



NIST SPECIAL PUBLICATION **756**

U.S. DEPARTMENT OF COMMERCE/National Institute of Standards and Technology

Laser Induced Damage in Optical Materials: 1987



BOULDER DAMAGE SYMPOSIUM



STP 1038

The National Institute of Standards and Technology¹ was established by an act of Congress on March 3, 1901. The Institute'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 Institute conducts research to assure international competitiveness and leadership of U.S. industry, science and technology. NIST 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 Institute's technical work is performed by the National Measurement Laboratory, the National Engineering Laboratory, the National Computer Systems Laboratory, 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 Standards²
- 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:

- Computing and Applied Mathematics
- Electronics and Electrical Engineering²
- Manufacturing Engineering
- Building Technology
- Fire Research
- Chemical Engineering³

The National Computer Systems Laboratory

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 Laboratory consists of the following divisions:

- Information Systems Engineering
- Systems and Software Technology
- Computer Security
- Systems 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 Institute-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 Deformation³
- Polymers
- Metallurgy
- Reactor Radiation

¹Headquarters and Laboratories at Gaithersburg, MD, unless otherwise noted; mailing address Gaithersburg, MD 20899.

²Some divisions within the center are located at Boulder, CO 80303.

³Located at Boulder, CO, with some elements at Gaithersburg, MD.

Laser Induced Damage in Optical Materials: 1987

Proceedings of a Symposium sponsored by:

National Institute of Standards and Technology
(formerly 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 26–28, 1987

NIST (formerly NBS), Boulder, Colorado 80303

Edited by:

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

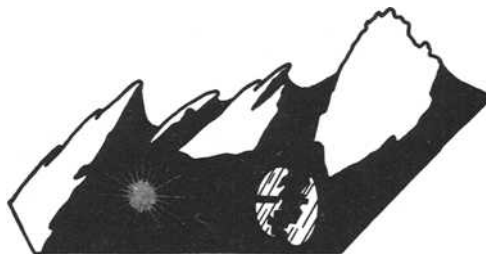
Arthur H. Guenther
Air Force Weapons Laboratory
Kirtland Air Force Base, New Mexico 87117

David Milam
Lawrence Livermore National Laboratory
Livermore, California 94550

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

M.J. Soileau
University of Central Florida
Orlando, Florida 32816

NOTE: As of 23 August 1988, the National Bureau of Standards (NBS) became the National Institute of Standards and Technology (NIST) when President Reagan signed into law the Omnibus Trade and Competitiveness Act.



BOULDER DAMAGE SYMPOSIUM

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

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, Ernest Ambler, Director
(formerly National Bureau of Standards)

Issued October 1988

Library of Congress Catalog Card Number: 88-600576

**National Institute of Standards and Technology
Special Publication 756, 650 pages (Oct. 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 Nineteenth Symposium on Optical Materials for High-Power Lasers held at the National Institute of Standards and Technology in Boulder, Colorado, on October 26-28, 1987. The Symposium was jointly sponsored by the National Institute of Standards and Technology, the American Society for Testing and Materials, the Office of Naval Research, the Defense Advanced Research Projects Agency, the Department of Energy, and the Air Force Office of Scientific Research. The Symposium was attended by over 190 scientists from the United States, Canada, the United Kingdom, India, Japan, France, Taiwan, and the Federal Republic of Germany. 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, Dr. Brian E. Newnam of the Los Alamos National Laboratory, and Dr. M. J. Soileau of the University of Central Florida. They also served as editors of this report.

The editors assume full responsibility for the summary, conclusions, and recommendations contained in the report, and for the summaries of discussion found at the end of each paper. 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 Twentieth Annual Symposium on this topic will be held in Boulder, Colorado, October 26-28, 1988. 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 1988 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. It is our intention to pause and reflect on progress over the past twenty years of the Symposium on Optical Materials for High Power Lasers. It will be our pleasure to present a comprehensive array of tutorial lectures by distinguished workers in the field of laser induced damage in optical materials.

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 our Gala Twentieth Annual Symposium.

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

Disclaimer

Certain papers contributed to this publication have been prepared by non-NIST authors. These papers have not been reviewed or edited by NIST; therefore, the National Institute of Standards and Technology accepts no responsibility for their accuracy, nor for their comments or recommendations.

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 Institute of Standards and Technology, nor does it imply that the equipment, instruments, or materials identified are necessarily the best available for the purpose.

CONTENTS

	<u>Page</u>
Foreword	iii
H.E. Bennett, A.H. Guenther, D. Milam, B.E. Newnam, and M.J. Soileau	
Disclaimer	iv
Symposium Welcome	xiii
D. Milam	
Summary of Meeting	1
H.E. Bennett, A.H. Guenther, D. Milam, B.E. Newnam, and M.J. Soileau	
1.0 Introduction	1
2.0 Overview	2
3.0 Acknowledgments	6
4.0 References	7

Materials and Measurements

Influence of Optical Components for Laser Processing	10
A. Giesen, S. Borik and U. Schreiner	
Materials for Aerospace/Large Optics	17
W.W. Ernst	
Production and Properties of Perrhenate-Doped Alkali Halide Crystals	22
O.H. Nestor and J.F. Figueira	
Solubility of Pt in Nd Phosphate Laser Glass	29
T. Izumitani, M. Matsukawa and H. Miyade	
Effect of Residual Organic Carbon in Mother Solution of Potassium Dihydrogen Phosphate on Damage Threshold of the Crystals for High Power Lasers	35
A. Yokotani, T. Sasaki, K. Yoshida	
T. Yamanaka, S. Nakai and C. Yamanaka	
Laser Damage on Zinc Selenide and Cadmium Telluride Using the Stanford Mark III Infrared Free Electron Laser	41
Stephen V. Benson, Eric B. Szarmes	
Brett A. Hooper, Edwin L. Dottery and John M.J. Madey	

Laser Damage in Silicon Avalanche Photodiode	50
M.A. Acharekar	
Multiphoton Photoconductivity and Laser Induced Damage in Alkali-Halide Crystals under Picosecond Pulses from YAG:Nd Laser and its Harmonics	68
S.V. Garnov, A.S. Epifanov, S.M. Klimentov	
A.A. Manenkov and A.M. Prokhorov	
Radiation-Induced Absorption in Fused Silica	79
G.H. Miley, R. Chapman	
J. Nadler and W. Williams	
Radiation Effects in Amorphous SiO₂ for Windows and Mirror Substrates	89
E.J. Friebele and P.L. Higby	
Ultrafast Imaging of Optical Damage in PMMA	98
Taehyoung Zyung, Hackjin Kim	
Jay C. Postlewaite and Dana D. Dlott	
Recent Progress in Understanding Fundamental Mechanisms of Laser Induced Damage in Optical Polymers	105
K.M. Dyumaev, A.A. Manenkov, A.P. Maslyukov, G.A. Matyushin	
V.S. Nechitailo and A.M. Prokhorov	
Large Scale Damage Testing in a Production Environment	112
C.L. Weinzapfel, G.J. Greiner, C.D. Walmer, J.F. Kimmons	
E.P. Wallerstein, F.T. Marchi, J.H. Campbell, J.S. Hayden	
K. Komiya and T. Kitayama	
A New Average-Power Damage Test Facility at LLNL	123
E.A. Hildum, F. Rainer and D. Milam	
Developments in Beam Profiling with a CCD Area Array Detector	128
Robert M. O'Connell, Rui J. Ferreira and Alan F. Stewart	
A Sensor for Production Oriented Damage Testing at 1.06 μm	137
J.W. Arenberg, C.L. Schoen and D.W. Mordaunt	
Mapping of Surface Defects of Optical Components by a High Speed Surface Analysis System	141
Ramin Lalezari and Robert Knollenberg	

Scattered Light as a Laser Damage Diagnostic	142
Alan F. Stewart and Arthur H. Guenther	

The Growth and Stability of Ag Layers on Cu(110) Monitored by Second-Harmonic Generation	151
R.E. Muenchausen, M.A. Hoffbauer and T.N. Taylor	

Surfaces and Mirrors

Super-Polished Silicon Carbide Mirror for XUV Radiation	152
K. Yoshida, Y. Kato, S. Nakai	
K. Kurosawa and W. Sasaki	

Ultrafine Polishing of Tungsten and Molybdenum Mirrors for CO₂ Laser	153
M. Yamashita, S. Hara and H. Matsunaga	

A New Forming Technology Using Laser Damage	163
Yoshiharu Namba	

UV Light Cleaning of Silica Surfaces for Improved Laser Damage of AR Coatings	164
K. Yoshida, H. Yoshida, Y. Kato, S. Nakai and M. Ohtani	

Laser Induced Surface Emission of Neutral Species and its Relationship to Optical Surface Damage Processes	165
L.L. Chase and L.K. Smith	

Laser Induced Particle Emission as a Precursor to Laser Damage	175
Fred E. Domann, Alan F. Stewart and Arthur H. Guenther	

A Chemical Precursor to Optical Damage? Studies by Laser Ionization Mass Spectrometry	187
N.S. Nogar and R.C. Estler	

Ion Emission Kinetics of Laser Damage to Semiconductor and Dielectric Thin Film Surfaces	196
Jahja I. Trisnadi, Yong Jee	
Rodger M. Walser and Michael F. Becker	

Laser Induced Desorption and Second Harmonic Generation from the (111) Surface of Barium Fluoride	205
J. Reif, H.B. Nielsen, O. Semmler, P. Tepper	
E. Matthias, E. Fridell, E. Westin and A. Rosen	
Multiphoton Absorption Near Surface Damage Thresholds of Ionic Crystals and Metals	217
E. Matthias, S. Petzoldt, A.P. Elg	
P.J. West and J. Reif	
Laser Fluorescence Spectroscopy of Zinc Neutrals Originating from Laser- Irradiated and Ion-Bombarded Zinc Sulfide and Zinc Surfaces	227
H.F. Arlinghaus, W.F. Calaway, C.E. Young	
M.J. Pellin, D.M. Gruen and L.L. Chase	
Damage to Fused Silica Windows While Under Simultaneous Exposure to Flowing Solvents and Laser Radiation at 308 nm	237
Billie R. Mauro, Stephen R. Foltyn and Virgil Sanders	
Laser Damage Studies of Ion Beam Milled Fused Silica	241
S.R. Wilson, D.W. Reicher, J.R. McNeil, J.J. McNally	
Kent Stowell, D. Milam, R. Gonzales and F. Rainer	

Thin Films

Diamond, a Potentially New Optical Coating Material	246
Albert Feldman, Edward N. Farabaugh	
Y.N. Sun and Edgar S. Etz	
Wavelength Dependence of Edge Filter Absorption	257
L.J. Basegio and M.K. von Gunten	
Minimizing Scattering in Multilayers: Technique for Searching Optimal Realization Conditions	265
C. Amra	
A Comparison of Various Rugate Filter Designs	272
C.K. Carniglia	
Comparative Study of Reactively Evaporated vs. Ion-Plated TiO₂ Thin Films	278
Karl H. Guenther, Boon Loo, Hans K. Pulker	
Andreas Saxer and Steven C. Seitel	

Ion Assisted Deposition of Optical Thin Films at Reduced	
Substrate Temperature	279
Forrest L. Williams, J.R. McNeil	
J.J. McNally and G.J. Exarhos	
Optical Properties of Low Energy Ion Assisted Deposited TiO₂ Films	280
M. Ghansyam Krishna, K. Narasimha Rao	
M. Adinarayana Murthy and S. Mohan	
HR Coatings Prepared from Colloidal Suspensions	286
Ian M. Thomas, John G. Wilder and Raymond P. Gonzales	
1064 nm and 350 nm Radiation Stability of Low Density ThO₂-SiO₂	
High-Reflective Coatings Deposited from Sols	290
H. Floch, J.J. Priotton, J.F. Mengue and C. Cordillot	
Oxide Optical Coatings Prepared by Metal-Organic Vapor Deposition	300
Raymond Brusasco	
Deposition With Ultra-Fine Particles	308
Arthur C. Day	
Cluster Beam Deposition for Optical Thin Films	309
E.M. Waddell, B.C. Monachan	
K.L. Lewis, T. Wyatt-Davies and A.M. Pitt	
Measurement of HR Coatings Absorptance at 10.6 Microns by Mirage Effect	320
P.J. Baron, A. Culoma, A.C. Boccara and D. Fournier	
Basic Studies of Optical Coating Thermal Properties	328
Randall T. Swimm	
Studies of the Thermal Stability of Thin Film Structures	338
K.L. Lewis, A. Miller, I.T. Muirhead and J. Staromlynska	
Raman Studies of Inherent and Applied Stress in Thin Optical Films	352
G.J. Exarhos, W.S. Frydrych, K.F. Ferris and N.J. Hess	
Optical Measurements of Surface Oxide Layer Formation on Metal Films	361
Marion L. Scott	
The Properties of Laser Annealed Dielectric Films	369
Alan F. Stewart, Arthur H. Guenther and Fred E. Domann	

Video Image Processing of Laser-Illuminated Coating Defects	388
J.E. Auburn and M.B. Moran	
Operational Limits for ZnSe/ThF₄ Multilayer Mirrors in the Los Alamos Free-Electron Laser Oscillator	404
Brian E. Newnam and Steven C. Bender	
Damage Threshold of Oscillator Mirrors in Mark III FEL	405
David A.G. Deacon, Stephen V. Benson John M.J. Madey and John Schultz	
Laser Induced Damage Measurements of Free Electron Laser Optical Components	409
L. John Jolin, Virgil E. Sanders and Steven J. Salazar	
Database of Average-Power Damage Thresholds at 1064 nm	410
F. Rainer, E.A. Hildum and D. Milam	
Causes of Damage in Multilayer Dielectric Coatings Exposed to High Average Power Visible Laser Radiation	419
David M. Aikens and John R. Taylor	
On the Role of Water in the Laser Conditioning Effect	430
J.W. Arenberg and M.E. Frink	
Optical Coatings for High-Power Nd-Lasers	440
F.S. Faizullov, A.I. Erokhin, V.I. Kovalev, S.I. Sagitov B. Brauns, V. Goepner, G. Herrendorfer, D. Schafer W. Wolf and H. Zscherpe	
Pulse Length Scaling Results at 248 nm	450
J. Boyer	
Measurements of Ultra-Wide Pulse Damage Thresholds of Anti-Reflection Coated IR Materials at 10.6 μm	451
R.S. Eng, J.G. Grimm, J. Greene J.A. Daley and N.W. Harris	
Sample Ranking vs. Damage Threshold Criteria in Small Spot Size Laser Damage Testing	462
S.D. Carson, P. Gorbett and S.L. Seiffert	

Fundamental Mechanisms

Intrinsic Optical Damage in Potassium Bromide at 532 nm	465
X.A. Shen, Peter Braunlich, Scott C. Jones and Paul Kelly	
The Discovery of Laser-Induced Intrinsic Optical Damage in Wide-Gap Materials at Visible Wavelength	476
Peter Braunlich, Scott C. Jones, X.A. Shen R. Thomas Casper and Paul Kelly	
The Laser Damage Mechanism for NaCl and KBr at 532 nm - Theoretical Predictions and Experimental Tests	485
R. Thomas Casper, Scott C. Jones, X.A. Shen Peter Braunlich and Paul Kelly	
New Data Regarding the Thermal Laser-Damage Model and the Accumulation Phenomena in Silicon	492
Stephen P. Fry, Rodger M. Walser and Michael F. Becker	
Observation of Two Photon Absorption Prior to Laser-Induced Damage in ZrO₂	501
Nastaran Mansour, Kamjou Mansour M.J. Soileau and Eric W. Van Stryland	
Intense-Field Optical Interband Excitations in Semiconductors and Insulators	502
W. Becker, J.K. McIver and A.H. Guenther	
Behavior Studies on Dirt Spikes in Laser Discharge and their Effects on Thyatron Operations	509
Chin E. Lin, C.Y. Yang and C.L. Huang	
ADDENDUM	518
Thermal Shock: A Contributing Factor to Laser Damage in Optical Thin Films used for High Power Continuous Wave Laser Optics	519
J. R. Palmer	
Reverse Thermal Wave Approximation for Temperature Transients in Optical Thin Films and Substrates - Reflective Optics for High Power Repetitive Pulsed Lasers	546
J. R. Palmer	

Reverse Thermal Wave Approximation for Temperature Transients in Optical Thin Films and Substrates - Reflective Optics for High Power Continuous Wave Lasers	579
J. R. Palmer	
High Power Continuous Wave and Repetitive Pulsed Thermal Shock Laser Damage to Metallic Reflective Optics	614
J. R. Palmer	
APPENDIX I. List of Attendees	623

OPENING COMMENTS - 19TH ANNUAL DAMAGE SYMPOSIUM

D. Milam

Lawrence Livermore National Laboratory

University of California

P.O. Box 5508, L-490

Livermore, California 94550

The chairmen of the 1987 Boulder Damage Conference wish first to acknowledge continued support by the National Institute of Standards and Technology. Access to NIST facilities and contributions by individuals in that organization have provided a stable and comfortable environment during this series of 19 conferences. For the 1987 meeting, we had the assistance of Bob Kamper, Director, NIST Boulder, of Aaron Sanders, Leader of the Optical Electronic Metrology Group, and of an administrative staff: Susie Rivera, Edit Haakinson, and Ann Mannos. Major contributions to the organization and operation of the conference were again made by Pat Whited of the Air Force Weapons Laboratory.

This year we will have 73 papers presented by authors from 15 countries. As in previous years, the majority of the authors are affiliated with either a university or a commercial organization, while the remainder are affiliated with a national laboratory.

As has become typical, the topic most often discussed will be damage in thin films. This effort has consumed 30 to 55 percent of our effort in each year since 1977. Including the papers at this conference, we have heard 265 reports of studies related to some aspect of the production of damage resistant films. Sixteen different processes for making films have been investigated. Conservatively estimated, execution of this work required at least 100 man years. Since many participated without sharing authorship, the total effort expended was probably much greater than the conservative estimate.

Progress is apparent. Films made by several processes are better than they were 20 years ago, and our industrial facilities can now coat substrate with diameter exceeding 1 m. Films with higher density, lower stress, and lower scatter have been produced by several ion-assisted technologies. Solution-deposited silica antireflection coatings have excellent damage resistance. We have learned much about making coatings for both ultraviolet and infrared applications. Other examples of progress could be cited.

However, with few exceptions, progress has been incremental and many questions remain unanswered. The fundamental mechanism for damage in films is still a subject of debate. Large coaters do not produce films with quality equal to those that have been made in smaller research machines. And, after having studied 15 competing processes, we still rely heavily on a technique that was available 20 years ago, electron-beam evaporation.

Considering the magnitude of our past effort and the number of unresolved issues, it is possible without being overly cynical to question whether these issues can be resolved by a larger but similar effort. Note that I do not question whether progress is possible; past effort did produce a few exceptional optical coatings with thresholds 2-5 times larger than thresholds of commercially available films. We have not reached a fundamental limit.

It is more difficult to suggest what else should be done than it is to cite unresolved issues. Without pretending to know the specific steps that should be taken, I would comment on two general topics. The first is my growing concern that we have not established an adequate flow of real information from research into production. The hypothesis underlying much of our research is that information obtained through the relatively inexpensive study of small samples made in small research machines can be transferred to improve large coatings made in production machines. However, large coatings do not have thresholds as large as those frequently reported in studies of small samples. When sliced into the black and white version, this implies either that research concepts have been evaluated by production groups and found to be ineffective, or that research concepts have not been evaluated. If the former is true, is it because the research data are wrong, or do fundamental differences in large and small coaters prevent transfer of information? If the results are not being evaluated, is this caused simply by the press of production schedules and the large cost of doing research in large machines? Some rather blunt comment by our production community, which could be made without divulging the detailed proprietary aspects of coating production, would be of great value.

The second general concern is the now elderly problem of identifying the defects responsible for coating damage. Work done between 1972 and 1974 indicated that damage to coatings is initiated in very small volumes. The few exceptions are instances where spatially averaged absorption is important -- in coatings used in the far UV or far IR or those used in lasers operating at high average power. Much effort has been spent in the study of these defects, but their basic nature remains a mystery. My belief is that nonstoichiometric subvolumes are the defects which most often determine the damage resistance. However, I reach this conclusion through a rather circuitous argument and cannot prove that it is correct. Other candidates are impurities from the substrate itself, from compounds used in polishing or cleaning of the substrate, or from the coating chamber, or film imperfections such as pinholes, grain boundaries, or local areas of poor adhesion. Lacking identification of the limiting defect, we are left with the two general routes we have so far followed -- the somewhat random search for a coating process that makes perfect films, or the somewhat random tuning of existing coating processes. Since our search pattern would be narrowed by that ability to remove even some of the contenders from the list, identification of limiting defects is the most important issue before us.

U.S. Department of Commerce

National Institute of Standards and Technology
(formerly National Bureau of Standards)
Gaithersburg, MD 20899

Official Business

Penalty for Private Use \$300



Stimulating America's Progress
1913-1988