, the substrate temperature T_s , the H partial pressure p_H , the argon pressure p_{Ar} and the r.f. power have all been varied.

Evaluation of the results of the variation of these deposition parameters is done through study of the variations in conductivity, thermopower, absorption edge, vibrational absorption, H-evolution, photoluminescence and field-effect. A detailed discussion of these results is not appropriate here, but the conclusions can be given in summary form.

Increasing the substrate T_s might be expected to heal the network, and it does, but high T_s ($> 300^\circ\text{C}$) leads also to less incorporation of H *for a fixed* p_H . As a result, dangling bond defects are not adequately compensated. The best T_s now appears to be the highest temperature which, while not inducing crystallization, still alloys incorporation of H to eliminate dangling bonds. This means that T_s and p_H must be simultaneously increased.

The H-content C_H is not a linear function of the H-partial pressure p_H . In our apparatus, C_H increases with p_H for $p_H \leq \sim 10^{-3}$ Torr and C_H either remains constant or even decreases slightly for $p_H \geq \sim 10^{-3}$ Torr. This is attributed (as was reported last year) to changes in the nature of the atomic and molecular species in the plasma when the gas content is changed with r.f. current held constant. Films of the same C_H produced at different p_H have been found to possess quite different properties. This has been one of the most significant discoveries of this report period. Films prepared at low p_H have a

smaller density of gap states, as determined by measurements of hopping transport through them, and field effect. They are therefore most suitable for shift of the Fermi level by P, As or B doping, and they show the best photoluminescence. Films of the same C_H but prepared at high p_H have a much higher (order of magnitude) density of gap states, as revealed by hopping transport and field effect. However, interestingly, they uniformly give a higher photoresponse. We hypothesize that the *distribution* of states in the gap, determining the Fermi level, and also trapping and release, is important for the photoconductive response. Obviously this has direct relevance to optimization for solar cell applications.

The effect of varying the argon pressure has also been studied, predicated on the supposition that damage to the growing film can result from very energetic Si or Ar atoms/ions. Increased p_{Ar} reduces the mean free paths of the depositing species below the inter-electrode distance and so reduces their kinetic energy. On the other hand, too high a p_{Ar} may reduce the ions' energy to thermal values, which may be counter-productive, in that the low surface mobility can lead to "fluffy" porous films. It is indeed found that an optimum p_{Ar} exists, all other conditions being held constant. Thus, for example, the photoresponse rises then saturates around $p_{Ar} = 30$ m Torr, the transport remains activated with reduced activation energy up to $p_{Ar} \sim 30$ m Torr but above this shows an increasing curvature with temperature, and the photoluminescence also goes through a weak maximum in this pressure range. Furthermore films made at $p_{Ar} > 30$ m Torr show a tendency to oxidize after deposition suggesting a large surface area as might be expected for an extremely porous film.

II.9 Use of the Field Effect to Determine the Pseudogap State Density in Amorphous $\text{Si}_{1-x}\text{H}_x$ Alloys. D.A. Anderson and W. Paul, Contracts DAAG-29-77-G-0059 and N00014-75-C-0648; Research Unit 3.

During this report period, we have developed an apparatus to estimate the density of states in the gap of sputtered $\text{a-Si}_{1-x}\text{H}_x$ alloys through measurement of the field effect. In brief, the field effect technique uses a configuration similar to an MOS device to deposit charge in the surface layers of a semiconductor. The amount of charge is given by the applied field and the capacitance of an insulating dielectric. The charge raises the Fermi level at the surface by filling the states at the Fermi level. The shift in the Fermi level, in turn, is found from the change in activation energy for conduction parallel to the altered surface layer. Despite assumptions and questionable simplifications in the analysis practiced generally in the field, the method has been widely used to give the gap density of states in $\text{a-Si}_{1-x}\text{H}_x$ alloys.

Our measurements have been carried out on alloys of different H-content. The deduced density of states profile depends on the H-content, c_{H} , and also on the pressure of H gas, p_{H} , used to obtain a given c_{H} . The samples which give a high gap density of states also show structure in the photoluminescence spectrum and high hopping conductivity which is consistent with the field effect data. Thus it seems clear that the addition of this technique will help our overall research.

II.10 Photoconductivity in Amorphous $\text{Si}_{1-x}\text{H}_x$ Alloys. D.A. Anderson, G. Moddel, and W. Paul, Contracts N00014-75-C-0648 and DAAG-29-77-G-0059; Research Unit 3.

We have extended our earlier measurements to determine the spectral response, the temperature dependence, and the time decay characteristic of photoconductivity of samples of $\text{a-Si}_{1-x}\text{H}_x$ alloys prepared under different conditions of H partial pressure. From the photoconductivity magnitude and the decay time after illumination is removed, we have estimated the (trap-limited) drift mobility, which is between 10^{-2} and 10^{-3} $\text{cm}^2/\text{Volt-sec.}$ for electrons at room temperature. There are significant variations of the decay time with illuminating light intensity, whose investigation continues.

In parallel with this work, a collaborative effort has been started with Professor John Brebner of the University of Montreal to determine the drift mobility by direct time-of-flight methods. A report of the preliminary success of this work will be given by members of the two groups at the next meeting of the Canadian Physical Society.

Publications of the Research Reported in Sections II.6 to II:10.

1. M.A. Paesler and W. Paul, "Photoluminescence of r.f. Sputtered Hydrogenated Amorphous Silicon," *Bull. Am. Phys. Soc.*, 23, 247 (1978).
2. M.A. Paesler and W. Paul, "Photoluminescence in Sputtered Amorphous Silicon-Hydrogen Alloys," submitted to *Phil. Mag.*
3. S. Oguz and M.A. Paesler, "Evolution of Hydrogen from Reactively Sputtered Amorphous Silicon," *Bull. Am. Phys. Soc.*, 23, 247 (1978).

4. W. Paul and E.C. Freeman, "Infrared Vibrational Spectra of Si-H Bonds in a-Si," *Bull. Am. Phys. Soc.*, 23, 249 (1978).
5. E.C. Freeman and W. Paul, "Infrared Vibrational Spectra of r.f. Sputtered Hydrogenated Amorphous Silicon," *Phys. Rev. B* 18, 4288 (1978).
6. E.C. Freeman and W. Paul, "Optical Absorption Edge of Sputtered Hydrogenated Amorphous Silicon," *Bull. Am. Phys. Soc.*, 23, 249 (1978).
7. M.A. Paesler, D.A. Anderson, E.C. Freeman, G. Moddel, and W. Paul, "A New Development in the Study of Amorphous Si-H Alloys: The Story of O," *Phys. Rev. Lett.*, 41, 1492 (1978).
8. W. Paul, "Amorphous Semiconductors," Proceedings of the Third International Conference on Physics and Contemporary Needs, Nathiagali, Pakistan, to be published by Plenum Press.
9. E.C. Freeman and W. Paul, "Optical Constants of r.f. Sputtered Hydrogenated Amorphous Silicon," submitted to *Phys. Rev.*
10. D.A. Anderson, G. Moddel, M.A. Paesler, and W. Paul, "The Importance of Argon Pressure in the Preparation of r.f. Sputtered Amorphous Si-H Alloys," to be published in *J. Vac. Science and Technology*.

II.11 Vacancy Stabilization. L. Huisman, A. Carlsson, H. Ehrenreich, and C.D. Gelatt, Contracts N0014-75-C-0648, NSF DMR77-24295 and NSF DMR77-10210; Research Unit 1.

First principles calculations of the effect of vacancies on the heat of formation of the refractory compounds TiO and TiC have provided insight into the qualitative features which distinguish the vacancy-forming properties of these systems.¹ In stoichiometric TiC at low temperature, the equilibrium vacancy concentration is less than one percent, while in TiO it is on the order of ten percent on both sublattices. Detailed calculations of the electronic structure, and simple model Hamiltonian analogs, demonstrate the features of the metal-vacancy interaction which lead to vacancy stabilization. This new insight should prove useful in

understanding defect formation in other systems, such as reconstructed surfaces and distorted phases of nominally A-15 structure compounds, that exhibit defects in a high-symmetry structure at equilibrium.

Reference

1. L. Huisman, A. Carlsson, H. Ehrenreich, and C.D. Gelatt, "Defects Systems: A New Stabilization Mechanism in Compounds," to be published.

II.12 Electronic Theory of Disordered Semiconductors. C.D. Gelatt and S. Kivelson, Contracts N00014-75-C-0648 and NSF DMR77-24295; Research Unit 1.

The report of the effective mass theory formalism for non-crystalline systems is completed.¹ We find that charged substitutional impurities in a model of amorphous Si induce large radius, small binding energy impurity states whose properties are quite similar to those of the corresponding impurity states in crystalline Si. The qualitative features of this calculation have been confirmed² in exactly soluble extension of the Lloyd model. The influence of such spatially large states on the temperature and time dependence of photoluminescence in amorphous Si is currently under investigation.

We have analyzed conductivity in disordered insulators in which carriers move by phonon-assisted hopping, and demonstrated that the DC conductivity is finite, even in systems characterized by a large dispersion in hopping integrals among sites with a narrow range of energies, in contrast to the vanishing DC conductivity predicted by the results of Scher and Montroll based on a single-site decoupling of the configuration

average developed by Scher and Lax. This result calls into question conclusions about the electronic states in such systems drawn from analysis of transient photoconductivity using the Scher and Montroll formalism.

References

1. S. Kivelson and C.D. Gelatt, Jr., "Effective Mass Theory in Non-Crystalline Solids," *Phys. Rev. B*, to be published.
2. S. Kivelson and C.D. Gelatt, Jr., "Impurity States in a Disordered Insulator: The Lloyd Model," submitted to *Phys. Rev. B*.
3. S. Kivelson, "Hopping Transport and the Continuous-Time Random Walk," submitted to *Phys. Rev. B*.

II.13 Interfaces. A. Carlsson and H. Ehrenreich, Contract N00014-75-C-0648; Research Unit 1.

Ehrenreich's interests in semiconductor theory have been renewed because of his involvement as Chairman of a group formed at the suggestion of the White House OSTP studying solar photovoltaic energy conversion.¹ As a member of ARPA's Materials Research Council he has been and continues to be involved in investigations concerning physical size limitations in computer elements in connection with very large scale integration.

A better understanding of interfaces between semiconductors and oxides, semiconductors and metal, and even semiconductors and electrolytes represents an important ingredient in both areas. Questions such as the conditions under which one expects states localized in the vicinity of the interface and the effects of disorder on interface states are being studied by the use of model Hamiltonians. The Heine-Weaire Hamiltonian has been

used to study the electronic structure of the interface between a semiconductor and simple cubic metal. This same Hamiltonian has also been generalized to apply to SiO_2 in order to investigate some of the basic properties of the Si-SiO₂ interface, in particular, the formation of localized states. It is hoped that a better understanding of the passivation process will emerge from the latter investigation and that additional insight will be obtained concerning the height of Schottky barriers from studies of the semiconductor-metal interface.

Reference

1. *Principal Conclusions of the American Physical Society Study Group on Solar Photovoltaic Energy Conversion* (H. Ehrenreich, Chairman), American Physical Society, 1979.

II.14 Electrons in a Random Potential. M.J. Stephen, Contract N00014-75-C-0648; Research Unit 1.

According to the band theory an electron moving in a random potential is described by a diffusion equation. However, for sufficiently large disorder, diffusion becomes impossible and the electron becomes localized in space. A critical energy E_c (the mobility edge) in the band of allowed states separates localized states from extended states and, depending on the position of the Fermi energy, the material behaves as a semiconductor or a metal. We have developed a self-consistent theory to describe the mobility edge. Self-consistent integral equations for the distribution functions of the real and imaginary parts of the electron self-energy are obtained. The self-consistent approximation consists in neglecting the

effects of closed loops. The theory is exact in one dimension and is equivalent to a mean field approximation in higher dimensions. The determination of the mobility edge reduces to the solution of a linear integral equation and this has been solved approximately for some choices of the random potential. The determination of the diffusion constant and correlation length requires a solution of the integral equation near the mobility edge and this work is in progress.

III. INFORMATION ELECTRONICS CONTROL AND OPTIMIZATION

Personnel

Prof. R.W. Brockett

Prof. P. Caines

Prof. Y.C. Ho

Dr. C. Byrnes

Dr. T. Dwyer

Dr. R. Goodrich

Dr. G. Goodwin

Dr. B. Kurtaran

Dr. R. Suri

Mr. D.M. Chiu

Mr. D. Delchamps

Mr. M.A. Eyler

Mr. T. Iwata

Mr. P. Lu

Mr. N. Papadopoulos

Mr. L. Servi

Mr. M. Shayman

Mr. T. Taylor

Mr. W. Wong

III.1 Data Base System Problems. Y.C. Ho, B. Kurtaran, and D.M. Chiu, Contracts N00014-75-C-0648, N00014-78-C-0531, and NSF Grant ENG 76-11824; Research Unit 9.

(i) Query Optimization

Consider a single query such as "how many foreign born males over 35 are teaching in an eastern university with a student population over 15,000 and whose research interest is in system theory?" To retrieve the answer from the U.S. census data base, one can visualize a pass through the census data with an appropriate filter. However, if one is to answer hundreds and thousands of such queries per day using the data base, then such a naive

approach is clearly infeasible. Optimization in terms of file management, storage allocation, and the sequencing and processing of intermediate results become necessary. Two pertinent and recent references are Wong and Youssefi¹ and Eswaran.²

Abstractly, the problem can be considered as follows: Let the vector x represent the "state" of the data base. It is supposed to reflect the size of the various relations currently in store, their access mechanisms, indices and directories, and all the logical/physical parameters effective retrieval. As we process the query, intermediate results and relations appear which take the data base to a new "state" which is determined by the choice of intermediate processing decisions. Thus, a dynamic control problem takes shape. The object is to choose the processing decision optimally so that some criterion such as the processing time or effort is minimized subject to the constraints that the final state contains the desired output. We have formulated two simplified versions of the query optimization problem in a distributed data base. A report is under preparation.

(ii) Security and Access

Typically, in data base systems, the concept of an access matrix (rows represent users; columns, data) is used to determine "who can access what". As various "grant" and "revoke" commands are given by different users to each other in a distributed and random manner, the access matrix or the state of access evolves in a rather complex way effecting the security levels (exposure) or various data items. What is generally desired is that some overall security requirement, such as "no low level user should gain access to high level data" be insured. To use a gross analogy, by insisting that $\text{Re } \lambda_i(A) < 0$, a local property, we can insure that $x(t)$

(defined through $\dot{x} = Ax$) approaches zero as $t \rightarrow \infty$, a global property. Similarly, by imposing local requirements on how access is modified by local transition of "grant" and "revoke", we wish to insure overall secure information flows. Two pertinent references are (3) and (4). Our work⁵ represents a marriage of the ideas in (3) and (4).

References

1. E. Wong and K. Youssefi, "Decomposition-A Strategy for Query Processing," *ACM Transactions on Database Systems*, 1, #3, 223-241 (1976).
2. M.W. Blasgen and K.P. Eswaran, "Storage and Access in Relational Data Bases," *IBM System Journal*, 4, 363-377, December (1977).
3. D.E. Denning, *Secure Information Flow in Computer Systems*, Ch. 2, Ph.D. Thesis, Purdue University (1975), and "A Lattice Model of Secure Information Flow," *Comm. of ACM*, 19, 236-242, May (1976).
4. P.P. Griffith and B.W. Wade, "An Authorization Mechanisms for a Relational Database System," *ACM Transactions on Database Systems*, 1, #3, 242-255, September (1976).
5. Y.C. Ho and B. Kurtaran, "Data Base Access and Security Viewed as Dynamic and Stochastic System Problems," *1979 Conference on Information Science and Systems*, John Hopkins University, April (1979).

III.2 Teams and Organizations. Y.C. Ho and N. Papadopoulos, Contracts N00014-75-C-0648, N00014-78-C-0531, N00014-77-C-0533, and NSF Grant ENG 76-11824; Research Unit 9.

We studied the question of "who should know what" in the context of a general quadratic team problem with linear information structure. In this context two matrices C and H^+ are of central importance. The matrix C is dependent only on the payoff structure while H^+ , being the generalized inverse of the information structure matrix H , depends only on it. Rows of

C shows how different states of nature (i.e., the environment) effects each decision maker. Columns of H^+ detail how each piece of information can help in estimating the states of nature. The combination of C and H^+ then answers the question "which piece of information is of use to which decision maker". The implication of this to the organization of communication is obvious.

Reference

1. Y.C. Ho and N. Papadopoulos, "Further Notes of Redundancy in Teams," *IEEE Transactions on Automatic Control*, April 1979 (to appear).

III.3 Buffer Storage Problem in a Production Line. Y.C. Ho and A. Eyler, Contract N00014-75-C-0648, and The Charles Stark Draper Lab., Inc., Contract DL-H-162176; Research Unit 9.

A problem of long standing in manufacturing is the optimal allocation of buffer storage in a serial production line which is subject to random failures and repairs of its component machines. This problem can be formulated as a problem in Markov chain analysis with combinatorially large state space. We present a general solution to this problem. The key ingredient in the solution is an efficient scheme for the computation of the gradient component of the line throughput to buffer size increases at individual locations. Analytical results and experimental verification have been obtained. The method of gradient calculation is general and can be adopted to calculate sensitivities of production efficiency for other parameters.

Reference

1. Y.C. Ho, A. Eyler, and T.T. Chien, "A Gradient Technique for General Buffer Storage Design in a Serial Production Line," *Proceedings of the 1978 IEEE Decision and Control Conference*, San Diego, Calif., January 1979.

III.4 Decentralized Resource Management in Large Systems. Y.C. Ho and R. Suri, Contract N00014-75-C-0648, NSF Grant ENG 76-11824, and The Charles Stark Draper Lab., Inc., Contract DL-H-162176; Research Unit 9.

The study of Large-Scale Systems is becoming increasingly important, as is reflected by the recent devotion of an entire issue of a prominent journal¹ to the topic of "Large-Scale Systems and Decentralized Control." Our recent work^{2,3} studies the application of decentralization to one aspect of such systems, namely, the problem of Resource Management in Large Systems.

In a large operational system, where a very large number of activities share a number of limited resources, this Resource Management problem has three main objectives. The first (the "Initial Allocation" or "Design" problem) is to find an assignment of resources to all the activities, such that all the system constraints are satisfied, and all activities are operating, so that the system as a whole can operate. The second (the "New-Assignment" problem) is to find a rationale for allocating resources to new activities. It is presumed that new activities are initiated frequently enough that we do not wish to resolve the entire problem. The third objective ("Periodic Review" problem) is to find an efficient way of reallocating resources in order to reflect the changing needs of the individual activities, as well as the changes in total resource usages.

The main contributions of our work is to extend the applicability of decentralized techniques to problems where the resource usages functions are ill-behaved (e.g., discontinuous). We prove the existence of a decentralized solution, and give efficient algorithms guaranteed to converge to this solution.

Our approach enables efficient solution of a problem with over 60,000 activities, each of which has a 16-dimensional decision vector. This one-million dimensional problem would be hard and impractical to solve by other methods.

References

1. *IEEE Transactions of Automatic Control*, Vol. AC-23, No. 2, April 1978.
2. R. Suri, "Resource Management in Large Systems," Division of Applied Sciences, Harvard University, Technical Report No. 671, December 1978.
3. R. Suri and Y.C. Ho, "An Algorithm for Resource Management in Large Systems," *Proceedings 17th IEEE Conference on Decision and Control*, San Diego, Calif., January 1979.

III.5 Identification of Time Invariant Linear Systems from Non-Stationary Cross-Sectional Data. P.E. Caines, Contract N00014-75-C-0648; Research Unit 10.

We have developed a new theory and methodology for the identification of linear time invariant finite dimensional systems from non-stationary cross-sectional data. The parameters of a system model are estimated from repeated observations on a set of transient output samples of the system, where each sample is of finite duration. This work and its underlying theory is described in the papers (1-4); it permits parameter identification for a class of systems for which this was not previously possible.

In our theory we formulate the notion of (non-stationary) system identifiability as that of unique stochastic realizability.² That is to say, a parameterized system is identifiable if (exact) estimates of the output process covariance lead to unique estimated values of the system parameters. We have recently shown² that for non-stationary systems of the form appearing in (1) one has (local identifiability) without any condition on the stability of the system. This result gives significant scope to the applications of the technique described in (1). In addition the computer program presented in (5) is being currently improved in terms of its efficiency and flexibility.

References

1. R.L. Goodrich and P.E. Caines, "Linear System Identification from Non-Stationary Cross-Sectional Data," *IEEE Trans. on Automatic Control*, Vol. AC-24, No. 2, April 1979. Also presented at IEEE Conf. on Decision and Control, San Diego, Calif., January 1979.
2. R.L. Goodrich and P.E. Caines, "On the Non-Stationary Covariance Realization Problem," to appear *IEEE Trans. on Automatic Control*. Also presented at IEEE Conf. on Decision and Control, San Diego, Calif., January 1979.
3. R.L. Goodrich and P.E. Caines, "Necessary and Sufficient Conditions for Local Identifiability," *IEEE Trans. on Automatic Control*, Vol. AC-24, No. 1, pp. 125-127. Also presented at IEEE Conf. on Decision and Control, San Diego, Calif., January 1979.
4. R.L. Goodrich and P.E. Caines, "Time Invariant Linear System Identification from Non-Stationary Cross-Sectional Data," presented at IMA Conference, "Analysis and Optimization of Stochastic Systems," Oxford, U.K., September 1978.
5. R.L. Goodrich, *Stochastic Models of Human Growth*, Ph.D. Thesis, Division of Applied Sciences, Harvard University, May 1978.

III.6 Deterministic and Stochastic Adaptive Control. P.E. Caines,
Contract N00014-75-C-0648; Research Unit 10.

We have studied the problem known in systems science as the adaptive control problem. The issue here is whether it is possible to stabilize an unstable (linear) dynamical system whose parameters are unknown. This is to be achieved by simultaneously estimating the system parameters and continuously designing improved feedback control laws. Although there exist several examples of successfully operating adaptive control regulators in industry, a theoretical study of their behavior has eluded research workers for years. Some important partial results have recently appeared in (1) and (2).

We showed³⁻⁶ that stabilizing adaptive control is indeed possible for multi-input multi-output linear systems with the control laws being chosen from a large class of simple and intuitively appealing parameter estimation and control algorithms. In addition, by the use of recent results in probability theory, the analogous problem for stochastic systems was solved. It should be emphasized that although the underlying systems to be controlled are linear the closed loop system with its learning and control regulator is nonlinear.

References

1. A. Feuer and A. Morse, "Adaptive Control of Single-Input Single-Output Linear Systems," *IEEE Trans. Automatic Control*, Vol. AC-23, No. 4, pp. 557-570, August 1978.
2. B. Egardt, "Stability of Model Reference Adaptive and Self-Tuning Regulators," Ph.D. Thesis, Dept. of Automatic Control, Lund Institute of Technology, March 1978.
3. G.C. Goodwin, P.J. Ramadge, and P.E. Caines, "Discrete Time Multivariable Adaptive Control," Research Report, Div. of Appl. Sciences, Harvard University, November 1978. Submitted to *IEEE Trans. on Automatic Control*.

4. G.C. Goodwin, P.J. Ramadge, and P.E. Caines, "Discrete Time Stochastic Adaptive Control," Research Report, Div. of Appl. Sciences, Harvard University, December 1978. Submitted to *SIAM J. Control and Optimization*.
5. G.C. Goodwin, P.J. Ramadge, and P.E. Caines, "Ultimate Objectives and Prior Knowledge in System Identification," Research Report, Div. of Appl. Sciences, Harvard University, December 1978. Submitted for presentation at *5th IFAC Symposium on Identification and System Parameter Estimation*.
6. G.C. Goodwin, P.J. Ramadge, and P.E. Caines, "Some Recent Results in Stochastic Adaptive Control," to be presented at the *Conference on Information Sciences and Systems*, Johns Hopkins University, Baltimore, Maryland, March 1979.

III.7 Nonlinear Systems. R.W. Brockett, Contract N00014-75-C-0648; Research Unit 8.

In our paper¹ we examine the structure of the necessary conditions of optimal control using the Volterra series results developed over the last few years. This approach goes beyond earlier efforts in this direction in that it includes the effect of terminal constraints and describes the minimal amount of smoothness on the system and performance measure necessary to find necessary conditions which are also sufficient. The results of this paper are paralleled by recent developments in the mathematical programming literature associated with the group around Ben-Israel.

Reference

1. R.W. Brockett, "Lie Theory, Functional Expansions and Necessary Conditions in Singular Optimal Control," in *Mathematical Control Theory*, (W.A. Coppel, ed.), Springer Lecture Notes in Mathematics, Springer Verlag, Berlin, 1978.

III.8 Estimation Theory. R.W. Brockett, Contract N00014-75-C-0648;
Research Unit 8.

In reference (1) we describe a new point of view on the conditional density equation--the basic equation of nonlinear filtering. We show there the connection between the existence of simple filters and certain Lie algebras. This point of view allows us to describe certain estimation problems which are not linear and Gaussian but which have, nonetheless, simple filtering algorithms.

Reference

1. R.W. Brockett, "The Geometry of the Conditional Density Equation," Proceedings of the Oxford Conference on Stochastic Systems, Oxford, England, 1978 (with J.M.C. Clark), to appear.

III.9 Linear Systems. R.W. Brockett, Contract N00014-75-C-0648; Research Unit 8.

We have just completed work on the celebrated "output-feedback" problem, obtaining by classical geometric techniques the most extensive, and in some cases the sharpest, results currently available. This has ramifications in stability theory and the same techniques also apply to problems of adaptive control, e.g., the stabilization of systems depending on parameters. In reference (1) we discuss entirely unexpected connection between the theory of linear and nonlinear systems.

Reference

1. C.I. Byrnes, "On Certain Families of Rational Functions Arising in Dynamics, *Proc. of the 1979 Conference on Decision and Control*, IEEE, N.Y.

Publications:

1. R.W. Brockett, "Lie Theory, Functional Expansions and Necessary Conditions in Singular Optimal Control," in *Mathematical Control Theory*, (W.A. Coppel, ed.), Springer Lecture Notes in Mathematics, Springer Verlag, Berlin, 1978.
2. R.W. Brockett, "Modeling and Estimation with Bilinear Stochastic Systems," *Trans. of the 24th Conference of Army Mathematicians*, 1978.
3. R.W. Brockett, "The Geometry of the Conditional Density Equation," *Proceedings of the Oxford Conference on Stochastic Systems*, Oxford, England, 1978 (with J.M.C. Clark), to appear.
4. R.W. Brockett, "The Geometry of the Partial Realization Problem," *Proceedings of the 1979 Conference on Decision and Control*, IEEE, N.Y.
5. R.W. Brockett, "Stochastic Control and the Second Law of Thermodynamics," *Proceedings of the 1979 Conference on Decision and Control*, IEEE, N.Y. (with J.C. Willems).
6. R.W. Brockett, "Finite Dimensional Nonlinear Estimation," *Journées sur L'Analyse des Systèmes* Bordeaux, 1978.
7. C.I. Byrnes, "On Certain Problems of Arithmetic Arising in the Realization of Linear Systems with Symmetries," *Journées sur L'Analyse des Systèmes*, Bordeaux, 1978.
8. C.I. Byrnes, "Feedback Invariants for Linear Systems Defined Over Rings," *Proc. of the 1979 Conference on Decision and Control*, IEEE, N.Y.
9. C.I. Byrnes, "On Certain Families of Rational Functions Arising in Dynamics," *Proc. of the 1979 Conference on Decision and Control*, IEEE, N.Y.
10. C.I. Byrnes, "Applications of Algebraic Geometry in System Theory," to appear in *Amer. J. of Math.*, April 1979 (with P.L. Falb).

IV. ELECTROMAGNETIC PHENOMENA

Personnel

Prof. T.T. Wu	Mr. R. Bansal
Prof. R.W.P. King	Mr. J.E. Baum (summer)
Prof. M. Krook	Mr. D.J. Blejer
Dr. J. deBettencourt	Mr. H.-M. Lee
Dr. T.K. Sarkar (until May 31)	Mr. M.J. Miller
Dr. L.C. Shen (summer)	Ms. M. Owens
	Ms. B.H. Sandler

Research in the area of electromagnetic radiation is directed toward the solution of practical problems through the complete understanding of the underlying physical phenomena. This involves the coordinated application of modern analytical, numerical, and experimental techniques and the use of high-speed computers and precision instrumentation. Most practically significant problems in this area are sufficiently complicated that extensive computation and measurement are often required to justify approximations that are usually necessary. Where possible, general formulas are obtained and verified experimentally so that the phenomenon under study can be understood physically in analytical form and not just as a set of numbers.

The researches are conveniently grouped under two main headings, viz., *antennas and waves in and over dielectric, conducting, and plasma media*, and *antennas in air*. The first group is concerned with the circuit, radiating, and scattering properties of antennas and arrays and the waves

generated by them in their dependence on the electrical properties of a material medium (lake water, sea water, earth, ice, living tissue, plasma, etc.) in various forms and degrees of proximity. The antennas may be directly embedded in the medium or separated from it by a layer of insulation. The second group of investigations deals with the detailed electrical properties of complicated metal radiating and scattering structures in air including especially electrically thin and thick crossed conductors used to model an aircraft.

ANTENNAS AND WAVES IN AND OVER DIELECTRIC,
CONDUCTING, AND PLASMA MEDIA

IV.1 Theoretical and Experimental Study of the Scattering from an Obstacle Above the Earth. H.-M. Lee, T.T. Wu, and L.C. Shen, Contracts N00014-75-C-0648 and F19628-77-C-0146; Research Unit 11.

A knowledge of the electromagnetic field scattered by targets located on or above the surface of the earth is of primary importance in radar. This field is radiated by the currents induced in the target by the incident plane wave. It follows that a first step in evaluating the scattered field is the determination of the induced currents. These depend not only on the geometrical and electrical characteristics of the scattering target and the direction and polarization of the incident wave, but also on the proximity of the earth with its conducting and dielectric properties. In effect, the current in the target corresponds to a continuous distribution of infinitesimal dipoles, each with appropriate amplitude and relative phase. Thus, the total scattered field is the vector sum of the contributions by all of the small dipoles, each with its particular amplitude and phase. The field of one of the infinitesimal dipoles is the solution of the Sommerfeld problem.

The thin circular loop is the most convenient target to analyze initially because of its rotational symmetry and its usefulness in the construction of composite targets. Furthermore, the current distribution and scattered field are well known when the loop is isolated, i.e., sufficiently far from the earth. Among loops that possess rotational symmetry around the z-axis normal to the earth's surface, the cylindrical

loop (cut from a cylinder of zero thickness with its height much smaller than its radius and the incident wavelength) has the simplest integral equations for the two components of the surface current excited by an external field. Although the two integral equations can be decoupled, their evaluation is exceedingly difficult due to the many widely varying parameters. In a recent report,¹ a variational approach is used to solve the problem. The solution is extended to multiple loops and to multiple loops each with arbitrary cross section. Attempts are continuing to obtain an analytical solution to the decoupled integral equations. The lowest-order analytical solution to this problem was originally derived by T.T. Wu in his study of the loop antenna.² The next-order correction to the kernel of the decoupled integral equations has now been obtained. It is expected that this knowledge will help in the solution of other problems, including the loop placed above the earth.

The circular loop is also a simple target for use in a systematic program of measurement. As described in detail in an earlier report,³ one set of measurements has been completed of the field scattered by horizontal resonant and nonresonant circular loops and by a straight wire one-half wavelength in length over a wide range of sizes, angles of incidence, and heights outdoors over the earth. These results were also presented as a conference paper.⁴ An apparatus has been constructed to continue the measurements systematically over a tank of water with variable conductivity. A comprehensive experimental study is in progress.

References

1. T.T. Wu and H.-M. Lee, "Scattering of Electromagnetic Waves by Obstacles in the Presence of the Earth's Surface: Current Distribution on Perfectly Conducting Cylindrical Loops in an Incident Electromagnetic Field," Final Scientific Report, RADC Contract F19628-77-C-0146, to be issued.

2. T.T. Wu, "Theory of the Thin Circular Loop Antenna," *J. Math. Phys.*, vol. 3, pp. 1301-1304, November-December 1962.
3. R.W.P. King, H.-M. Lee, and L.C. Shen, "Scattering from Obstacles over the Earth," Scientific Report No. 1, RADC Contract F19628-77-C-0146, to be issued.
4. L.C. Shen, R.W.P. King, R. Bansal, and H.-M. Lee, "The Measurement of the Scattered Fields from a Metal Loop and a Straight Wire Placed Above the Ground," presented at the National Radio Science Meeting, held at the University of Colorado, Boulder, January 9-13, 1978.

IV.2 Numerical and Analytical Determination of Electromagnetic Fields of Antennas in the Earth Near Its Interface with Air. R.W.P. King, B.H. Sandler, and L.C. Shen, Contract N00014-75-C-0648; also NSF Grant ENG-76-17596 with the University of Houston; Research Unit 11.

The calculation of the electromagnetic field in a dissipative half-space due to an infinitesimal electric dipole in the same half-space and with its axis parallel to the interface is a classic problem closely related to the work of Sommerfeld on the field in air due to a dipole also in air above a dissipative earth. It has been the subject of extensive investigations. In an earlier paper,¹ expressions for the three cylindrical components of the electric field were obtained from Baños' general formulas in terms of complex integrals. These were evaluated numerically for a range of frequencies and radial distances from a horizontal dipole in sea water, lake water, and dry earth. An alternative derivation that proceeds directly from Maxwell's equations and the boundary conditions² has led to equivalent integral expressions. These have been evaluated by a less time-consuming program. As a result, more comprehensive calculations have been possible. Tables have been prepared of the generally useful, radial component of the electric field for radial distances from 100 m to 100 km,

frequencies from 10 to 10^9 Hz, effective relative permittivities from $\epsilon_{er} = 2$ to 80, and effective conductivities from $\sigma_e = 4 \times 10^{-6}$ to 4 Si/m. In a paper now being prepared³ three practical ranges of the parameters are selected for careful study and interpretation. These are dry earth ($\epsilon_{er} = 4$, $\sigma_e = 0.00004$ to 0.04 Si/m), moist earth ($\epsilon_{er} = 20$, $\sigma_e = 0.0004$ to 0.4 Si/m), and water ($\epsilon_{er} = 80$, $\sigma_e = 0.004$ to 4 Si/m). Extensive graphs and contour diagrams of E_ρ serve to display the characteristics of propagation in their dependence on the frequency, the radial distance, the depth, and the electrical parameters of the earth. They are interpreted in terms of the approximate formulas of Baños which are evidences of the lateral-wave nature of the field.

For actual transmission, antennas of finite size are required. The problem of determining the field of a finite antenna in or above a dissipative half-space is difficult since it involves not only the shape and dimensions of the antenna, but also the conducting and dielectric properties of the earth. The field generated by the currents in an extended conductor can be calculated from the known field of an infinitesimal dipole only after the distributions of current have been determined in their dependence on the properties of the earth. A paper has been written⁴ which treats three special cases of a horizontal wire in or close to a dissipative earth. These are an end-driven Beverage-type antenna, a horizontal wire as a scatterer in the presence of the earth, and an embedded insulated traveling-wave antenna. For each of these, an analytically determined distribution of current is available that takes full account of the electrical properties of the adjacent or surrounding material half-space provided the medium is electrically dense and the height of the antenna

(when in air) is sufficiently small. For the embedded insulated antenna with insulation radius b , the depth d below the surface must be large enough so that the medium is effectively infinite, i.e., $d^2 \gg b^2$. Also, the insulated part of the antenna must be electrically thin in terms of both wave numbers k_1 of the material half-space and k_0 of the insulation, viz., $k_1 b < 1$ and $k_0 b < 1$. For each of the three cases, expressions for the most useful component of the radiated or scattered field are formulated.

In a related study⁵ special attention is given to the eccentrically insulated traveling-wave antenna embedded beneath the surface of the earth. This antenna is particularly useful for subsurface communication by lateral waves since its field pattern is highly directive upward. Simple analytical formulas for the input impedance, current distribution, and field pattern are derived that incorporate the recent advances in determining the properties of antennas of finite size in the presence of the air-earth boundary. A step-by-step procedure for designing an eccentrically insulated traveling-wave antenna is given. To increase the directivity further, a broadside array of eccentrically insulated traveling-wave antennas can be used.

Since lateral-wave transmission is inefficient even when fairly directive eccentrically insulated traveling-wave antennas are used, relatively large amounts of power must be supplied to the antenna in order to generate a significant field at a distance. The question arises: How intense is the field radiated upward into the air? Is this sufficiently intense to be hazardous to living organisms? This is the subject of a new paper,⁶ in which accurate calculations are made of the electric and magnetic fields in the air above a horizontal electric dipole in the sea, a lake, and the earth. This is carried out directly from the exact general integrals.

Useful approximate expressions for the field in air above the transmitting dipole are also obtained which indicate that the limiting forms given by Baños are oversimplified for the determination of the phases. Numerical calculations from the exact formulas are also made of the electric and magnetic fields on the surface directly over the embedded dipole, and approximate simple formulas are derived and compared. In all cases, the Poynting vector is directed upward into the air and not, as stated by Baños, downward from the air into the conducting half-space. These results are in complete agreement with the theory of embedded antennas which indicates that it is possible to transmit from a dipole within a dielectric or conducting body out into the surrounding air, - a process which requires an upward directed Poynting vector in the air.

References

1. R.W.P. King and B.H. Sandler, "Subsurface Communication Between Dipoles in General Media," *IEEE Trans. Antennas Propagat.*, vol. AP-25, pp. 770-775, November 1977.
2. R.W.P. King and G.S. Smith, *Antennas in Matter: Fundamentals, Theory, and Applications*, The M.I.T. Press, Cambridge, Mass., in press.
3. R.W.P. King, B.H. Sandler, and L.C. Shen, "A Comprehensive Study of Subsurface Propagation from Horizontal Electric Dipoles," submitted for publication.
4. R.W.P. King, "Electromagnetic Waves and Antennas Above and Below the Surface of the Earth," *Radio Science*, Special Issue on the Communication of Professor Bremmer's 75th Birthday, March-April 1979.
5. L.C. Shen and R.W.P. King, "An Eccentrically Insulated Traveling-Wave Antenna for Subsurface Communication," submitted for publication.
6. R.W.P. King and L.C. Shen, "Radiation Into the Air Above a Horizontal Dipole in the Earth," submitted for publication.

IV.3 Transmission and Reception with Bare and Insulated Antennas Embedded in Skin. R.W.P. King and B.H. Sandler, Contract N00014-75-C-0648; and NSF Grant ENG 73-03507 A01 with Northeastern University; Research Unit 11.

Transponders are embedded in or located just outside a living organism for the remote monitoring of various quantities such as body temperature, heart beat, and intensity of radiation. Alternatively, it may be of interest to use an embedded or externally attached transponder to identify or locate animals in their environment. The successful operation of such systems depends greatly on the proper design of transmitting and receiving antennas for use within or near a living organism. For this, it is necessary to know the magnitude, phase and polarization of the electric field at different points of observation in the body and just outside its surface. Furthermore, the complete circuit properties (admittance, current, and charge per unit length) of the embedded or attached antenna are of interest in their dependences on the electrical properties of the environment.

The electric field in a body has the commonly assumed simple properties of an exponentially attenuated traveling plane wave only when (a) the exciting field is a normally incident, plane wave, (b) the body is large enough to permit its surface to be treated as locally plane, and (c) internal reflections can be neglected. At other than normal incidence, the wave transmitted into the body is inhomogeneous with surfaces of constant phase and constant amplitude that neither coincide nor travel in the same direction. It follows that the field acting to induce currents in an embedded antenna is quite different from that acting on the same antenna in air at the same other than normal angle of incidence. The determination of the current is further complicated at any angle of incidence if the attenuation constant

of the medium is low enough or if the body is small enough or consists of electrically different layers to make internal reflections and the associated standing waves significant.

A complete investigation has been reported¹ on the voltage generated by an incident plane wave across the load of a bare or insulated receiving dipole at various depths in a half-space composed of a single homogeneous material with the electrical properties of skin. This includes the determination of the impedance of the antenna in the particular environment. The reciprocal problem of obtaining the voltage across the load in a receiving antenna located at a distant point in air by an emf applied to a bare or insulated dipole embedded at various depths in a half-space of skin has also been solved.² Specifically, two-way communication between an element embedded up to 1 cm in skin and an outside unit at a distance of 4.3 m at the optimum frequency of 700 MHz or 1 m at 3 GHz has been analyzed. The solution of the electromagnetic problem of the transponder at various depths in a homogeneous half-space of skin is thus completed.

A further investigation has been made³ to extend these analyses to receiving and transmitting antennas located in or near the surface of a three-layered half-spacing consisting of finite thicknesses of skin and fat on an infinite depth of muscle. In particular, the properties of bare and insulated antennas are examined when successively located in the air just outside the body and at the centers of the layers of skin and fat, and at a fixed distance in the muscle. The electromagnetic problems that require solution for the centrally loaded receiving antenna include the determination of the following quantities: (a) The electric field at all points where a transponder may be located in terms of the incident field

at the surface of the skin. (b) The driving-point impedance Z_0 of the bare and insulated antennas when located successively in the air and in the layers of skin, fat and muscle. (c) The current in the load for both types of antenna in each of the four locations. (d) The voltage V_L across the load Z_L . For the transmitting mode, the additional quantity required is the ratio $|V_L|/|V^e|$ of the voltage V_L across the load of the receiving antenna in air to the driving voltage V^e applied across the terminals of the embedded transmitting antenna. Bare and insulated antennas are considered over a frequency range up to 3 GHz with layer thicknesses of skin from 0.1 to 1.0 cm, and of fat from 0 to 1.5 cm. The application of the results to finite bodies is discussed.

References

1. R.W.P. King, "Embedded Bare and Insulated Antennas," *IEEE Trans. Bio-medical Eng.*, vol. BME-24, pp. 253-260, May 1977.
2. R.W.P. King, "Transmission and Reception with Embedded Antennas," *IEEE Trans. Biomedical Eng.*, vol. BME-25, pp. 397-400, July 1978.
3. R.W.P. King, S. Prasad, and B.H. Sandler, "Transponder Antennas In and Near a Three-Layered Body," submitted for publication.

IV.4 Theoretical and Experimental Study of Electromagnetic Fields and Antennas in Dissipative and Dielectric Cylinders. R. Bansal, Contract N00014-75-C-0648; Research Unit 11.

The complex physical problem associated with the transmission of an electromagnetic signal from an antenna in air to another located at an arbitrary distance inside a finite material body is of considerable practical interest. Such an investigation is of importance, for example, in the study

of the properties of antennas embedded in dielectric, poorly conducting aircraft, in the determination of the biomedical hazards of EM radiation of living biological systems, and in the use of embedded transponders. The problem is also closely related to diffraction by bodies in the resonant regions and to scattering by dielectric objects.

As a first step in the investigation, a systematic experimental study has been initiated to determine the distribution of the electric field (in both amplitude and phase) inside a finite circular cylinder of water enclosed in a styrofoam container when illuminated by an approximately plane wave. An experimental setup for this purpose has been designed, fabricated, and thoroughly tested. The setup includes an indoor aluminum ground plane, a transmitter consisting of a quarter-wave monopole backed by a corner-reflector, and the probing system located at the receiving end inside a water cylinder. For experimental reasons a thin central conducting tube is included along the axis of the cylinder of water; this is needed to shield the transmission lines leading to the probes. The probing system makes use of a pair of dipoles to measure simultaneously the amplitude and phase of the axial and transverse components (the z and ϕ components in the usual cylindrical coordinates) of the electric field. The radial component (ρ component) of the electric field cannot be measured in the present setup since the radial arm supporting the dipoles necessarily interferes with the radial component of the electric field.

At low frequencies it is quite difficult to generate an incident plane-wave field indoors. On the other hand, since the wavelength in water is much shorter than the free-space wavelength, it is undesirable--from physical design considerations in the receiving system--to use very high transmission frequencies. As a compromise between these two conflicting

requirements, 10^8 Hertz has been selected as the transmitter frequency, at least initially. The setup can be modified easily to make measurements over a wide band of frequencies.

After the preliminary testing was completed, field measurements were started in a cylinder of distilled water with $kh = 1.5\pi$ and $ka = 1.6$, where k is the wave number in distilled water, h is the half-length of the cylinder, and a is the radius of the cylinder. These measurements are nearing completion. Measurements in salt-water cylinders are then planned. The electrical properties (relative permittivity and conductivity) of the salt-water solutions will be measured using a simple coaxial-line setup developed previously at Harvard.¹

The theoretical determination of the electric field in a finite body when illuminated from outside is difficult. Some attempts at numerical solutions have been made in recent years.^{2,3} These and other possible methods are currently being investigated and will be applied to the water cylinder with and without the central conductor. It is hoped that the experimental results will serve as the basis for an analytical-numerical solution within experimentally determined useful ranges of the parameters.

References

1. G.S. Smith, "A Theoretical and Experimental Study of the Insulated Loop Antenna in a Dissipative Medium," Tech. Report No. 637, JSEP Contract N00014-67-A-0298-0005, DEAP, Harvard University, Cambridge, MA, April 1973, pp. 52-60.
2. D.E. Livesay and K.M. Chen, "Electromagnetic Fields Induced Inside Arbitrarily Shaped Biological Bodies," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-22, pp. 1273-1280, December 1974.
3. P.W. Barber, "Resonance Electromagnetic Absorption by Nonspherical Dielectric Objects," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-25, pp. 373-381, May 1977.

IV.5 Experimental Studies of Antennas in Plasmas. M.J. Miller, Contract
N00014-75-C-0648; Research Unit 11.

The performance of a cylindrical antenna of half-length h in a material medium depends on both βh and α/β . In a plasma medium α/β and β are indirectly related to the ratio of the operating frequency ω to the plasma frequency ω_p and the ratio of the collision frequency ν to ω_p . Changing the operating frequency of a plasma-immersed cylindrical antenna within a 10 to 1 range can change β more than 3 orders of magnitude while the α/β ratio can easily vary throughout the range $0 < \alpha/\beta < 100$. A conference paper has been accepted for presentation¹ which will compare the results of an experimental investigation to measure the impedances and distributions of current and charge of antennas in a plasma with the corresponding theoretically calculated quantities. Use will be made of the general theory for a cylindrical antenna in a homogeneous, isotropic, dissipative medium² which applies to antennas of electrical length βh from zero to more than 2π immersed in a medium whose α/β ratio can vary from zero to 10. The experimental apparatus used to measure the electrical performance of a plasma-immersed antenna consisted of a controlled d.c. helium discharge contained in a 15 cm diameter pyrex tube. Plasma frequencies were in the 0.4 - 1 GHz range, and ν/ω_p was as large as 0.2. The antenna was a bare, 11 cm long, cylindrical monopole driven from a precision coaxial line. It was fitted with small movable probes to measure distributions of current and charge. The coaxial feed line had calibrated voltage and current probes connected to a vector voltmeter which was interfaced with a small computer so that antenna impedances could be measured and plotted during experimentation.

References

1. D. Preis, M.J. Miller, and R.W.P. King, "The Cylindrical Antenna in a Plasma Medium: A Critical Comparison of Experiment with Theory," accepted for presentation at the 1979 IEEE International Conference on Plasma Science, Quebec, Canada, June 4-6, 1979.
2. R.W.P. King, B. Sandler, and T.T. Wu, "Cylindrical Antenna Immersed in Arbitrary Homogeneous Isotropic Media," *J. Appl. Phys.*, vol. 40, pp. 5049-5065, December 1969.

IV.6 Antennas in Matter: Fundamentals, Theory, and Applications. R.W.P. King, G.S. Smith, M. Owens, and T.T. Wu, Contracts N00014-75-C-0648, F19628-76-C-0057, and F44620-72-C-0021, and NSF Grant ENG 75-14455; Research Unit 11.

The results of current and past researches, supported by the above Contracts and Grant, on bare and insulated antennas in and over dissipative or dielectric media have been integrated into a three-part book manuscript.¹ Part I is devoted primarily to the simple, transmission-line-like behavior of the insulated antenna. A brief introduction is also given to the bare antenna in an approximate, quite simple form. Both types of antenna are studied as probes in material media. The propagation of plane waves and pulses in such media is also treated. Part II is an advanced theoretical treatment of antennas in various media. It begins with a detailed study of the electromagnetic equations in homogeneous, isotropic media including the careful formulation of constitutive relations. The complete theory of the bare dipole in a general medium is presented and this is followed by a rigorous analysis of the insulated antenna. Similar analyses are provided for the bare and insulated loop antennas. The concluding chapter in Part II treats the problem of subsurface communication between antennas

near the plane interface between air and a general half-space. Finally, Part III is concerned with the construction of experimental models and the techniques of measurement relating to antennas and probes in a general dissipative or dielectric medium.

Reference

1. R.W.P. King and G.S. Smith, *Antennas in Matter: Fundamentals, Theory, and Applications*, The M.I.T. Press, Cambridge, Mass., in press.

ANTENNAS IN AIR

IV.7 Single and Crossed Electrically Short and Thin Tubular Cylinders.

R.W.P. King, D.J. Blejer, and B.H. Sandler, Contract N00014-75-C-0648 and Grant AFOSR-76-3073; Research Unit 11.

The surface densities of current and charge induced on tubular, highly conducting cylinders and intersecting cylinders by a normally incident plane wave depend in both their axial and transverse distributions on the length and radius of the individual conductors. When $ka \leq 0.1$, the general series of transverse Fourier components is well approximated by two terms for both E- and H-polarizations. When $kh > 1$, $ka \leq 0.1$, the zero-order axial current dominates and thin-cylinder theory and junction conditions are adequate to determine the axial distributions. A paper has been written¹ and presented² in which it is shown that, as kh is reduced to satisfy the conditions $ka < kh \ll 1$, the magnitude of the rotationally symmetric axial current decreases to small values and the first-order axial currents together with the transverse current dominate. All of these have

nonrotationally symmetric transverse distributions. They are determined by the local incident magnetic field and are in a large measure independent of junction conditions. The paper points out the significance of the surface currents and charges on aircraft illuminated by an incident electromagnetic pulse containing low-frequency components for which the dimensions of the aircraft are electrically short. For them, calculations of currents and charges by thin-cylinder approximations and junction conditions are inadequate and must be supplemented with or even replaced by currents and charges calculated from the first-order term in the transverse Fourier representation.

References

1. R.W.P. King, D.J. Blejer, and B.H. Sandler, "Current Induced on Single and Crossed Electrically Short and Thin Tubular Cylinders by a Normally Incident, Plane Electromagnetic Wave," to appear in *IEEE Trans. on Antennas and Propagation*.
2. R.W.P. King, D.J. Blejer, and B.H. Sandler, "Current Induced on Single and Crossed Electrically Short and Thin Tubes by a Normally Incident, Plane Electromagnetic Wave," presented at the 1978 USNC/URSI Meeting, held at the University of Maryland, College Park, May 15-19, 1978.

IV.8 Surface Currents and Charges Induced on Electrically Thick Cylinders, Crossed Cylinders, and Cylinders Crossed with Horizontal Flat Plates by an Incident Plane-Wave Field. R.W.P. King, D.J. Blejer, and M. Krook, Contract N00014-75-C-0648 and Grant AFOSR-76-3073; Research Unit 11.

A systematic study of the distributions of current and charge induced on crossed metal structures was begun with electrically thin wires for which complete analytical^{1,2} and experimental^{3,4} solutions were obtained. The

study was continued with crossed electrically thick tubular cylinders for which no theoretical analysis is available so that a primarily experimental investigation was carried out.⁵ However, theoretical distributions of the currents and charges on isolated tubular cylinders with arbitrary lengths and radii were evaluated^{6,7} with E- and H-polarized illuminations both for standardizing the techniques of measurement⁸ and for interpreting the experimental observations on crossed cylinders. The initial measurements were carried out using cylinders and crossed cylinders with $ka = 1$. More recently, these have been extended to cylinders and crossed cylinders with $ka = 2$.⁹

The next major step in an approach to a model of an aircraft is a study of the currents and charges on the surfaces of an electrically thick circular cylinder with a transverse member consisting of a flat plate.¹⁰ With the aid of graphs a detailed description is given of the experimentally determined distributions of the currents and charges induced by a normally incident plane electromagnetic wave on all of the surfaces of a metal cross formed by a vertical tubular cylinder and a horizontal flat plate. The cylinder is a wavelength in circumference and 1.75λ high over a large ground plane. The horizontal plate consists of two equal arms that extend 0.75λ from the surface of the cylinder; it is 0.2125λ wide and 0.0255λ thick. It is centered at a height of 1.25λ from the ground plane. The distributions are compared with the corresponding ones on crossed tubular cylinders and on isolated cylinders. In general, the currents and charges on a horizontal flat plate are less closely coupled to the currents and charges on the vertical cylinder than are those on a horizontal cylinder. The distributions are relatively simple, and are a useful approximation of the surface currents and charges induced on an aircraft.

References

1. R.W.P. King and T.T. Wu, "Analysis of Crossed Wires in a Plane-Wave Field," *IEEE Trans. Electromagn. Compatib.*, vol. EMC-17, pp. 255-265, November 1975.
2. R.W.P. King, "Currents Induced in a Wire Cross by a Plane Wave Incident at an Angle," *IEEE Trans. Antennas Propagat.*, vol. AP-25, pp. 775-781, November 1977.
3. R.W. Burton and R.W.P. King, "Induced Currents and Charges on Thin Cylinders in a Time-Varying Electromagnetic Field," *IEEE Trans. Electromagn. Compatib.*, vol. EMC-17, pp. 140-155, August 1975.
4. R.W. Burton and R.W.P. King, "Measured Currents and Charges on Thin Crossed Antennas in a Plane-Wave Field," *IEEE Trans. Antennas Propagat.*, vol. AP-23, pp. 657-664, September 1975.
5. R.W.P. King, D.J. Blejer, and R.W. Burton, "Surface Currents and Charges on Crossed Electrically Thick Cylinders in a Normally Incident, Plane-Wave Field," *Radio Science*, vol. 13, pp. 93-105, January-February 1978.
6. R.W.P. King, B. Sandler, T.T. Wu, R.W. Burton, C.C. Kao, and L.C. Shen, "Surface Currents and Charges on an Electrically Thick Conducting Tube in an E-Polarized, Normally Incident, Plane-Wave Field, 1, Theory," *Radio Science*, vol. 11, pp. 687-699, August-September 1976.
7. R.W. Burton, R.W.P. King, and D.J. Blejer, "Surface Currents and Charges on an Electrically Thick and Long Conducting Tube in E- and H-Polarized, Normally Incident, Plane-Wave Field," *Radio Science*, vol. 13, pp. 75-91, January-February 1978.
8. R.W. Burton, R.W.P. King, and D.J. Blejer, "Surface Currents and Charges on an Electrically Thick Conducting Tube in an E-Polarized, Normally Incident, Plane-Wave Field, 2, Measurements," *Radio Science*, vol. 11, pp. 701-711, August-September 1976.
9. R.W.P. King, D.J. Blejer, S.-K. Wan, and R.W. Burton, "Currents and Charges Induced by a Normally Incident Plane Wave on Single and Crossed Tubular Cylinders with $ka = 2$," *Radio Science*, vol. 13, pp. 107-119, January-February 1978.
10. R.W.P. King, D.J. Blejer, and R.W. Burton, "Surface Currents and Charges on a Cross Formed by an Electrically Thick Cylinder and a Flat Plate in a Normally Incident, Plane-Wave Field," *Radio Science*, scheduled to appear in May-June 1979 issue.

IV.9 Currents and Charges on Cylinders in a Parallel-Plate Transmission Line. R.W.P. King, D.J. Blejer, J.E. Baum, T.K. Sarkar, and M. Krook, Grant AFOSR-76-3073 and Contract N00014-75-C-0648; Research Unit 11.

In order to determine the magnitudes and distributions of currents and charges induced on the surfaces of an aircraft when it encounters an electromagnetic pulse generated by a nuclear explosion, large simulators have been constructed in which the aircraft can be exposed to a hopefully comparable electromagnetic environment. One important type consists of a parallel-plate transmission line or open waveguide with tapered triangular ends, between the conductors of which a pulse with a plane wave front must travel. Since the relevant pulse contains a frequency spectrum with wavelengths that extend from very long to relatively short compared to the dimensions of the aircraft, the separation of the two conductors of the transmission-line simulator cannot be kept small compared to all of the wavelengths in the pulse as required for TEM transmission without propagating higher modes. It follows that TEM-mode transmission-line theory can be applied only to the very low frequency part of the spectrum. The properties of the simulator at higher frequencies are difficult to determine accurately. One approach is to measure the electric field in a model simulator at one or more of the relevant higher frequencies, and then seek to interpret its distribution theoretically. This has been done in a carefully designed model simulator at a frequency of 625 MHz.¹⁻³ When, as in this case, the frequency is so high that kh is not small compared to one, most of the energy supplied by the generator is radiated into the surrounding space, and only a small fraction is dissipated in the load. The structure is essentially an antenna and not a transmission line.

Direct measurements were made of both the amplitude and phase of the vertical (E_z) and longitudinal (E_y) components of the electric field throughout the working volume (region between the parallel plates), and of E_z on the surfaces of both conducting plates where $E_y = 0$. In order to interpret the measured results, the field in the working volume was represented approximately in terms of the mode theory of the infinite parallel-plate waveguide. For the operating wavelength $\lambda = 48$ cm, four modes are well above cut-off. They are the TEM, TM_{01} , TM_{02} and TM_{03} modes. Comparisons with the measured data indicate that the assumed approximate representation of the field by the superposition of ideal parallel-plate modes is a good one throughout the working volume of the simulator. It is also evident that the total E_z differs greatly from the part contributed by the TEM mode alone. This is true particularly near the top where the difference between the incident spherical wave in the sloping sections and the plane wave in the working volume is greatest. There is no difference on the ground plane. Note also that the field in the working volume is not a pure traveling wave with constant amplitude, but includes a large standing wave. TE modes contribute only negligibly and are ignored.

Measurements are currently being taken at a second high frequency, $f = 264$ MHz, where with the separation h between the parallel plates reduced from 108 cm to 75 cm, h is now $.65\lambda$ rather than 2.25λ of the previous case. Now only the TEM and TM_{01} modes are below cut-off. These can be uniquely determined from the longitudinal and transverse components of the electric field. TE modes are neglected. The TEM mode is determined at $z/h = 0.5$ where the vertical component, E_z , of the electric field of

the TM_{01} mode is zero. E_z for the TM_{01} mode is the difference between the total measured E_z and E_z for the TEM mode. The measured longitudinal component of the electric field, E_y , belongs entirely to the TM_{01} mode. An attempt was made to measure the axial component, H_y , of the magnetic field in order to determine the magnitude of possible TE modes. This is difficult since a loop antenna must be used as the probe. Any asymmetries in the loop or nonuniformities in the field due to the presence of the edges of the upper plate will allow unbalanced currents to be excited. Several shielded and unshielded loop probes have been constructed and tested. The symmetry of the probes was tested by comparing the response of the probe in a fixed position when reversed and unreversed. The asymmetry of the probes could not be reduced below 10%. The loop probes were also tested near the ground plane and the parallel plate for their ability to detect the null in the vertical component of the magnetic field required by the boundary conditions. A deep null was detected at the ground plane but not at the parallel plate. It appears that currents induced on the conducting tube that supports the loop combined with small asymmetries in the loop make it impossible to measure the very small longitudinal component, H_y , of the magnetic field.

Another area of investigation during this reporting period has been the suppression of undesired components of the field in the working volume. As a preliminary representation of the suggested spatial modal filter, a parallel array of center-loaded half-wave dipoles was positioned longitudinally in the working volume in the $z = h/2$ plane for different values of y . No attenuation of the E_y component of the field was detected. Further studies are to be carried out.

References

1. D.J. Blejer and R.W.P. King, "Measured Electric Fields in a Model Simulator," presented at the 1978 Nuclear EMP Meeting, held at the University of New Mexico, Albuquerque, June 6-8, 1978.
2. M. Krook, R.W.P. King, D.J. Blejer, T.K. Sarkar, and S.-K. Wan, "The Electric Field in a Parallel-Plate EMP Simulator: Theoretical and Experimental Results," Interim Scientific Report, Grant AFOSR-76-3073, July 31, 1978.
3. R.W.P. King and D.J. Blejer, "The Electromagnetic Field in an EMP Simulator at a High Frequency," to appear in *IEEE Trans. on Electromagnetic Compatibility*.

IV.10 Theoretical and Experimental Study of the Ferrite Rod Antenna.

D.V. Giri and R.W.P. King, Contracts N00014-67-A-0298-0005 and N00014-75-C-0648, and the Microwave Physics Branch, Ballistic Research Laboratories, U.S. Army Aberdeen Proving Ground, Maryland; Research Unit 11.

This research project was completed some time ago. During this reporting period a technical report was issued¹ which presents the concluding part of the study, namely, the theoretical analysis of practical ferrite rods of *finite* length. The earlier work² had developed a theory to treat the electrically small loop antenna loaded by an *infinitely* long, homogeneous, isotropic, but lossy, ferrite rod. In the second report, two different approaches are used. The first method makes use of the analogy between the ferrite rod antenna and the conducting cylindrical dipole antenna to derive an integral equation for the magnetic current on an infinitely permeable ferrite antenna. By letting $h \rightarrow \infty$, the integral equation is shown to be consistent with the earlier results for the infinite antenna. Appropriate corrections to the integral equation are then made by

treating the ferrite as an imperfect magnetic conductor, and an approximate, three-term expression for the current is obtained. The second, more rigorous method obtains two coupled integral equations in terms of the tangential electric field and the tangential electric surface current from independent treatments of the interior (ferrite) and exterior (free space) problems. The coupled equations are then solved numerically by the moment method. Finally, the results of the two theories are compared with experimental measurements made on eleven different antenna configurations. The agreement is good for all cases with discrepancies occurring only very close to the driving point.

References

1. D.V. Giri and R.W.P. King, "Electrically Small Loop Antenna Loaded by a Homogeneous and Isotropic Ferrite Cylinder - Part II," Technical Report No. 668, JSEP Contract N00014-75-C-0648, DAS, Harvard University, Cambridge, Mass., July 1978.
2. D.V. Giri, "Electrically Small Loop Antenna Loaded by a Homogeneous and Isotropic Ferrite Cylinder - Part I," Technical Report No. 646, JSEP Contract N00014-67-A-0298-0005, DEAP, Harvard University, Cambridge, Mass., July 1973.

THIS PAGE IS BEST QUALITY PRACTICABLE FROM COPY FURNISHED TO DDC

JAW REPORTS DISTRIBUTION LIST

Director
National Security Agency
AFPM: Dr. T. J. Smith
Port George S. Road, MD 20755

Refinement Documentation Center
AFPM: DR-PC (Mrs. V. Caputo)
Cameron Station
Alexandria, VA 22314

Asst. Dir.
Office of Director of Defense
Research and Engineering
The Pentagon
Washington, DC 20315

Defense Advanced Research
Project Agency
AFPM: Dr. S. Reynolds
1400 Wilson Boulevard
Arlington, VA 22209

Commander
US Army Air Defense School
AFPM: DR-AD-PC
Fort Bliss, VA 79914

Commander
US Army Ammunition R&D Command
AFPM: DR-AD-PC
Fort Belvoir, MO 63601

Commander
US Army Ballistic Research Lab.
AFPM: DR-AD-PC
Redstone Arsenal
Anniston, AL 36405

Commander
US Army Command and General
Staff College
AFPM: DR-AD-PC
Fort Leavenworth, KS 66027

Commander
US Army Communications Command
AFPM: DR-AD-PC
Fort Monmouth, NJ 08401

Commander
US Army Materials and Mechanics
Research Center
AFPM: DR-AD-PC
Pittsburgh, PA 15217

Commander
US Army Materiel Development
and Logistics Command
AFPM: DR-AD-PC
5015 Eisenhower Avenue
Alexandria, VA 22311

Commander
US Army Missile R&D Command
AFPM: DR-AD-PC
Redstone Arsenal, AL 36405

Commander
US Army Satellite Communications
Agency
AFPM: DR-AD-PC
Fort Monmouth, NJ 08401

Commander
US Army Security Agency
AFPM: DR-AD-PC
Arlington Hall Station
Arlington, VA 22211

Project Manager
AFPM: DR-AD-PC
BPT Building
West Long Branch, NJ 07764

Commander/Director
Atmospheric Sciences Lab. (RSC)
AFPM: DR-AD-PC
White Sands Missile Range, NM 88002

Commander
US Army Electronics Command
AFPM: DR-AD-PC (Dr. R. S. Barnett)
Fort Monmouth, NJ 07703

Director
DR-PC
AFPM: DR-AD-PC (Mrs. Miller)
Fort Monmouth, NJ 07703

Commander
US Army Electronics Command
AFPM: DR-AD-PC (Dr. R. S. Barnett)
Fort Monmouth, NJ 07703

Director
Electronic Warfare Lab. (RSC)
AFPM: DR-AD-PC
White Sands Missile Range, NM 88002

Executive Secretary, DR-PC/DRP
US Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709

Commander
Frankford Arsenal
Deputy Director
Pittsburgh-Craig Laboratory
Philadelphia, PA 19137

Project Manager
Ballistic Missile Defense Program Office
AFPM: DR-AD-PC (Dr. A. G. Galt)
1300 Wilson Blvd.
Arlington, VA 22209

Commander
Harry Diamond Laboratories
AFPM: Dr. John F. Renshaw
2800 Powder Mill Road
Adelphi, MD 20783

AFPM (DR-AD-PC)
Washington, DC 20310

Commander
US Army Electronics Command
Fort Monmouth, NJ 07703
AFPM: DR-AD-PC (Dr. J. A. Kohn)
DR-AD-PC (Dr. J. A. Kohn)
DR-AD-PC (Dr. J. A. Kohn)
DR-AD-PC (Dr. J. A. Kohn)
DR-AD-PC (Dr. J. A. Kohn)
DR-AD-PC (Dr. J. A. Kohn)
DR-AD-PC (Dr. J. A. Kohn)
DR-AD-PC (Dr. J. A. Kohn)

CDR Robert Ross
Senior Standardization Representative
US Army Standardization Group, Canada
Canadian Forces Headquarters
Ottawa, Ontario, Canada K1A 2J2

Director
Night Vision Laboratory
AFPM: DR-AD-PC
Port Belvoir, VA 22060

Commander
Pittsburgh Arsenal
AFPM: DR-AD-PC
Dover, NJ 07801

Dr. Sidney Ross
Technical Director
AFPM: DR-AD-PC
Frankford Arsenal
Philadelphia, PA 19137

US Army Research Office (Hq)
AFPM: DR-AD-PC
P.O. Box 12211
Research Triangle Park, NC 27709

Director
Division of Neuropsychiatry
Walter Reed Army Institute of
Research
Washington, DC 20012

White Sands Missile Range
AFPM: DR-AD-PC
White Sands Missile Range, NM 88002

Dr. Robert Barrett
AFPM: DR-AD-PC
Manassas Park, VA 20108

Dr. Carl F. Ross
AFPM: DR-AD-PC
Wichita Falls, TX 76711

Dr. S. Champagne
AFPM: DR-AD-PC
Wright-Patterson AFB, OH 45433

Dr. S. P. Dolan
AFPM: DR-AD-PC
Manassas Park, VA 20108

Dr. W. Edwards
AFPM: DR-AD-PC
Wright-Patterson AFB, OH 45433

Professor R. E. Postman
Head, Dept. of Electrical Eng.
AFPM: DR-AD-PC
Wright-Patterson AFB, OH 45433

Dr. Alan Garavito
AFPM: DR-AD-PC
Wright-Patterson AFB, OH 45433

USAF European Office of Aerospace
Research
AFPM: DR-AD-PC
1440, New York 09510

Dr. Richard J. Owen
Dept. of Electrical Engineering
USAF Academy, CO 80840

Dr. Murray Rosenblum (RSC)
Head Air Development Center
AFPM: DR-AD-PC
Offices AFB, NY 13441

Dr. G. Rosenberger
Air Force Materiel, TSC
Air Force Office of Scientific
Research
AFPM: DR-AD-PC
Holling Air Force Base, DC 20332

Dr. L. Kravitz
Air Force Materiel, TSC
Air Force Office of Scientific
Research
AFPM: DR-AD-PC
Holling Air Force Base, DC 20332

Dr. R. S. Larson
AFPM: DR-AD-PC
Wright-Patterson AFB, OH 45433

Dr. Richard P. Mack
AFPM: DR-AD-PC
Manassas Park, VA 20108

Dr. John H. Smith (Hq)
AFPM: DR-AD-PC
Manassas Park, VA 20108

Dr. Richard Pined
AFPM: DR-AD-PC
Manassas Park, VA 20108

Dr. J. R. Ryan
Chief Scientist
AFPM: DR-AD-PC
Wright-Patterson AFB, OH 45433

Dr. R. E. Webb, Jr. (Hq)
Head Air Development Center
AFPM: DR-AD-PC
Offices AFB, NY 13441

Dr. G. W. Hefner
Air Force Office of Scientific
Research
AFPM: DR-AD-PC
Holling Air Force Base, DC 20332

Dr. G. W. Hefner
Air Force Office of Scientific
Research
AFPM: DR-AD-PC
Holling Air Force Base, DC 20332

Dr. R. S. Allsister
Naval Surface Weapons Center
AFPM: DR-AD-PC
White Oak
Silver Spring, MD 20910

Naval Weapons Center
AFPM: DR-AD-PC
Chase Lake, CA 92555

Dr. M. L. Blund
Technical Director
Naval Weapons Center
San Diego, CA 92132

Naval Research Laboratory
AFPM: DR-AD-PC
4555 Overlook Avenue, NW
Washington, DC 20375

Dr. R. S. Allsister
Naval Surface Weapons Center
AFPM: DR-AD-PC
White Oak
Silver Spring, MD 20910

Dr. G. G. Gould
Technical Director
Naval Coastal System Lab.
Pittsburgh, PA 15217

Naval Ocean Systems Center
AFPM: DR-AD-PC
271 Catalina Boulevard
San Diego, CA 92132

Naval Ocean Systems Center
AFPM: DR-AD-PC
271 Catalina Boulevard
San Diego, CA 92132

Donald B. Kirk
Professor and Chairman
Electronic Engineer, CP-304
Naval Postgraduate School
Monterey, CA 93940

Naval Air Development Center
AFPM: DR-AD-PC
271 Catalina Boulevard
San Diego, CA 92132

Naval Research Laboratory
AFPM: DR-AD-PC
4555 Overlook Avenue, NW
Washington, DC 20375

Capt. R. E. Hefner
Naval Sea Systems Command
AFPM: DR-AD-PC
2511 Jefferson Davis Hwy
Arlington, VA 22202

Dr. S. J. Mueller
Naval Air Systems Command
AFPM: DR-AD-PC
2511 Jefferson Davis Hwy
Arlington, VA 22202

Dr. J. R. Miller, Jr.
Naval Surface Weapons Center
AFPM: DR-AD-PC
Dahlgren, VA 22448

Naval Ocean Systems Center
AFPM: DR-AD-PC
271 Catalina Boulevard
San Diego, CA 92132

Naval Air Development Center
AFPM: DR-AD-PC
271 Catalina Boulevard
San Diego, CA 92132

Naval Ocean Systems Center
AFPM: DR-AD-PC
271 Catalina Boulevard
San Diego, CA 92132

Naval Surface Weapons Center
AFPM: DR-AD-PC
271 Catalina Boulevard
San Diego, CA 92132

Naval Training Equipment Center
AFPM: DR-AD-PC
271 Catalina Boulevard
San Diego, CA 92132

Naval Undersea Center
AFPM: DR-AD-PC
San Diego, CA 92132

Naval Undersea Systems Center
AFPM: DR-AD-PC
San Diego, CA 92132

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Office of Naval Research
AFPM: DR-AD-PC
800 North Quincy Street
Arlington, VA 22217

Los Alamos Scientific Laboratory
AFPM: DR-AD-PC
P.O. Box 1663
Los Alamos, NM 87544

Dr. Dean Michael
Program Director
Solid-State Physics
Division of Materials Research
National Science Foundation
1800 G Street
Washington, DC 20540

Dr. F. C. Schueh, MD-7
National Information and Space
Administration
AFPM: DR-AD-PC
Washington, DC 20546

A. Sane Thornton
Deputy Director, Institute for
Computer Sciences and Technology
National Bureau of Standards
Washington, DC 20234

Director
Columbia Radiation Laboratory
Columbia University
138 West 120th Street
New York, NY 10027

Director
Coordinated Science Laboratory
University of Illinois
Urbana, IL 61801

Director of Laboratories
Division of Applied Sciences
Harvard University
Massachusetts Hall
Cambridge, MA 02138

Director
Electronic Research Center
The University of Texas
Engineering-Science Bldg. 112
Austin, TX 78713

Director
Electronic Research Laboratory
University of California
Berkeley, CA 94720

Director
Electronic Research Laboratory
University of Southern California
Los Angeles, CA 90007

Director
Microscopy Research Institute
Polytechnic Institute of New York
333 Jay Street
Brooklyn, NY 11201

Director
Research Laboratory of Electronics
Technology
Cambridge, MA 02139

Director
Stanford Electronics Laboratory
Stanford University
Stanford, CA 94305

Director
Stanford Electronics Laboratory
Stanford University
Stanford, CA 94305

Director in Charge
Office of Research, Development,
Test and Evaluation
AFPM: DR-AD-PC
The Pentagon, Room 50760
Washington, DC 20330

Dr. L. Hume
Naval Electronics Systems Command
AFPM: DR-AD-PC
Code 3042, MC 81
2511 Jefferson Davis Hwy
Arlington, VA 22202

David W. Taylor
Naval Ship Research and
Development Center
AFPM: DR-AD-PC
Groton, MD 20644

Naval Research Laboratory
AFPM: DR-AD-PC
4555 Overlook Avenue, NW
Washington, DC 20375

Dr. C. R. Turner
AFPM: DR-AD-PC
2511 Jefferson Davis Hwy
Arlington, VA 22202

Naval Ocean Systems Center
AFPM: DR-AD-PC
271 Catalina Boulevard
San Diego, CA 92132

Dr. W. A. Von Winkle
Associate Technical Director
for Technology
Naval Undersea Systems Center
San Diego, CA 92132

Dr. Oron H. S. Strick
Director, Film Service
US Naval Observatory
Massachusetts Avenue at
34th Street, NW
Washington, DC 20390

Dr. Howard W. Stael
Deputy Director
National Bureau of Standards
National Science Foundation
1800 G Street
Washington, DC 20540

Dr. Jay Harris
Program Director
Services and News Program
National Science Foundation
1800 G Street
Washington, DC 20540

Dr. Jay Harris
Program Director
Services and News Program
National Science Foundation
1800 G Street
Washington, DC 20540

Dr. Jay Harris
Program Director
Services and News Program
National Science Foundation
1800 G Street
Washington, DC 20540

Dr. Jay Harris
Program Director
Services and News Program
National Science Foundation
1800 G Street
Washington, DC 20540