NBS SPECIAL PUBLICATION 746

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Laser Induced Damage in Optical Materials: 1985

BOULDER DAMAGE SYMPOSIUM

STP 1015

The National Bureau of Standards[1] was established by an act of Congress on March 3, 1901. The Bureau's overall goal is to strengthen and advance the nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research to assure international competitiveness and leadership of U.S. industry, science and technology. NBS work involves development and transfer of measurements, standards and related science and technology, in support of continually improving U.S. productivity, product quality and reliability, innovation and underlying science and engineering. The Bureau's technical work is performed by the National Measurement Laboratory, the National Engineering Laboratory, the Institute for Computer Sciences and Technology, and the Institute for Materials Science and Engineering.

The National Measurement Laboratory

Provides the national system of physical and chemical measurement; coordinates the system with measurement systems of other nations and furnishes essential services leading to accurate and uniform physical and chemical measurement throughout the Nation's scientific community, industry, and commerce; provides advisory and research services to other Government agencies; conducts physical and chemical research; develops, produces, and distributes Standard Reference Materials; provides calibration services; and manages the National Standard Reference Data System. The Laboratory consists of the following centers:

- Basic Standards[2]
- Radiation Research
- Chemical Physics
- Analytical Chemistry

The National Engineering Laboratory

Provides technology and technical services to the public and private sectors to address national needs and to solve national problems; conducts research in engineering and applied science in support of these efforts; builds and maintains competence in the necessary disciplines required to carry out this research and technical service; develops engineering data and measurement capabilities; provides engineering measurement traceability services; develops test methods and proposes engineering standards and code changes; develops and proposes new engineering practices; and develops and improves mechanisms to transfer results of its research to the ultimate user. The Laboratory consists of the following centers:

- Applied Mathematics
- Electronics and Electrical Engineering[2]
- Manufacturing Engineering
- Building Technology
- Fire Research
- Chemical Engineering[3]

The Institute for Computer Sciences and Technology

Conducts research and provides scientific and technical services to aid Federal agencies in the selection, acquisition, application, and use of computer technology to improve effectiveness and economy in Government operations in accordance with Public Law 89-306 (40 U.S.C. 759), relevant Executive Orders, and other directives; carries out this mission by managing the Federal Information Processing Standards Program, developing Federal ADP standards guidelines, and managing Federal participation in ADP voluntary standardization activities; provides scientific and technological advisory services and assistance to Federal agencies; and provides the technical foundation for computer-related policies of the Federal Government. The Institute consists of the following divisions:

- Information Systems Engineering
- Systems and Software Technology
- Computer Security
- System and Network Architecture
- Advanced Systems

The Institute for Materials Science and Engineering

Conducts research and provides measurements, data, standards, reference materials, quantitative understanding and other technical information fundamental to the processing, structure, properties and performance of materials; addresses the scientific basis for new advanced materials technologies; plans research around cross-cutting scientific themes such as nondestructive evaluation and phase diagram development; oversees Bureau-wide technical programs in nuclear reactor radiation research and nondestructive evaluation; and broadly disseminates generic technical information resulting from its programs. The Institute consists of the following Divisions:

- Ceramics
- Fracture and Deformation[3]
- Polymers
- Metallurgy
- Reactor Radiation

[1]Headquarters and Laboratories at Gaithersburg, MD, unless otherwise noted; mailing address Gaithersburg, MD 20899.
[2]Some divisions within the center are located at Boulder, CO 80303.
[3]Located at Boulder, CO, with some elements at Gaithersburg, MD

Laser Induced Damage in Optical Materials: 1985

Proceedings of a Symposium Sponsored by:
National Bureau of Standards
American Society for Testing and Materials
Office of Naval Research
Department of Energy
Defense Advanced Research Project Agency
Air Force Office of Scientific Research

October 28–30, 1985

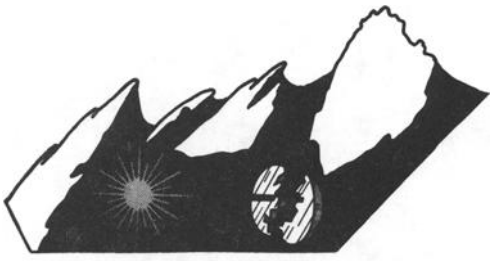
NBS, Boulder, Colorado 80303

Edited by:
Harold E. Bennett
Naval Weapons Center
China Lake, California 93555

Arthur H. Guenther
Air Force Weapons Laboratory
Kirtland Air Force Base, New Mexico 87117

David Milam
Lawrence Livermore National Laboratory
Livermore, California 94550

Brian E. Newnam
Los Alamos National Laboratory
Los Alamos, New Mexico 87545



U.S. DEPARTMENT OF COMMERCE, C. William Verity, Secretary

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

Issued July 1988

Library of Congress Catalog Card Number: 88–600557

National Bureau of Standards Special Publication 746
Natl. Bur. Stand. (U.S.), Spec. Publ. 746, 576 pages (July 1988)
CODEN: XNBSAV

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1988

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402–9325

Foreword

The Proceedings contain the papers presented at the Seventeenth Symposium on Optical Materials for High-Power Lasers held at the National Bureau of Standards in Boulder, Colorado, on October 28-30, 1985. The Symposium was jointly sponsored by the National Bureau of Standards, the American Society for Testing and Materials, the Office of Naval Research, the Defense Advanced Research Project Agency, the Department of Energy, and the Air Force Office of Scientific Research. The Symposium was attended by over 215 scientists from the United States, Israel, India, the United Kingdom, Japan, Federal Republic of Germany, and the Soviet Union. It was divided into sessions devoted to the following topics: Materials and Measurements, Mirrors and Surfaces, Thin Films, and finally, Fundamental Mechanisms. The Symposium Co-Chairmen were Dr. Harold E. Bennett of the Naval Weapons Center, Dr. Arthur H. Guenther of the Air Force Weapons Laboratory, Dr. David Milam of the Lawrence Livermore National Laboratory, and Dr. Brian E. Newnam of the Los Alamos National Laboratory. They also served as editors of this report.

The editors assume full responsibility for the summary article which contains an overview of the Symposium. The manuscripts of the papers presented at the Symposium have been prepared by the designated authors, and questions pertaining to their content should be addressed to those authors. The interested reader is referred to the bibliography at the end of the summary article for general references to the literature of laser damage studies. The Eighteenth Annual Symposium on this topic will be held in Boulder, Colorado, November 3-5, 1986. A concerted effort will be made to ensure closer liaison between the practitioners of high-peak power and the high-average power community.

The principal topics to be considered as contributed papers in 1986 do not differ drastically from those enumerated above. We expect to hear more about improved scaling relations as a function of pulse duration, area, and wavelength, and to see a continuing transfer of information from research activities to industrial practice. New sources at shorter wavelengths continue to be developed, and a corresponding shift in emphasis to short wavelength and repetitively-pulsed damage problems is anticipated. Fabrication and test procedures will continue to be developed, particularly in the diamond-turned optics and thin film areas.

The purpose of these symposia is to exchange information about optical materials for high-power lasers. The editors will welcome comment and criticism from all interested readers relevant to this purpose, and particularly relative to our plans for the Eighteenth Annual Symposium.

H. E. Bennett, A. H. Guenther,
D. Milam, and B. E. Newnam
Co-Chairmen

Disclaimer

Certain papers contributed to this publication have been prepared by non-NBS authors. These papers have not been reviewed or edited by NBS; therefore, the National Bureau of Standards accepts no responsibility for comments or recommendations contained therein.

Certain commercial equipment, instruments, and materials are identified in this publication in order to explain the experimental procedure adequately. Such identification in no way implies approval, recommendation, or endorsement by the National Bureau of Standards, nor does it imply that the equipment, instruments, or materials identified are necessarily the best available for the purpose.

CONTENTS

Mirrors and Surfaces

Thin Films

Fundamental Mechanisms

WELCOME

H. E. Bennett
Michelson Laboratory, Naval Weapons Center
China Lake, CA 93555

On behalf of co-chairmen Art Guenther, Brian Newnam, Dave Milam, and myself, I welcome you to the Seventeenth Annual Symposium on Optical Materials for High-Power Lasers. We have a record number of papers this year and a record attendance also; it promises to be an excellent conference. We especially want to welcome our many foreign guests, most of whom are contributing papers to the meeting. Many of them have come a long way and it is a commentary on the quality of this meeting that scientists from around the world will arrange to come here and share with us their insights into the difficult questions surrounding laser damage to materials. Some of their contributions have been quite significant too. For example, Professor Manenkov of the Soviet Union started a whole new line of investigation with his paper on NaCl damage limits a few years ago. Professor Yoshiharu Namba of Japan started us to thinking about float polishing, Dr. Achim Bubenzer and his colleagues from West Germany helped to clarify the science behind hard, diamondlike carbon coatings, and last year, Dr. Keith Lewis from Great Britain encouraged us to think that, using MBE techniques, thin films can be prepared which exhibit bulk properties instead of having several orders-of-magnitude more absorption than bulk material and so on. I could easily name many others from outside the United States who have contributed greatly to the well-deserved reputation of this conference for being a must for anyone who is interested in laser damage to optical components. We are proud of the international cooperation shown here in attacking problems in fundamental science, which knows no boundaries. In this spirit let me caution those of you who are engaged in applied research and development as well as more fundamental studies to avoid embarrassing our foreign guests and jeopardizing the excellent reputation of this conference by engaging in inappropriate discussions in the halls. These are not cleared areas. Let us concentrate our efforts in the next three days on understanding the fundamental problems associated with optical materials and laser damage to them. In this we can all work together.

Optics is a fashionable field to work in now. I remember in the fifties that it was suggested to me that research on optical properties of materials had no future, everything had been discovered which was of any useful interest, and only adding more decimal points to the optical constants remained to be done. The laser came along about then and was regarded as a new and interesting curiosity; a solution looking for a problem. Since then it has been used to solve many problems. Surgery, communications, data recording, laser welding, surface modification, and space applications are a few that come to mind. In all of them we are dealing with optical trains which, although they may not transmit high energies, do have to handle high powers. Lasers have introduced a new dimension into optical systems which we may call power optics. Electrical engineers have an analogous field, power engineering, where

they study how to handle the output of hydroelectric dams and other sources of power. Electrical engineering also encompasses small-signal processing in the radio and microwave fields. The analogous field in optical design deals with telescopes, microscopes, cameras, etc. and is often referred to as classical optics. With the advent of power optics, for which this conference is one of the main forums, we enter a new kind of optical design, one in which the underlying physics is not well understood.

At first glance the problem seems simple enough. A high enough intensity of laser energy causes either reversible or irreversible damage to the optical components reflecting or transmitting the laser energy. But why do components damage and why do damage thresholds of similar samples vary by as much as one or two orders-of-magnitude? The absorption coefficients of the component substrate and coating obviously should be related to the damage threshold, but frequently they are not. Even so, what makes the materials absorb? Figure 1 shows some of the mechanisms which have been studied as causes of intrinsic absorption in low absorption dielectrics. Other mechanisms have also been proposed, but these will suffice to demonstrate that even intrinsic absorption is not necessarily simple. On the other hand, there is considerable evidence that extrinsic effects dominate laser damage in low absorption regions, and these may be even more complicated. Worse yet, absorption from extrinsic or intrinsic effects may be completely unimportant. Structural effects may be the key, or the high-field strengths involved in laser beams may cause dielectric breakdowns or non-linear effects. Sub-picosecond pulses get us down to the time intervals characteristic of atomic processes, with consequent changes in the rules, and one concludes that laser damage is not so simple after all.

We have made many important advances over the years in our understanding of laser damage. Most have been reported here first, and the back issues of the Conference Proceedings are regarded by most of the community as a gold mine of information on the subject. Many of the back issues can be obtained from the American Society for Testing Materials, the professional sponsor for this conference. Some advances which come to mind are the understanding of self focussing (which is not yet perfect), the effect of scratches and voids on damage thresholds (also not complete), the asymmetry of laser damage thresholds for the front and back surfaces of windows caused by standing-wave fields, the development of experimental techniques to measure various key parameters. We still do not understand the origin of surface absorption, but at least we can measure it and scale damage thresholds for small spot-sizes to larger beam diameters for some types of surfaces. To understand laser damage phenomena, diverse disciplines such as crystal growth, thin film technology, surface finishing technology and others are required, and some notable advances have been reported here in these fields. One I remember was the achievement of absorption coefficients of 10^{-4} cm^{-1} range at 10.6 μm wavelength for both KCl and ZnSe, orders-of-magnitude better than had been possible previously. Many other examples of progress could be mentioned and some of these fields are among the most well-represented at this year's Symposium. Thin film technology, for example, is now consistently the subject of more than one quarter of all the papers presented in these Symposia.

Plenty of technical problems remain to be solved. One of the most puzzling is the reason for the decrease in damage threshold seen for multiple pulses, and the general behavior of components to rep-rate pulses. The subject of short-wavelength laser components is a fascinating one and brings in all the physics of multiphoton processes and the happy discovery that things are not as hopeless as they seemed at first. Many other topics could be mentioned, and indeed are in the Conference Program which you all have. This is the largest conference we have ever had, let us hope that it will also be seen in future years as one of the best. Enjoy and profit by the 2 1/2 days that we are about to embark on.

Let me close by mentioning some items of which you all should be aware. First, save Tuesday evening. There will be a Wine and Cheese Tasting extravaganza that evening, and I hope that you all can come, get to know each other on a more personal basis, exchange ideas, and enjoy some fine wine and unusual cheeses and goodies.

Let us take this opportunity to thank our professional sponsor of this conference, the American Society for Testing Materials, often familiarly known as the ASTM, and also our financial sponsors. They are (1) the Air Force Office of Scientific Research, (2) the Office of Naval Research through the Naval Weapons Center, (3) Lawrence Livermore National Laboratory, (4) Los Alamos National Laboratory, (5) The Defense Advanced Research Projects Agency, and (6) the National Bureau of Standards. The Bureau does a great deal to make this meeting possible, and we particularly acknowledge the support of Robert A. Kamper, Director of the Boulder Laboratories of NBS, and Aaron A. Sanders, Group Leader of the Electromagnetic Technology Division, who performs the functions of Conference Coordinator and Fundraiser. His secretary, Ms. Susie Rivera continues to perform an outstanding job in managing the conference manuscripts, sending out notices, typing editors comments, and generally keeping the show on the road. She is aided by several other secretaries here at the Bureau. Ann Mannos here at the Bureau handles the finances. No set of acknowledgments would be complete without reference to the outstanding work done by Pat Whited, Art Guenther's secretary, in making this Symposium happen. Finally, and most importantly, my cochairmen Brian Newnam, Dave Milam and I want you to join with us in thanking Art Guenther, who with Alex Glass started these Symposia and who, in spite of his impossibly busy schedule as Chief Scientist of the Air Force Weapons Laboratory, is still supplying much of the motive force to keep it going. We hear that he is to be awarded the Distinguished Senior Executive Award in Washington, D.C. and that it will be presented personally to him by President Reagan. Let us all stand and give a round of applause.

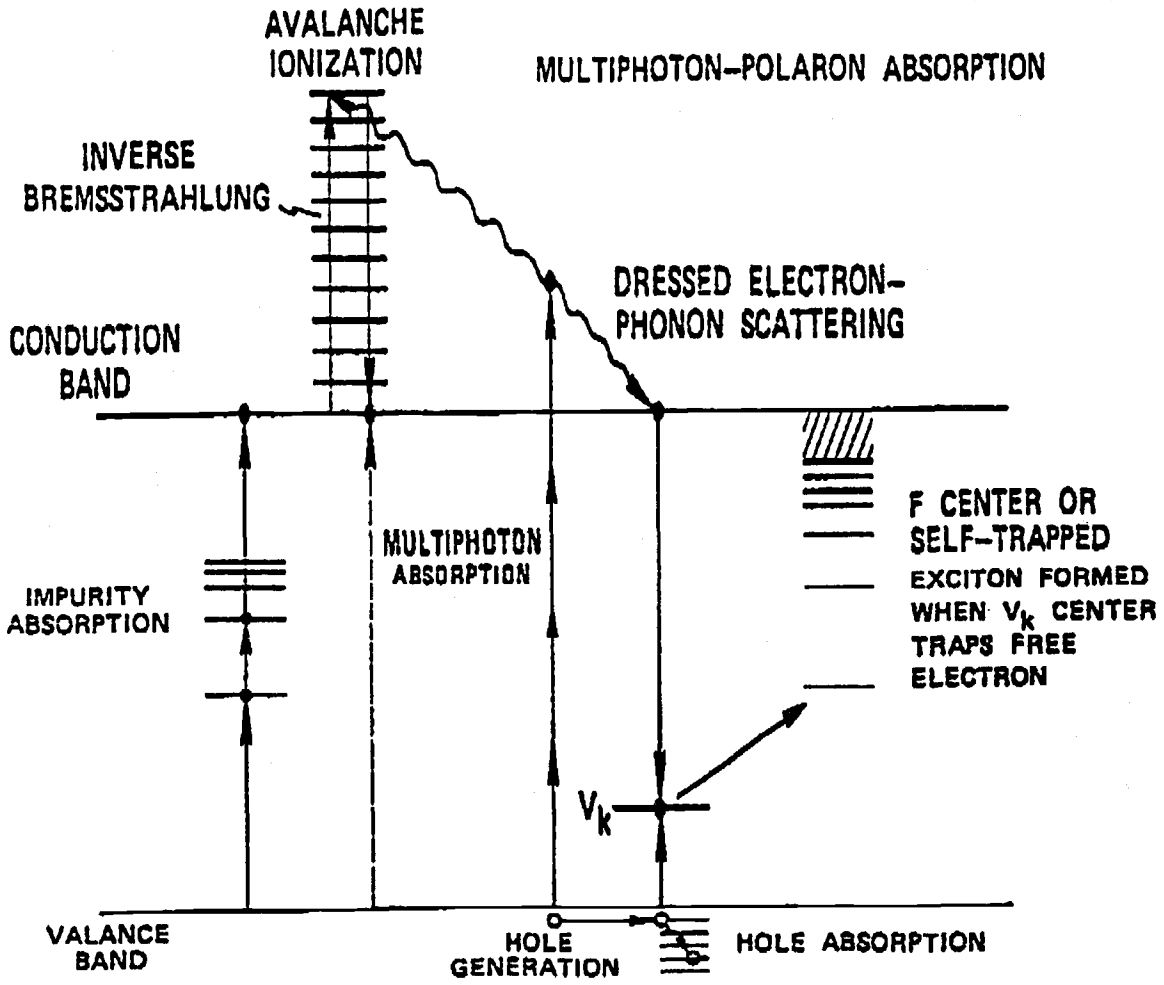


Fig. 1 Some suggested mechanisms for laser damage in solids.

NBS-114A (REV. 2-8C)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBS/SP-746	2. Performing Organ. Report No.	3. Publication Date July 1988

4. TITLE AND SUBTITLE

Laser Induced Damage in Optical Materials: 1985

5. AUTHOR(S) Harold E. Bennett (NWC), Arthur H. Guenther (AFWL)
David Milam (LLNL) and Brian E. Newnam (LANL)

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL BUREAU OF STANDARDS
U.S. DEPARTMENT OF COMMERCE
BOULDER, CO 80303

7. Contract/Grant No.

8. Type of Report & Period Covered

Final

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

National Bureau of Standards (NBS)
American Society for Testing and Materials (ASTM)
Office of Naval Research (ONR)
Department of Energy (DOE)
Defense Advanced Research Project Agency (DARPA)
Air Force Office of Scientific Research (AFOSR)

10. SUPPLEMENTARY NOTES

Library of Congress Catalog Card Number 88-600557

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The Seventeenth Annual Symposium on Optical Materials for High-Power Lasers (Boulder Damage Symposium) was held at the National Bureau of Standards in Boulder, Colorado, October 28-30, 1985. The Symposium was held under the auspices of ASTM Committee F-1, Subcommittee on Laser Standards, with the joint sponsorship of NBS, the Defense Advanced Research Project Agency, the Department of Energy, the Office of Naval Research, and the Air Force Office of Scientific Research. Over 215 scientists attended the Symposium, including representatives from the United States, the United Kingdom, Israel, India, Japan, the Federal Republic of Germany, and the Soviet Union. The Symposium was divided into sessions concerning Materials and Measurements, Mirrors and Surfaces, Thin Films, and Fundamental Mechanisms. As in previous years, the emphasis of the papers presented at the Symposium was directed toward new frontiers and new developments. Particular emphasis was given to materials for high-power apparatus. The wavelength range of prime interest was from 10.6 μm to the uv region. Highlights included surface characterization thin film-substrate boundaries, and advances in fundamental laser-matter threshold interactions and mechanisms. Harold E. Bennett of the Naval Weapons Center, Arthur H. Guenther of the Air Force Weapons Laboratory, David Milam of the Lawrence Livermore National Laboratory, and Brian E. Newnam of the Los Alamos National Laboratory were co-chairmen of the Symposium. The Eighteenth Annual Symposium is scheduled for Nov. 3-5, 1986, at the National Bureau of Standards, Boulder, Colorado.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

laser damage; laser interaction; optical components; optical fabrication; optical materials and properties; thin film coatings.

13. AVAILABILITY

☒ Unlimited

☐ For Official Distribution. Do Not Release to NTIS

☒ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

☐ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

576

15. Price

INSTRUCTIONS

FORM NBS-114A: BIBLIOGRAPHIC DATA SHEET. This bibliographic data sheet meets the standards adopted for use by all U.S. Government agencies. It is needed for NTIS processing and must accompany all NBS papers, those appearing in nongovernmental media as well as those in NBS series, since all reports of NBS technical work are normally entered into the NTIS system. For all GPO publications, it becomes an integral part of the document and is widely used by librarians and abstractors.

Items 1, 2 – Complete if information is available; otherwise Publications Office will complete later. If non-NBS publication, state "see item 10" (Enter other agency sponsor's report number if requested to do so, and enter NBSIR number under item 2).

Item 3 – Complete if known; otherwise Publications Office will complete.

Items 4, 5 – Complete as shown on manuscript. When NBS-114A is resubmitted along with NBS-266, following publication of non-NBS media papers, these items must agree with published paper.

Item 6 – If not NBS, blank out and enter Grantee/Contractor name and address, or if performed jointly, show both.

Item 7 – Complete when applicable.

Item 8 – Enter "Interim," "Final," or period covered.

Item 9 – Enter all sponsors' names and addresses. Include NBS if also a sponsor.

Item 10 – Enter other relevant information, i.e., related or superseded documents. Also used by Publications Office for Library of Congress catalog number, and entry of non-NBS media citation upon receipt of Form NBS-266 from author. Check block if appropriate and attach SF185.

Item 11, 12 – Prepare abstract and key words with special care. These are published separately by NBS, NTIS, and other bibliographic services, and are vital elements in guiding readers to your paper. The key words will be used as entries in a subject index. See NBS Communications Manual for additional guidance.

Item 13 – Indicate "Unlimited" – for open-literature documents cleared under NBS editorial procedures, or "For official distribution. Do not release to NTIS" – for limited, restricted, or need-to-know material (See Communications Manual). Publications Office will mark appropriate "order" box and complete Stock Number when known.

Items 14, 15 – Leave blank. To be completed by Publications Office or call Printing and Duplicating for NBSIR's.

USCOMM-DC 6043-P80

*U.S. GOVERNMENT PRINTING OFFICE: 1988-216-825

NBS Technical Publications

Periodical

Journal of Research—The Journal of Research of the National Bureau of Standards reports NBS research and development in those disciplines of the physical and engineering sciences in which the Bureau is active. These include physics, chemistry, engineering, mathematics, and computer sciences. Papers cover a broad range of subjects, with major emphasis on measurement methodology and the basic technology underlying standardization. Also included from time to time are survey articles on topics closely related to the Bureau's technical and scientific programs. Issued six times a year.

Nonperiodicals

Monographs—Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

Handbooks—Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications—Include proceedings of conferences sponsored by NBS, NBS annual reports, and other special publications appropriate to this grouping such as wall charts, pocket cards, and bibliographies.

Applied Mathematics Series—Mathematical tables, manuals, and studies of special interest to physicists, engineers, chemists, biologists, mathematicians, computer programmers, and others engaged in scientific and technical work.

National Standard Reference Data Series—Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a worldwide program coordinated by NBS under the authority of the National Standard Data Act (Public Law 90-396). NOTE: The Journal of Physical and Chemical Reference Data (JPCRD) is published quarterly for NBS by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements are available from ACS, 1155 Sixteenth St., NW, Washington, DC 20056.

Building Science Series—Disseminates technical information developed at the Bureau on building materials, components, systems, and whole structures. The series presents research results, test methods, and performance criteria related to the structural and environmental functions and the durability and safety characteristics of building elements and systems.

Technical Notes—Studies or reports which are complete in themselves but restrictive in their treatment of a subject. Analogous to monographs but not so comprehensive in scope or definitive in treatment of the subject area. Often serve as a vehicle for final reports of work performed at NBS under the sponsorship of other government agencies.

Voluntary Product Standards—Developed under procedures published by the Department of Commerce in Part 10, Title 15, of the Code of Federal Regulations. The standards establish nationally recognized requirements for products, and provide all concerned interests with a basis for common understanding of the characteristics of the products. NBS administers this program as a supplement to the activities of the private sector standardizing organizations.

Consumer Information Series—Practical information, based on NBS research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.

Order the **above** *NBS publications from: Superintendent of Documents, Government Printing Office, Washington, DC 20402.*

Order the **following** *NBS publications—FIPS and NBSIR's—from the National Technical Information Service, Springfield, VA 22161.*

Federal Information Processing Standards Publications (FIPS PUB)—Publications in this series collectively constitute the Federal Information Processing Standards Register. The Register serves as the official source of information in the Federal Government regarding standards issued by NBS pursuant to the Federal Property and Administrative Services Act of 1949 as amended, Public Law 89-306 (79 Stat. 1127), and as implemented by Executive Order 11717 (38 FR 12315, dated May 11, 1973) and Part 6 of Title 15 CFR (Code of Federal Regulations).

NBS Interagency Reports (NBSIR)—A special series of interim or final reports on work performed by NBS for outside sponsors (both government and non-government). In general, initial distribution is handled by the sponsor; public distribution is by the National Technical Information Service, Springfield, VA 22161, in paper copy or microfiche form.

National Bureau of Standards
Gaithersburg, MD 20899

Official Business
Penalty for Private Use $300