

**An Assessment of the
National Institute of
Standards and Technology
Building and Fire Research
Laboratory: Fiscal Year 2008**

The National Academies Press

**AN ASSESSMENT OF THE
NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
BUILDING AND FIRE RESEARCH
LABORATORY**

FISCAL YEAR 2008

Panel on Building and Fire Research

Laboratory Assessments Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the panel responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Contract No. SB134106Z0011 between the National Academy of Sciences and the National Institute of Standards and Technology, an agency of the U.S. Department of Commerce. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the agency that provided support for the project.

International Standard Book Number-13: 978-0-309-12734-9

International Standard Book Number-10: 0-309-12734-3

Copies of this report are available from

Laboratory Assessments Board
Division on Engineering and Physical Sciences
National Research Council
500 Fifth Street, N.W.
Washington, DC 20001

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, <http://www.nap.edu>.

Copyright 2008 by the National Academy of Sciences. All rights reserved.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

PANEL ON BUILDING AND FIRE RESEARCH

ROBERT J. HITCHCOCK, Lawrence Berkeley National Laboratory, *Chair*
RONALD G. BURG, CTL Group
MARTIN FISCHER, Stanford University
CATHERINE E. WOLFGAM FRENCH, University of Minnesota
KRISTIN H. HEINEMEIER, University of California, Davis
PATRICK J. HUGHES, Oak Ridge National Laboratory
CLAS A. JACOBSON, United Technologies Research Center
CLIFF JONES, City of Tempe, Arizona
JOHN JUDGE, Liebert-Emerson Network Power
PAULO J.M. MONTEIRO, University of California, Berkeley
R. SHANKAR NAIR, Teng and Associates, Inc.
R. BYRON PIPES, Purdue University
LLOYD M. ROBESON, Air Products and Chemicals, Inc. (retired)
ADEL F. SAROFIM, University of Utah
RICHARD E. SCHULER, Cornell University
RICHARD L. TUCKER, University of Texas
STEVEN R. WINKEL, The Preview Group, Inc.
ANTENEH Z. WORKU, Dow Chemical Company

Staff

JAMES P. McGEE, Director
ARUL MOZHI, Senior Program Officer
CY BUTNER, Senior Program Officer
LIZA HAMILTON, Administrative Coordinator
JONATHAN ELLSAESSER, Senior Project Assistant

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Melvyn C. Branch, University of Colorado,
John T. Christian, Consulting Engineer,
Richard G. Little, University of Southern California,
James E. McGrath, Virginia Polytechnic Institute and State University,
John W. Mitchell, University of Wisconsin, and
Richard N. Wright, National Institute of Standards and Technology (retired).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Alton Slay, Warrenton, Virginia. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring panel and the institution.

Contents

SUMMARY	1
THE CHARGE TO THE PANEL AND THE ASSESSMENT PROCESS	5
MEASUREMENT SCIENCE FOR BUILDING ENERGY TECHNOLOGIES	8
MEASUREMENT SCIENCE FOR BREAKTHROUGH IMPROVEMENTS IN CONSTRUCTION PRODUCTIVITY	14
MEASUREMENT SCIENCE FOR PREDICTING LIFE CYCLE PERFORMANCE OF NANOCOMPOSITE INFRASTRUCTURE MATERIALS	19
DISASTER RESILIENT STRUCTURES AND COMMUNITIES (HURRICANES AND EARTHQUAKES)	23
DISASTER RESILIENT STRUCTURES AND COMMUNITIES (FIRES)	29
PROGRAMS FUNDED UNDER THE AMERICA COMPETES ACT	37
OVERALL CONCLUSIONS	40

Summary

A panel of experts appointed by the National Research Council (NRC)—the Panel on Building and Fire Research—has assessed the scientific and technical work of the Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST). The panel visited the laboratory and reviewed its activities. As requested by the Director of NIST and described further in the next chapter on the charge to the panel and its assessment process, the scope of the assessment included the following criteria: (1) the technical merit of the current laboratory programs relative to the current state of the art worldwide; (2) the adequacy of the laboratory facilities, equipment, and human resources, as they affect the quality of the laboratory technical programs; and (3) the degree to which the laboratory programs in measurement science and standards achieve their stated objectives and desired impact. In addition to these three criteria, the panel was asked by the Director of NIST to assess the projects within the BFRL conducted under the America COMPETES Act of 2007, which supports the President’s American Competitiveness Initiative (ACI).¹ That work focuses on disaster-resilient structures and communities, including efforts related to hurricanes, wildland fires, and earthquakes (including community-scale loss estimation). Following is a brief summary of the panel’s conclusions, based on its assessment using these criteria.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

Overall the technical merit of the programs reviewed within the BFRL is very high and generally at a state-of-the-art level. The programs have clear ties to the overall BFRL Strategic Priority Areas and are well aligned with the mission of NIST, which is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life. Technical quality is demonstrated by the acceptance of submissions to high-impact publications and the adoption of technical results and findings in codes and standards. The publications that document results from the laboratory receive extensive internal review before their submission for publication. With few exceptions, the BFRL staff who were reviewed by the panel are fully aware of work being done elsewhere and have exceptional links with the external community, demonstrated by membership and active participation in professional and trade committees and on codes and standards development bodies. There is good balance in BFRL work between anticipatory, longer-term research and activities that respond to the immediate needs of customers.

ADEQUACY OF INFRASTRUCTURE

The equipment and facilities supporting current BFRL work are excellent and, except for specifically noted cases (the large-scale structural fire test facility and

¹ See Domestic Policy Council, Office of Science and Technology Policy, 2006, *American Competitiveness Initiative*, Washington, D.C. “America COMPETES Act” is the short title for the America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act of 2007 (Public Law 110-69).

construction productivity metrics work space), do not appear to be a limiting factor. For virtually all of the research reviewed there is either adequate laboratory equipment and very impressive laboratory facilities or current planning to make appropriate additions to the current facilities. The updating and modernizing of NIST-related test equipment and procedures must continuously be considered. In the area of structural engineering (disaster-resilient structures and communities), the BFRL has moved away from experimentation and is outsourcing some experiments. For outsourcing, planning should be put in place to establish requirements for the adequate control and oversight of the quality of experimental measurements.

The BFRL staff has a critical mass of scientific and technical competencies and is well qualified to conduct the programs underway. However, it is short-staffed in several areas if it is to achieve the full potential of current and planned future efforts. There are serious concerns relative to the attracting, recruiting, training, and retaining of staff for future needs. A plan needs to be developed to address present and future staffing needs, mentoring and staff development, retention strategies, technical and project management training, and the provision of the human resources (HR) support necessary to implement the plan without unduly taxing the time of scientific personnel. While recruiting specific qualified individuals will require contacts from scientific personnel, HR can support regular recruitment activities at national meetings of relevant societies and learn the processes of other industries (e.g., the more widespread use of recruiters). Also, help is needed from HR, the Office of Personnel Management, and the Congress in opening opportunities to noncitizens (such as permanent residents).

There has been a significant change in personnel over the past 3 years, in particular in technical leadership positions within the BFRL. It is not clear that there have been systematic development opportunities to prepare individuals for this transition. The backgrounds of the staff at the BFRL are highly technical, and training in technical program management principles may be warranted.

Available funding, at least prospectively, appears adequate for success in most current areas of work if the funding materializes. The laboratory's base funding from Congress provides a foundation for sustaining programs comparable to the funding for most federally sponsored research institutions. Base funding has grown modestly every year since fiscal year (FY) 2002, and based on the American Competitiveness Initiative, the America COMPETES Act, and planned administration requests, there appears to be a very positive prospect of doubling base funding over 10 years. Some areas in which the BFRL is already involved could be more effectively addressed, given additional funding. For example, national economic opportunities and global environmental threats justify considerably more funding on energy-related work.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

The BFRL has a strong foundation and record of excellent results in achieving program objectives and disseminating research results and findings. BFRL researchers are active participants in major professional and trade organizations and on standards and code-setting committees, with demonstrated success in moving research results to standards and codes. Product dissemination is accomplished through numerous channels, including professional publications and conferences, industry materials such as training

manuals, and Web sites.

The panel was presented with a clear articulation of the mission and of the strategic directions for the BFRL. However, this strategic vision is not always complemented by detailed roadmaps and associated metrics that can be used to evaluate progress. At the present time, it appears that the achievement of stated objectives is mainly assessed by monitoring program progress against program-developed milestones. This process may be effective on a project-by-project basis but may be insufficient as an effective methodology for assessing a group of projects that have interdependent objectives related to larger strategic goals for the BFRL. The BFRL should consider adopting more formal project management techniques that are commonly used in industry.

PROGRAMS FUNDED UNDER THE AMERICA COMPETES ACT

The BFRL sees Disaster Resilient Structures and Communities (Hurricanes and Earthquakes) as a key focus area for addressing the objectives of the ACI and the America COMPETES Act. In FY 2008, the funding levels in the BFRL were not increased as had been anticipated. As a result, the programs in this area have suffered from lack of adequate support. These programs are only now taking shape.

NIST assumed leadership of the National Earthquake Hazards Reduction Program (NEHRP) in 2005; however, the effort appears to be early in its development stages within NIST. The program has strong leadership and good overall perspective on direction and objectives. In terms of progress on earthquake-related issues within NIST, there has been limited technical progress. Staffing and integration with other BFRL projects (multi-hazard projects) still need to be addressed. Care should be taken that the role of the overall management responsibility for NEHRP does not interfere with the NIST technical programs associated with earthquake engineering.

The extent of damage from wildland-urban interface (WUI) fires has grown as a result of increased construction at the interface, which in turn has been aggravated where weather is hotter and drier. The BFRL is uniquely qualified to address the many facets of the WUI fires, drawing on the laboratory's competencies in characterizing and modeling fire spread in buildings, its large-scale fire facilities, its extensive connections in the fire community internationally, and its expertise in deriving lessons from fire investigations. The skills demonstrated in the investigations of the World Trade Center (WTC) building collapse and the Warwick, Rhode Island, Station nightclub fire make the engagement with the WUI situation timely and potent.

The panel's recommendations relative to the WUI fire research in support of the ACI are twofold. The first is to prepare technology roadmaps that clearly indicate the use of additional funding for the BFRL and state with precision and rigor what milestones are being targeted and what stakeholders will be affected. The BFRL should fully embrace technical portfolio management tools and processes that are routinely employed in industry, including processes for project management (e.g., the Stage-Gate product innovation process) and elements of the Design for Six Sigma paradigm (a method for eliminating defects in processes) to quantify the necessary robustness of the research results in order to ensure their transition to industrial practice. Secondly, the BFRL should also move aggressively beyond the characterization of components to the full

consideration of systems, particularly as characterized by the very successful past work for the WTC and what is clearly emerging for the WUI area. The focus on systems is critical to the science of measurement and U.S. competitiveness. The BFRL should employ new technologies from systems engineering and dynamical systems and should make full use of advances in information technology.

The remaining chapters of this report contain a more detailed description of the charge to the panel and its assessment process and present detailed assessment findings within each of five Strategic Priority Areas that organize the research programs within the BFRL into core competency areas aligned with high-level BFRL goals. The five Strategic Priority Areas are (1) Measurement Science for Building Energy Technologies, (2) Measurement Science for Breakthrough Improvements in Construction Productivity, (3) Measurement Science for Predicting Life Cycle Performance of Nanocomposite Infrastructure Materials, (4) Disaster Resilient Structures and Communities (Hurricanes and Earthquakes), and (5) Disaster Resilient Structures and Communities (Fires). A separate chapter on “Programs Funded Under the America COMPETES Act” is included to examine and review the progress of all of the FY 2007-funded initiatives relevant to the BFRL and to comment on these program growth areas explicitly in this report. The report concludes with a chapter presenting the overall conclusions of the panel.

The Charge to the Panel and the Assessment Process

At the request of the National Institute of Standards and Technology, the National Academies, through the National Research Council, has since 1959 annually assembled panels of experts from academia, industry, medicine, and other scientific and engineering environments to assess the quality and effectiveness of the NIST measurements and standards laboratories, of which there are now nine,² as well as the adequacy of the laboratories' resources. In 2008, NIST requested that five of its laboratories be assessed: the Building and Fire Research Laboratory, the Manufacturing Engineering Laboratory, the Materials Science and Engineering Laboratory, the NIST Center for Neutron Research, and the Physics Laboratory. Each laboratory was assessed by a separate panel of experts; the findings of the respective panels are summarized in separate reports. This report summarizes the findings of the Panel on Building and Fire Research.

For the FY 2008 assessment, NIST requested that the panel consider the following criteria as part of its assessment:

1. The technical merit of the current laboratory programs relative to the current state of the art worldwide;
2. The adequacy of the laboratory facilities, equipment, and human resources, as they affect the quality of the laboratory technical programs; and
3. The degree to which the laboratory programs in measurement science and standards achieve their stated objectives and desired impact.

The panel adopted the following additional assessment criteria under each broad factor to make them more explicit:

1. The technical merit of the current laboratory programs relative to the current state of the art worldwide.
 - *Relative Technical Caliber*: How does the technical quality of the laboratory compare to current state-of-the-art capabilities worldwide?
 - *Relevance*: Do the projects reflect a broad understanding of comparable work being done elsewhere (at other government laboratories, universities, and industry)?
 - *Balance*: Does the laboratory adequately balance anticipatory, longer-term research and activities that respond to immediate customer needs?
2. The adequacy of the laboratory facilities, equipment, and human resources, as they affect the quality of the laboratory technical programs.
 - *Available Tools*: Is the state of the equipment and facilities adequate to meet project objectives and customer needs?
 - *Critical Mass*: Are the available scientific and technical competencies adequate to achieve success? Is available funding adequate to achieve

² The nine NIST laboratories are the Building and Fire Research Laboratory, the Center for Nanoscale Science and Technology, the Chemical Science and Technology Laboratory, the Electronics and Electrical Engineering Laboratory, the Information Technology Laboratory, the Manufacturing Engineering Laboratory, the Materials Science and Engineering Laboratory, the NIST Center for Neutron Research, and the Physics Laboratory.

success?

- *Agility*: Is the laboratory sustaining the technical competencies and capacity to respond quickly to critical issues as they arise?
3. The degree to which the laboratory programs in measurement science and standards achieve their stated objectives and desired impact.
- *Technical Planning*: Are appropriate milestones identified and do they appear feasible?
 - *Dissemination*: Is the laboratory regularly implementing sound and effective techniques and practices for delivering products and services to customers?
 - *Impact*: Will the laboratory products have a consequential, long-term impact?
 - *Responsiveness*: Are the research projects moving at a pace and in a direction that is well matched to current and emerging customer needs?

In addition, because NIST has begun to receive increases in funding through the President's ACI and the America COMPETES Act of 2007, the Director of NIST requested that the assessment panels specifically examine and review the progress of all of the FY 2007-funded initiatives relevant to their respective laboratories and comment on these program growth areas explicitly in their reports. At the BFRL, that work focuses on disaster-resilient structures and communities, including efforts related to hurricanes, wildland fires, and earthquakes (including community-scale loss estimation). Specifically, the panel was asked to examine and review progress on the following growth areas: the National Earthquake Hazards Reduction Program, wind engineering, multi-hazard failure analysis, and fires at the wildland-urban interface.

The context of this technical assessment is the mission of NIST, which is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve the quality of life. The NIST laboratories conduct research to anticipate future metrology and standards needs, to enable new scientific and technological advances, and to improve and refine existing measurement methods and services.

To accomplish the assessment, the NRC appointed a panel of 18 volunteers whose expertise closely matched that of the work performed by the BFRL staff. On the basis of their own individual expertise areas, the panel members were also assigned to five Strategic Priority Areas that organized the research programs within the BFRL into core competency areas aligned with high-level BFRL goals. The five Strategic Priority Areas are (1) Measurement Science for Building Energy Technologies, (2) Measurement Science for Breakthrough Improvements in Construction Productivity, (3) Measurement Science for Predicting Life Cycle Performance of Nanocomposite Infrastructure Materials, (4) Disaster Resilient Structures and Communities (Hurricanes and Earthquakes), and (5) Disaster Resilient Structures and Communities (Fires). The BFRL Web site provides additional information on BFRL programs.³

Each of the panel's Strategic Priority Area subgroups separately visited the BFRL staff working in its respective area for 1 day, during which it attended presentations, tours, and demonstrations and had a number of interactive sessions with the staff. These

³ See <http://www.bfrl.nist.gov/> for more information on BFRL programs. Accessed August 12, 2008.

reviews were conducted at the NIST facilities in Gaithersburg, Maryland, on March 18, 2008. Immediately following the subgroup visits, the entire panel assembled for a day-and-a-half meeting at the BFRL facility in Gaithersburg; during that time it attended interactive sessions with the laboratory managers, and the panel also met in a closed session to deliberate its findings and to define the contents of this assessment report.

The BFRL provided the panel with background materials, including a recent BFRL annual report; information on the BFRL budget, staffing, awards, and standards activities; a BFRL organizational chart; the NIST programmatic plan for FY 2009-2011; and a list of BFRL publications for FY 2007. BFRL staff also set up a Web site for panel members that provided additional links to further reference materials.

The approach of the panel to the assessment relied on the experience, technical knowledge, and expertise of its members, whose backgrounds were carefully matched to the technical areas within which the BFRL activities are conducted. The panel reviewed selected examples of the standards and measurements activities and the technological research presented by the BFRL. It was not possible to review the BFRL programs and projects exhaustively. The goal of the panel was to identify and report representative examples of accomplishments and to highlight opportunities for further improvement with respect to the technical merit of the BFRL work and its perceived impact with respect to achieving its own definition of its objectives, and to highlight specific elements of the resources and infrastructure within BFRL that are intended to support the technical work. These highlighted examples for each BFRL Strategic Priority Area are intended to collectively portray an overall impression of the laboratory, while preserving useful mention of specific suggestions for projects and programs that the panel considered to be of special note within the set of those examined. The assessment is currently scheduled to be repeated biennially. While the panel applied a largely qualitative rather than a quantitative approach to the assessment, it is possible that future assessments will be informed by further consideration of various analytical methods that can be applied.

The comments in this report are not intended to address each program within the BFRL exhaustively. Instead, this report identifies key issues and focuses on representative programs and projects relevant to those issues. Given the necessarily nonexhaustive nature of the review process, the omission of any particular BFRL program or project should not be interpreted as a negative reflection on the omitted program or project.

Measurement Science for Building Energy Technologies

The primary core competency for this Strategic Priority Area is measurement science for building energy technologies. Secondary core competencies for this area include information, communication, and automation technologies for the intelligent integration of building design, construction, and operations.

Areas of expertise within this Strategic Priority Area include energy efficiency, renewable and distributed energy sources, indoor air quality, building controls, alternative refrigerants, economics, the behavioral response of occupants, and codes and standards. The BFRL divisions that are active in this area are the Building Environment Division (BED) and the Office of Applied Economics (OAE). Groups within the BED include HVAC&R (heating, ventilating, air-conditioning, and refrigerating) Equipment Performance, Heat Transfer and Alternative Energy Systems, Mechanical Systems and Controls, Indoor Air Quality and Ventilation, and Computer-Integrated Building Processes. The primary BFRL goal in this strategic area is net zero, high-performance buildings, with programs in healthy and sustainable buildings and cybernetic building systems.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

The technical caliber of the programs in the Measurement Science for Building Energy Technologies strategic area is high. The areas of emphasis are very advanced and show both vision and mastery of the technologies involved. Examples include the following: (1) the new 90 K-900 K guarded hot plate apparatus for heat transmission measurements and the development of reference materials; (2) the facilities to sort out building integrated photovoltaic (PV) ratings; (3) the emulation facilities to test fault detection and diagnostics (FDD) tools; (4) the laser/photography/computational fluid dynamics approach to heat exchanger air-side maldistribution measurements; and (5) the lubricant luminescence measurement technique that established an understanding of how seeding nanoparticles into lubricant on the refrigerant side of a chiller can radically improve boiling heat transfer rates.

In FY 2007, the Building Environment Division produced numerous publications in professional journals, conference proceedings papers, NIST publications, and external reports. Technical staff members are engaged and influential in the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE), the International Institute of Refrigeration, the American Society of Mechanical Engineers (ASME), and ASTM (formerly known as the American Society for Testing and Materials), including a number of leadership positions at ASHRAE such as vice president, chair of the Standing Standard Project Committee (SSPC) 62.2 ventilation standards, and leadership within the research administration committee.

Generally the Building Environment Division projects tie to Measurement Science for Building Energy Technologies. The BFRL is most effective when it contributes measurement science to collaborations involving larger projects. Measurement science includes tools (e.g., algorithms and software) that enable collaborators to access the measurement science and to apply standards based on this information. Software development can become very resource-intensive, and so it is

important to keep a balanced focus that favors the development of measurement science over software development. In general, the projects within the BFRL maintain this balance.

With few exceptions, staff members are aware of work being done elsewhere. The Heat Pump Simulation Program appears to duplicate some of the capabilities of the widely used Heat Pump Design Model from the Oak Ridge National Laboratory, which has been available in Web-based versions for over a decade. Collaboration in cases such as this would strengthen each program and would avoid duplication of effort and resources.

Regarding the balancing of anticipatory, longer-term research with the activities that respond to immediate customer needs, the NIST Three-Year Programmatic Plan (FY 2009-2011) states: “Although NIST has not set a formal goal for the funding of high-risk basic research, NIST will invest approximately 12 percent of our R&D budget on high-risk research in FY 2008—a level that has been fairly consistent through the years. Increases requested in the President’s FY 2009 budget would increase the support at NIST for high-risk research to 17.8 percent of NIST’s research budget.”⁴ Compared to the overall budget allocation at NIST, the research in the building energy technologies area is more applied than basic, and, not surprisingly, no projects were found that were of significantly high risk. It is arguable that there was some risk that the lubricant luminescence measurement approach would not work in the nanofluid project.

The development of Net Zero Energy Buildings (NZEB) can clearly be a unifying goal in the Measurement Science for Building Energy Technologies strategic area. The BFRL is doing an excellent job of working on both the near-term and the long-term technologies that are needed to move toward this goal. The importance of the work with FDD, controls, and the commissioning of buildings should not be underestimated. Much can be learned from this work about real-world relevance and issues and the development of standards for measurement that can also impact codes. The laboratory’s work with FDD in residential units is novel and is well considered. Its past work with BACnet showed a very unique capacity to work with industry and in doing so to move industry in a completely new direction, which has led to open standards for building management systems and has increased the overall competitive position of the United States. (BACnet is a data communication protocol for Building Automation and Control Networks.) This same thinking should be applied to FDD and sensor networks and the overall technology foundations of NZEB.

Staff from the OAE play a crucial role within the BFRL, and to a lesser extent across other laboratories at NIST, in addressing questions of how measurement and standards information can be assembled and integrated to facilitate industry decisions and/or actions. In particular, this group has drawn from the latest available tools in the decision sciences to assist the BFRL in selecting which projects to pursue, to facilitate industrywide best practices in the selection of particular construction materials and systems (e.g., the busiBEES project, which investigates sustainability and carbon footprint metrics), and to predict the likely human response to the introduction of new

⁴ National Institute of Standards and Technology, 2008, *Three-year Programmatic Plan for the National Institute of Standards and Technology, U.S. Department of Commerce: Fiscal Years 2009-2011*, Washington, D.C., February 2, p. 9-41.

options and opportunities. In this last area there may be further opportunities to advance the state of understanding by, as an example, using techniques such as “real options” analysis to mirror actual human behavior that seems at odds with traditional choice models based on expected net present value estimates.

ADEQUACY OF INFRASTRUCTURE

Equipment and facilities supporting this strategic area were excellent and did not appear to be a limiting factor. All research being conducted at the BFRL in support of this strategic area has adequate laboratory equipment and very impressive laboratory facilities.

The BFRL has a critical mass of scientific and technical competencies in emerging building technologies and their measurement science needs. However, it is short-staffed in several areas (e.g., in the Mechanical Systems and Controls Group and the Heat Transfer and Alternative Energy Systems Group). The team investigating measurements of hydrogen proton exchange membrane fuel cells to characterize their suitability for backup power generation applications did not appear to be addressing reactive power, perhaps due to a lack of expertise in electrical engineering power on the team. Within the Mechanical Systems and Controls Group, a key researcher with significant expertise in FDD has left, and progress against the project milestones is currently constrained by the temporary staffing shortage.

The BFRL is experiencing difficulty in filling open positions. Staffing in energy-related fields is a problem industrywide, so NIST will have to compete with other entities in attracting staff. However, the BFRL needs to be much more innovative in recruiting and pulling especially from other industries (e.g., information technology, computer science) and learning from their processes for recruiting (e.g., more widespread use of recruiters). Recruiting and filling the open positions as well as overall staff development are key problems for the laboratory.

The Office of Applied Economics has had great difficulty historically in finding and recruiting highly trained economists who also have the knowledge base and the specific interest in technological detail to contribute effectively to the mission of the BFRL. The paucity of such economists and behavioral scientists has diminished slightly over the past several years. This may have occurred in part because Ph.D. programs in universities in the United States have become slightly less compartmentalized, and academic economic research has begun to employ numerical and experimental methods as well as traditional statistical tools, so its practitioners may have more avenues to interface with natural and physical scientists. The OAE has also begun to recruit at national conferences of the prominent economics societies. This approach of conducting wide searches paid a special dividend this year, resulting in the hiring of two new Ph.D. economists who significantly strengthen the OAE. Continuing this widespread search process annually is crucial for the long-run health of the office: even if the search in a particular year is not successful, the interview and recruitment process disseminates knowledge throughout the economics community about the laboratory and about the important and interesting work that is going on.

Available funding, at least prospectively, appears to be adequate for successful research at the BFRL in measurement science for building energy technologies if it

materializes. Overall for the BFRL, about two-thirds of the funding is base funding from Congress, which provides a foundation for sustaining programs comparable to most federally sponsored research institutions. The base funding has grown modestly every year since FY 2002, and based on the American Competitiveness Initiative, the America COMPETES Act, and planned administration requests, the prospect of doubling the base funding over a 10-year period appears very positive.

Several examples within the Measurement Science for Building Energy Technologies strategic area illustrate the ability to provide a quick response to critical issues, supporting the conclusion that the competencies and the capacity for agility are being maintained. For example, when the best laboratories could do no better than ± 7 percent, ± 12 percent, and ± 16 percent in round-robin measurement of the efficiency of solar conversion to power of crystalline, single-junction thin film, and multi-junction thin film PV modules, NIST was able to mount a program quickly to help resolve the problem. The lack of repeatability and comparability in volatile organic compound outgassing measurements for carpets and other building materials and the consequent BFRL response to this issue provide another example of the capability of the laboratory to respond to issues quickly and competently. The BFRL has a history of being able to respond quickly to issues that have arisen (e.g., the Indoor Air Quality Group's work on generators with the U.S. Consumer Product Safety Commission).

ACHIEVEMENT OF OBJECTIVES AND IMPACT

The BFRL has a strong foundation and record of excellent results in the building energy technologies area. Noteworthy examples include the development of BACnet, the application of novel optimization methods for HVAC&R equipment, and the work on the guarded hot plate. Each of these projects and many others embody the best in measurement science being applied to areas of critical interest to the nation.

The 23 projects conducted at BFRL under the Measurement Science for Building Energy Technologies strategic area all identified milestones that appeared feasible and clearly define the obstacles and the research challenges. The project descriptions provided a technical approach and resource requirements that are necessary to achieve the project objectives. The investigators for each project were identified, and cross-project connections were made where appropriate.

The project investigators in this strategic area regularly publish their results, and, more importantly, many of the projects have industry and university involvement and the project staff is active in outside organizations (ASHRAE, ASTM, and others) and their key technical committees. All of these linkages help disseminate and implement the research results.

There is a history within the BFRL of having a consequential, long-term impact—for example, HVAC communications harmonization via BACnet. Some current research areas certainly have the potential to have similar or greater impact in the future. For example, now that the value of retrocommissioning is gaining acceptance there is also growing awareness that benefits decay, and the process needs to be redone periodically. NIST has recognized that FDD implemented with sufficient embedded intelligence could capture the financial benefits and sustain them through continuous commissioning, without periodic manual “re-dos,” and has initiated work in this important area. The

laboratory is extremely well positioned to have a consequential, long-term impact on the advancement of NZEB; however, the leadership will have to plan and act strategically to develop the measurement science necessary to enable technology developments in this area. The laboratory should be planning for (and is planning with the Department of Energy) a large effort to define the path to NZEB and to insert the technology development effort resulting from the investments in building energy technology into this larger plan.

CONCLUSIONS

The economic opportunities and the environmental threats in the strategic area of Measurement Science for Building Energy Technologies justify considerably higher investment levels on energy-related work. BACnet is just one example of technology in a field where increased funding would yield significant energy benefits to the nation. By developing a globally recognized standard for building management systems, the team within the BFRL has already achieved results that will allow significant energy savings that enable other benefits from increased integration (a systems issue) across building subsystems. Leveraging this past success and accelerating it would enable the rapid advancement of FDD, automated commissioning, and the creation of standardized building components (e.g., variable frequency drives). In the energy-efficiency and environmentally acceptable areas of investments, it is also important to understand why and how potential developers and users respond to information, prices, and incentives, and to formulate procedures and implementation systems that have a high probability of success.

There is a concern that impending retirements of key staff, coupled with the significant recruiting challenges discussed above, will severely undermine the primary strength of the BFRL, which is its people. NIST should examine ways in which the Human Resources organization can help the BFRL recruit needed talent and develop effective succession plans. The importance of maintaining a cadre of appropriate expertise at the BFRL cannot be overemphasized. The focus on staffing is necessary to maintain the high quality of the BFRL staff and also to permit highly valuable investigators to focus on research rather than on recruitment activities.

Roadmaps for building energy technologies measurement sciences and standards should be developed and implemented, and a process for regularly updating them should be defined and tracked. The roadmaps should anticipate what will be needed in U.S. buildings over the next 10 to 20 years. Examples of areas potentially requiring measurement science and the development of corresponding standards include the following: advanced energy-efficiency technologies of all varieties; smart grid integration with intelligent buildings; cooling, heating, and power systems of all varieties and size ranges; building-integrated photovoltaic cells; small-building-scale wind turbines; fuel cells; green building materials; and residential automation systems are among a range of technologies that the BFRL needs to be aware of and in selected cases needs to nurture. In all cases, awareness of the impact on codes and standards for energy efficiency should be maintained.

A clear strategic link should be made between several existing research areas (e.g., FDD, commissioning, controls, life cycle assessment, and alternative energy systems) and the NZEB goals. A strategy should be developed to have a measurable

impact in this area (including development of specific interim and long-term [2020 or 2030] goals, scenario development, and the establishment of strategic partnering with universities and national laboratories in the United States and key partner countries, specifically including India and China).

Economics considerations should continue to be integrated within the technical work, because economic issues are often the barriers to technical innovation. For example, in scenarios for carbon footprint estimations, the BFRL is doing an excellent job of estimating the impacts of given energy-use reductions, but a strong link has not been made to the kinds of reductions that are ultimately possible, nor have the sometimes slow responses by the highly fragmented building industry and its customers been factored in to informational and implementation strategies.

The laboratory should accelerate field tests and demonstrations of all technologies (especially the work on FDD tools and sensor networks) even if they have to come at the expense of developing new tools. There is considerable benefit to the experience that will be obtained in field trials for the maturation and the transition of technology to industry. Field trial results can also be used to drive future technology investments, and the lack of the use of demonstrations is currently the barrier to a number of technologies being successfully transitioned to industry. The use of such processes as Stage-Gate for project management would bring out more clearly the role and the timing and the investments needed for effective field trial work. The field work will serve current stakeholder needs, help further develop BFRL's understanding of stakeholder needs, and help move BFRL technologies into the market more quickly. Technology evolution scenarios (i.e., how current technologies will grow into advanced new technologies) need attention, and the focus on developing investable roadmaps will assist in such scenario planning. Attempts to secure more direct industry funding to maximize the relevance of current work (e.g., heat exchanger optimization, nanoparticles for refrigerants, FDD) should be a focus of the laboratory.

Measurement Science for Breakthrough Improvements in Construction Productivity

The primary core competencies for the Strategic Priority Area of Construction Productivity are information, communication, and automation technologies for the intelligent integration of building design, construction, and operations.

Areas of expertise within this Strategic Priority Area include construction metrology, sensing and control technologies, and economics. The BFRL divisions active in this area are the Materials and Construction Research Division (MCRD), the Building Environment Division (BED), and the Office of Applied Economics (OAE). The active groups include the Construction Metrology and Automation Group in the MCRD and the Computer Integrated Building Processes Group in the BED. The primary BFRL goal in this strategic area is High Performance Construction Materials and Systems, and the key program is Construction Integration and Automation Technologies.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

Construction productivity is a very appropriate Strategic Priority Area for the BFRL. Construction industry productivity has generally declined over time, especially relative to other U.S. industries of comparable scale. The BFRL focus on measurement science in this area is appropriate because of the credibility of NIST in this area, the existing interfaces that NIST has with other organizations, its staff capabilities, the multiyear approaches that are necessary to have significant impact on this industry segment, and the rapid and fragmented nature of technology development in the building industry at large. By advancing measurement methods and related technologies, the BFRL work is a critical enabler of the adoption of performance-based standards in industry. Without such standardized and validated measurement methods and technologies, the introduction of performance-based standards will not occur on a large scale. The widespread adoption of performance-based standards is, therefore, vital to making the built environment more sustainable.

The specific activities of the BFRL in this Strategic Priority Area are fundamental to improving construction industry productivity and ambitious in their scope. If these activities are successful, they have the potential to achieve very large improvements in construction productivity; however, these activities, which befit the NIST mission, are relatively long range in nature. In the area of metrics for construction productivity, it is likely that the BFRL can continue to exploit its relationship with the Bureau of Labor Statistics (BLS) and the BLS data-gathering capabilities to expand the ability to correlate a myriad of variables and provide valuable industry insights. The BFRL work to establish standardized productivity measurement methods at the project and task level (e.g., methods to determine the quantities installed in an hour, during a task, or in a day) is well conceived and should continue or even be accelerated. The laboratory and field work (e.g., in Lansing) are excellent.

The real-time sensing and control efforts at the BFRL are well defined and implemented. They focus on the development of test methods for high-precision calibrations and standards development. The laboratory's indoor facility for testing

three-dimensional imaging systems and developing synthetic data sets using standardized artifacts (e.g., spheres and patterned disks) can be used for measuring the performance of construction site object-recognition technologies. This facility provides a strong initial effort and basis for future interlaboratory cooperation and the evolution of protocols. A strong technical basis has been developed, and promising progress is being made.

The development of an Intelligent and Automated Construction Job Site Testbed is underway at the BFRL; it is a natural extension of the three-dimensional imaging systems activity. The testbed development will be an evolutionary process in partnership with industry and academia and will be phased, first with an indoor testbed, followed by an outdoor testbed. The initial planning and conceptual thinking have been accomplished, and interfacing with other groups is underway.

The development of the Virtual Project Data Integration Testbed is consistent with the other strategic priority activities and incorporates those activities into its process. It brings together the various project phases and participants into an integrated potential for data exchange and the full utilization of building models.

Building Information Modeling (BIM) is a potential breakthrough technology for improving construction productivity—and indeed productivity across the complete life cycle of a facility, from pre-design planning, through design, fabrication, construction, commissioning, and operations and maintenance.

The ongoing work within the BFRL in this Strategic Priority Area is of very high technical merit. Staff is involved in virtually all of the BIM activities currently taking place in the United States (e.g., Fully Integrated and Automated Technologies [FIATECH], ASHRAE, and the International Alliance for Interoperability) and in international standards development activities (e.g., International Organization for Standardization [ISO]).

BIM activities in which BFRL staff members are participating are producing real products that are being adopted by industry, which illustrates the technical quality, usefulness, and relevance of this work as well as the working relationships of NIST staff with industry. Examples of these products include the Automated Equipment Information Exchange tools and the CIMSteel Integration Standards (CIS/2) work that responds to and supports the near-term industry adoption of BIM technologies for steel fabrication and construction. BFRL staff efforts within ISO and ASHRAE reflect a commitment to long-term activities to continue the development, dissemination, and adoption of BIM technologies. The projects on Metrics and Tools for Construction Productivity and the Virtual Project Data Integration Testbed address the NIST goal of identifying critical measurement gaps that act as a barrier to innovation, and specifically the need for reliable and unbiased performance data to speed the adoption of new and innovative technologies in the building and construction sector. The BFRL has already had a major participatory role in the Construction Industry Institute (CII) Benchmarking and Metrics program, which is responsible for the largest public database on construction projects in the industry.

ADEQUACY OF INFRASTRUCTURE

BFRL facilities and equipment appear at the present time to be adequate for the work underway. However, the BFRL currently has limited resources for addressing all

productivity problems in a \$1.4 trillion industry. Even though the space available for the work on the metrics for construction productivity has improved over the past years, NIST should find additional ways to further upgrade the space available for this work.

A primary limitation in resources at the present time relates to staffing. Increased staffing with technical competencies in information modeling and standards committee participation is needed. If new hires can be attracted to the BFRL, additional funding will be needed to support and retain them.

The advancement made in establishing the Intelligent and Automated Construction Job Site Research Testbed facility is noteworthy. This facility will become the testbed for new measurement science and is therefore critical to the BFRL's future in this area.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

Active participation and leadership in organizations such as FIATECH, CII, ASHRAE, and ISO are effective dissemination channels for products from the BFRL work in this Strategic Priority Area. BFRL staff members are extremely well positioned to have a consequential long-term impact on the advancement of BIM.

The researchers should develop better links to the software vendors who might develop tools for collecting, analyzing, and disseminating construction productivity measurements so that industry uptake of the methods developed at the BFRL can be quicker. Opportunities should also be explored for more collaboration with other laboratories at NIST on the productivity measurement methods concerning emerging large-scale problems, such as the state of the infrastructure in the United States, to see if this might drive the research agenda and focus.

The BFRL work is critical to illuminating the underlying issues of construction productivity and to establishing a framework and specific measurements, including standard specifications for carrying out and reporting such measurements, at the project and task levels. A suggestion in this respect is to establish such measurements for the office work (design, detailing, construction management, coordination), for the work in the supply chain (fabrication), and for the work in construction and facility handover and start-up. Such a focus would enable the BFRL to establish a framework that is currently lacking for assessing the impact of automation and integration technologies on engineering and construction productivity. In the future, this work should extend to the establishment of standard methods to measure the life cycle impacts of the materials and processes used in construction.

The recent success in several areas of work that have been ongoing for several years solidifies the good track record of the small, but productive BFRL team in this strategic area. These achievements include the following:

- The Automated Equipment Information Exchange data exchange protocol is now being adopted by industry (e.g., American Petroleum Institute, American Society for Manufacturing Engineers, Electric Power Research Institute, Hydraulic Institute, Institute for Nuclear Power Operations, and Process Industry Practices) for interoperable information representation and exchange. The laser-scanning work, in particular the walk-about scanning, holds great

promise to measure on-site production of physical work more rapidly and precisely in order to validate model-based design, detailing, planning, and coordination methods and to enhance safety on-site.

- The BFRL/NIST report⁵ on the cost of the lack of interoperability in the facility and construction industry has been extremely well received. The BFRL should consider further development and testing of the method for measuring the impact of interoperability (including interfaces and interactions) and should determine and standardize the underlying measurement methods and overall framework.
- The work at BFRL on the definition of model-based design and construction will also contribute significantly to the current discussion and adoption of building information modeling in the construction industry.

CONCLUSIONS

The ongoing work in this Strategic Priority Area of Measurement Science for Breakthrough Improvements in Construction Productivity within the BFRL offers the potential of very large improvements in industry productivity, is relatively long range in nature, and is befitting of the NIST mission. However, the phrase “construction productivity” may be a misleading rubric for this Strategic Priority Area, because the evolution and life cycle of a construction project involve many phases, including the definition of business need, facility planning, project planning, design and procurement, construction, start-up, commissioning, and operations. The overall measure of productivity involves much more than just the construction phase and is strongly dependent on the material/equipment/worker interface, which in turn requires flexible rules and regulations if it is to capitalize on emerging technological opportunities. It should be noted that the BFRL staff is actively involved with other organizations, such as the CII, that are aggressively addressing all life cycle phases and so are already familiar with these issues.

The BFRL has limited resources for addressing all of the productivity problems in a \$1.4 trillion industry. A number of worthwhile projects are currently underway, but the BFRL’s portfolio of projects needs to be clearly mapped to the larger context and evaluated for maximum impact given currently available resources. This strategic area is an example of an area in which roadmaps and portfolio management techniques would be most useful additions to the management tools used by NIST leadership to plan and execute projects. High-impact activities need to be resourced properly and over multiyear horizons in order to achieve the necessary results for the desired—and needed—impact.

For example, while BIM is recognized as a potential breakthrough technology for improving productivity throughout the building life cycle, this has been true for quite some time. BIM is a technology that requires a significant and sustained effort to push the industry toward adoption. The current pace and direction of effort within the BFRL are sufficient for initiating that push. However, a significant additional effort will be

⁵ National Institute of Standards and Technology, 2004, *Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry*, NIST GCR 04-867, August, Gaithersburg, Maryland.

required to respond to stakeholder needs such as certification testing once adoption is in progress. The importance of the development and implementation of protocols for certification testing (i.e., actual testing of products) has been recognized by the BFRL staff; however, this importance will increase as adoption progresses, and rising to the challenge will require a significant effort, including resourcing and recruiting appropriate staff levels and expertise that likely cannot be adequately undertaken with existing BFRL staff levels.

Measurement Science for Predicting Life Cycle Performance of Nanocomposite Infrastructure Materials

The primary core competencies for the Strategic Priority Area of Measurement Science for Predicting Life Cycle Performance of Nanocomposite Infrastructure Materials are performance, durability, and service-life prediction of building materials. Secondary core competencies include fire protection and fire spread within buildings and communities.

Materials-related areas of expertise within this Strategic Priority Area include concrete, nanotechnology, polymers, and materials flammability. Measurement-related expertise includes chemical, physical, mechanical, optical, and electrical properties of materials from nano- to macroscales, in addition to computational materials modeling. The BFRL divisions active in this area are the Materials and Construction Research Division (MCRD) and the Fire Research Division (FRD). The active groups include the Inorganic Materials Group and the Polymeric Materials Group (in the MCRD) and the Materials and Products Group (in the FRD). The primary BFRL goals in this strategic area are High Performance Construction Materials and Systems and Innovative Fire Protection Technologies. The key programs are the High-Performance Construction Materials and Systems Prediction and Optimization of Concrete Performance Program, the Service Life Prediction of Nanostructured Polymeric Materials Program, and the Reduced Risk of Fire Spread Program.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

The mission of the work in this strategic area involves the testing of nanocomposite materials to allow long-term structural utility. The utility of nanocomposite materials in the large infrastructural applications requires measurement science and models to predict performance to the level required for engineering applications. An additional concern involves the environmental and safety aspects of nanoparticle release into the atmosphere over the life cycle of the nanocomposite. Both of these concerns are critical for the acceptance of nanocomposite technology into commodity applications of the future, including civil engineering infrastructure applications (e.g., buildings, bridges). These goals are well aligned with the mission of NIST.

The projects of the Polymeric Materials Group and the Inorganic Materials Group were reviewed within this context. The integrating sphere-based ultraviolet chamber was discussed in detail. The information disclosed indicates that it is the most realistic experimental method of providing accelerated weathering data offering excellent agreement with natural outdoor weathering. This is quite important, as it allows for significant decreases in testing time while offering a high level of confidence that the accelerated results can be used to quantitatively predict long-term exterior performance—a testing capability desired by a multitude of industries but not currently available. A goal for this project is to achieve the transfer of this elegant testing methodology to industry and the military for the exterior performance assessment of new materials. In essence, the transfer of this testing capability to an independent laboratory with more routine

materials evaluation by a myriad of customers would constitute a major NIST achievement.

NIST has been at the forefront of nanocomposite research over the past several years. The BFRL staff members are leaders in developing a fundamental understanding of nanocomposites for decreasing the flammability of polymers by lowering the heat release rate (HRR) as measured by a cone calorimeter, and reducing the flammability of polyurethane (PU) foams using nanoadditives; they are also the first to develop flammability testing methods of flexible PU foams using a cone calorimeter. One of the major issues in the real world with respect to polymer flammability is the flammability of furniture and mattresses. The BFRL team has leveraged years of experience in polymer flammability and nanocomposites to tackle the problem of PU flammability by aligning the project to the mission of NIST that involves improving public safety and assisting industry in competitiveness. PU foam is highly flammable due to its low thermal conductivity, low decomposition temperature, and viscosity. The BFRL team developed a modified vertical cone calorimeter method to measure the flammability of flexible (melting) PU foams. The methodology developed will be useful in getting closer to solving the PU foam flammability problem and will develop bench-scale test methods for screening purposes, which will help speed the research and development of new solutions.

NIST has years of experience and competence with modeling techniques in various areas to provide high-quality prediction tools for flammability and related material properties. The modeling work on the mixing and dispersion of carbon nanotubes and fibers in polymers shows, for example, the dependence of the energy of mixing on the the radius of carbon nanotubes. As with any modeling work, steps need to be taken to verify the modeling results with real-world experiments to define the region of applicability and the accuracy that can be expected from predictive models and to clarify the goals for subsequent research efforts.

NIST also has a long tradition in the original and creative research on cementitious materials. The excellence of this work has been maintained and expanded into new endeavors. The BFRL staff has identified and addressed fundamental needs from the cement, aggregate, and concrete industry. The number of consortia in this area shows the impact of the research on the construction industry.

The NIST computer model for cement hydration is the best in the field, and it has been widely used in academia and industry. HydratiCA, the new version of this software program, is a significant improvement over earlier versions. It integrates well with the BFRL's Virtual Cement and Concrete Testing Laboratory. The Inorganic Materials Group has done an important service by taking the leadership in the new ASTM C1365 test method for the determination of the phases in Portland cement.

The development of sustainable materials and construction is of paramount importance for American leadership in civil infrastructure. The BFRL project whose goal is doubling the service life of these materials is potentially of breakthrough significance that could lead to a methodology for casting a new generation of reinforced concrete structures. To be successful, this project will require greater resources so that the researchers can optimize the chemicals to be added to the concrete mixture.

ADEQUACY OF INFRASTRUCTURE

While the Polymeric Materials Group and the Inorganic Materials Group would benefit from additional equipment (specifically, transmission electron microscopy), the need to add a technical staff member to support this capability is not considered a high enough priority relative to the other group responsibilities. There appears to be a concern among the BFRL staff that the time spent on administrative activities (such as budget planning, recruitment, and related activities) by the principal investigators may be interfering with their key technical responsibilities. Increased global interaction by the BFRL with the areas of the world experiencing technological growth (including China, India, and South America) is an important future goal. The flow of information thus far has been more unidirectional—specifically, other countries are deriving information from NIST. Competitive technology today requires global interaction; the United States no longer has a monopoly on emerging technology. The updating and the modernizing of NIST-related test equipment and procedures should be considered (the cone calorimeter is a case in point). This effort will enable the easy comparison of historical data and ensure continuity of standardized measurement methods.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

The accelerated weathering testing and modeling have been highly successful and appear to have met the project's goals and objectives to date, with the remaining goal being the adoption by end users and the availability of the capability in an independent laboratory. The development of a vertical flammability test for flexible polyurethane foams using the cone calorimeter could lead to bench-scale screening tools that will accelerate discovery and time to commercialization.

The development of the internal curing of concrete was an efficient method of reducing or eliminating the internal cracking of concrete leading to more durable structures. The Materials and Products Group within the FRD has attracted a number of guest researchers from renowned institutions that complement the ongoing projects. The international reputation of the division is reflected in the fact that several graduate students have come to do research projects at NIST, in some cases bringing their own funding. The number of publications, presentations, and workshop reports from the Fire Research Division are cited by scientists around the globe for their technical content, the importance of their subject, and the technical novelty of the approaches employed.

CONCLUSIONS

The projects in the strategic area of Measurement Science for Predicting Life Cycle Performance of Nanocomposite Infrastructure Materials are well aligned with the mission of NIST and should continue to focus on measurement science based on fundamental mechanistic understanding.

This Strategic Priority Area is of paramount importance to nanotechnology, because the assessment of the nanoparticle release into the environment is of considerable concern. To best accomplish this activity and disseminate results, the projects in this area should be highly integrated with those of the National Institutes of Health.

The BFRL has shown leadership in the development of the materials science of construction materials. This fundamental science has already found practical application in construction practice. The new activity of doubling the service life of construction materials could be critical to maintaining American competitiveness in the field of civil infrastructure. Increasing the life cycle of concrete is vital for the repair and upgrade of the aging civil infrastructure. The group can create a new paradigm in advanced cementitious material by optimizing the nanostructure of the material with appropriate chemical admixtures.

Reducing the flammability of polyurethane foam is extremely critical considering the worldwide use of these polymers in a number of applications. Using nanocomposites to reduce flammability and developing bench-scale flammability testing capabilities will not only develop fire-safe materials but will also accelerate the speed to market for these materials.

The budgeting process for the BFRL should include funding for principal investigators to support time for the exploration of other projects that are aligned with the NIST mission. This will encourage discovery and out-of-the-box thinking.

NIST should further highlight the accomplishments and the reports of the World Trade Center investigation program.

Disaster Resilient Structures and Communities (Hurricanes and Earthquakes)

The primary core competency for the Strategic Priority Area of Disaster Resilient Structures and Communities (Hurricanes and Earthquakes) is performance and resilience of structures and communities under extreme loads.

The areas of expertise within this Strategic Priority Area include structural engineering, wind engineering, earthquake engineering, structural performance in fires, computational modeling and analysis, and structural reliability. The BFRL divisions and offices active in this area are the Materials and Construction Research Division (MCRD), the National Earthquake Hazards Reduction Program (NEHRP) Office, and the Office of Applied Economics (OAE). One of the primary BFRL goals in this strategic area is Disaster Resilience. Key programs include the Safety of Threatened Buildings Program (wind engineering and multi-hazard failure analysis) and the NEHRP.

BACKGROUND

Several ongoing programs were reviewed by the panel: (1) the National Earthquake Hazards Reduction Program, for which the leadership was undertaken by NIST in 2005; (2) several programs that had been initiated in approximately 2001, including the Fire Resistant Design and Retrofit of Structures Program and the Prevention of Progressive Collapse Program; and (3) two relatively new initiatives that, in addition to NEHRP, directly address the priorities of the Disaster Resilient Structures and Communities strategic area, which are intended to meet the goals of the American Competitiveness Initiative. These latter programs address the topics of wind engineering and multi-hazard failure analysis. The investigation of the collapse of the World Trade Center (WTC) had a major impact on the resources in the Structures Program over the past 6 years. The final report on WTC 1 and 2 has been issued,⁶ and the group is nearing completion of the report on Building No. 7.

Earthquake Engineering (NEHRP Activities Associated with NIST)

Earthquake-related structural engineering research has not been a focus at the BFRL for the past 10 years. It is anticipated that with NIST assuming the leadership of NEHRP in 2005, the BFRL earthquake-related research program will be rejuvenated. The BFRL's efforts should be coordinated with other programs and agencies; this is particularly important given that the BFRL's work in earthquake-related structural engineering is anticipated to be computational, relying on associated laboratory work elsewhere. There are several current research focus areas (e.g., progressive collapse and multi-hazard failure analysis) that should be broadened to address earthquake-related issues as well. It is planned to build a new in-house research staff related to earthquake engineering issues in FY 2008 and FY 2009. Those hired should complement rather than

⁶ National Institute of Standards and Technology, 2005, *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Final Report of the National Construction Safety Team on the Collapse of the World Trade Center Tower*, NIST NCSTAR 1, Gaithersburg, Maryland.

overlap with the existing NIST Structures Program staff. There is a current plan to partner with the Applied Technology Council (ATC) and the Consortium of Universities for Research in Earthquake Engineering in conjunction with the three National Science Foundation (NSF)-sponsored earthquake engineering centers (Mid-America Earthquake Center, Multidisciplinary Center for Earthquake Engineering Research, and Pacific Earthquake Engineering Research). As the three centers are “sunset,” plans for the future should be developed. The plan for projects includes the following:

- The Quantification of Building System Performance and Response Parameters project (to provide technical support for seismic practice and code development), which includes beta testing of ATC-63 methodology that is to use nonlinear models of seismic force-resisting “archetype” structures intended to result in equivalent safety against collapse for buildings across different seismic resisting systems.
- The development of Performance-Based Seismic Design guidelines for Port and Harbor Facilities project: whereas the NEHRP’s previous focus has traditionally been on earthquake safety, there are now plans to address the national economy and security. This project, an example of that category, is the current focus of one of the NSF-funded grand challenge (GC) projects. The NEHRP sees a role that NIST can play in assisting the transfer of technology learned in the GCs into practice through the development of codes and standards. There are other opportunities with NSF GCs that may be identified in the future; the opportunities relate to nonductile frame systems and nonstructural elements.
- It is anticipated that the experimental work associated with the endeavors listed above will be conducted at existing laboratories external to NIST.

Fire Resistant Design and Retrofit of Structures

The Fire Resistant Design and Retrofit of Structures Program is well conceived and well integrated with other BFRL programs. Critical to this program is the construction of a large-scale structural fire test facility (see the “Adequacy of Infrastructure” subsection below).

Progressive Collapse

The tools being developed for the prediction of structural behavior at the limit of structural capacity, such as in the Quantification of Building System Performance and Response Parameters project, will be very valuable to researchers and designers of structures designed to withstand special threats. The BFRL’s work should be coordinated with the projects and programs at the Department of Defense and other agencies in order to eliminate duplication of effort and to ensure that the tools being developed are those that are the most needed.

Wind Engineering

The BFRL has exceptionally well qualified staff in the technical area of wind engineering. Although resources have been increased, the staff is at present handicapped by a lack of resources (specifically, convenient access to a wind tunnel). The BFRL staff has well-established links with codes and standards committees that should reduce the risk of the adoption of the research work product. The work in the area of wind engineering is consistent with ACI objectives as detailed by the NIST Three-Year Programmatic Plan. Adequate funding should be allocated for the computational wind tunnel (database-assisted design) for predicting extreme wind effects. This group needs permanent staff to support these activities and a plan for mentorship to ensure continued NIST strength in this critical area.

Multi-Hazard Failure Analysis

The Multi-Hazard Failure Analysis Program is in its early stages, and the current focus on wind speed and storm surge is appropriate. The program should be expanded to include other hazards such as earthquake and fire as part of a multi-hazard approach. The current reliance on state-funded data (specifically from Florida funding) is too limiting. A national effort to fund the securing of these critical data is imperative. This is a new effort consistent with the NIST Three-Year Programmatic Plan.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

The work being done within this Strategic Priority Area is generally at state-of-the-art level. The quality of the work is demonstrated by the acceptance of submissions to high-impact publications and by the transition of the work to codes and standards. Papers undergo extensive internal review before their submission for publication. The work under this Strategic Priority Area is clearly tied to the BFRL mission. Ties to the external community are demonstrated by the staff's membership and active participation in professional and trade committees.

Clear standards do not seem to be consistently applied within the BFRL to ensure the integrity of measurements (e.g., quality or certainty of data obtained from external facilities). The development of a curated database containing both experimental data and software developments should be made publicly available for all projects. This aspect currently seems lacking or not standardized, with current efforts occurring on an ad hoc basis.

ADEQUACY OF INFRASTRUCTURE

The primary focus of the current BFRL Structures Program is directed toward the development of advanced computational models. In some cases these models have taken up to 2 months to run on local workstations. An effort should be made to identify alternative computational capabilities, including the use of national supercomputing resources, to remove this bottleneck and to bring this aspect of the research program up to state-of-the-art usage of appropriate hardware. Laboratory experiments required for

validation are being outsourced by the BFRL rather than its maintaining or adding new capability, with one exception—in the area of fire research (see below). This approach is acceptable to the degree that the researchers can, in an effective and timely manner, outsource the work while ensuring the quality of the data. There appear to be some difficulties associated with securing resources at external laboratories due to contracting issues, with the exception of the use of other government laboratories (e.g., the Construction Engineering Research Laboratory). Methodologies or agreements should be developed to make this process more efficient and less onerous.

One area in which the BFRL has chosen to place its resources is in the development of a first-class large-scale fire testing facility (the proposed Structural Fire Endurance Laboratory). This facility would be large enough to test the performance of full-scale assemblies of interconnected elements, such as the intersection of floor, wall, and roof assemblies. This has been a huge void in the nation's capabilities, and the BFRL is a logical organization to house such a facility. This need was identified by the BFRL in 2004, but limited progress has been made to date. Preliminary plans should be developed for this facility and cost estimates prepared as soon as possible. Highest priority should be assigned to the development of this facility.

Current staff members in the Structures Group are well qualified to conduct the projects now underway. Although staff have the necessary technical expertise to plan and conduct the work, there are serious concerns relative to the attracting, recruiting, training, and retaining of staff for future needs. The BFRL needs to develop a plan that addresses present and future staffing needs, mentoring and staff development, retention strategies, and technical and project management training, and the necessary HR support needs to be provided to implement the plan. A specific impediment to recruiting new staff is the requirement that all staff be U.S. citizens. This limitation significantly reduces an already-limited pool of potential candidates and was frequently mentioned by existing Structures Group staff as a major barrier to recruiting qualified staff.

There has been a significant change in personnel within the BFRL, particularly in leadership positions. It is not clear that there have been leadership development opportunities to prepare individuals for this transition to significantly more and different levels of responsibility. The staff at the BFRL is highly technical, and the development of expertise in business management principles is warranted and should be addressed in the overall staffing plan.

Individual staff members seem to be driven to maintain expertise in a particular area, enhancing opportunities to be noted and recognized for specific contributions related to a relatively narrow focus area. Part of this motivation appears tied to the metrics used for determining merit raises and promotions (e.g., peer-reviewed publications). If an individual plays a supporting role across a number of areas there is less evidence of the particular individual's strength or stature, but such efforts may be significantly better overall for program effectiveness. NIST should consider changes in the criteria that it uses for recognizing and rewarding staff in order to encourage cooperation among its experts and their participation in projects in useful supporting roles.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

The Structures Group effort has excellent linkage with the BFRL mission. The work of the group has impact as demonstrated by the group's linkage with Standards Development Organizations and demonstrated success in moving research products to standards and codes (e.g., fire, structural robustness).

The BFRL needs to continue to leverage episodic events (e.g., the work on the WTC disaster) to benefit ongoing research and development (R&D). The value of these types of investigations is important to the work at NIST in terms of providing focus to ongoing programs and also of reinforcing the need for the creation and use of multidisciplinary teams of sufficient size to address national needs in the areas of measurement science.

The BFRL also needs to gain a better understanding of the economic drivers and barriers (e.g., support of obsolete prescriptive fire-resistance requirements by product manufacturers) as they relate to the implementation of R&D products. The behavioral responses of individuals and institutions to perceived threats and emergencies also need to be factored in to planning and designs.

Analysis models based on existing codes (e.g., LS-Dyna, Abaqus, Ansys) should be made available to the public. Time lines and milestones were not presented for most projects reviewed in this area by the panel. (Many projects were apparently slowed down by the demands of the WTC work.) No project has been terminated in recent years—leading to concerns as to whether ongoing projects are reassessed realistically for likely success on a regular basis. This is an example of where the project management techniques used extensively by industry (e.g., Stage-Gate processes) would be beneficial in portfolio management and in obtaining the full potential at the BFRL in project execution. The development and review of technology roadmaps are also essential in carrying out effective project management. It would be useful for the BFRL to develop objective measures of the impact of its work on stakeholders. Some efforts by BFRL scientific personnel to obtain small-funded assignments for themselves and their staff, separate from the overall grant-generation programs of the BFRL, represent an inefficient use of their time.

CONCLUSIONS

The programs in the Strategic Priority Area of Disaster Resilient Structures and Communities (Hurricanes and Earthquakes) are in general successful with respect to the criteria employed for this assessment. The technical merit of the programs reviewed was consistent with state-of-the-art standards and had a sound tie to the overall BFRL Strategic Priority Areas and a strong tie to codes and standards development. Some progress is needed in the area of data integrity (with regard to the quality of test data and calibrations) as more laboratory work is outsourced. The needs in the area of facilities and equipment have evolved owing to the trend to outsource large-scale structural laboratory tests. This trend to outsourcing is commendable and acceptable to the degree that data integrity and project delivery can be maintained. One area in which outsourcing is not a viable option is that of large-scale structural fire testing. The BFRL is developing plans to add this capability; the laboratory should accelerate the planning effort and

should secure the necessary resources to put the facility in place. In the area of human resources, priorities must be given to developing a long-term staffing plan that addresses the recruiting, training, and retaining of needed talent. This is especially important because staff attrition due to retirement is outpacing recruiting efforts. The process of assessing the achievement of stated project objectives needs clarification and should include the development of systemwide metrics. At the present time, it appears that the achievement of stated objectives is mainly assessed by monitoring program progress against program-developed milestones. Although this process may be effective on a project basis, it may be lacking as an effective methodology for assessing a group of projects with related objectives. The objectives for the reviewed projects support the initiatives outlined in the ACI.

Disaster Resilient Structures and Communities (Fires)

The primary core competency for the Strategic Priority Area of Disaster Resilient Structures and Communities (Fires) is fire protection and fire spread within buildings and communities.

The areas of expertise within this Strategic Priority Area include fire protection engineering (suppression, detection, and smoke control); combustion chemistry and fire dynamics; fire service technologies; egress design; elevator technology; occupant behavior; and codes and standards—as well as sensitivity to longer-run human relocation activities in response to apparent reduction in risk, and the consequent societal impacts. The BFRL division active in this area is the Fire Research Division (FRD). Active division groups include the Integrated Performance Assessment, Analysis, and Prediction Group; the Fire Metrology Group; and the Fire Fighting Technologies Group. The primary BFRL goals in this strategic area are Innovative Fire Protection Technologies and Homeland Security and Disaster Resilience. The key programs are the Reduced Risk of Fire Spread in Buildings Program, the Advanced Fire Service Technologies Program, the Advanced Measurement and Predictive Methods Program, the Safety of Threatened Buildings Program, and Fires at the Wildland-Urban Interface (WUI) Program.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

The BFRL continues to have core competence with high technical merit in the fire area, particularly in the design and execution of experiments and the consistent coupling of experiments to validate predictive physics-based computational tools. The project reviews for the Fires strategic area clearly showed strengths in the area of physics. There is a historical strength at NIST in developing deep physics understanding of fire (a broad characterization including, for example, initiation and spread) and capturing the physics in both modeling and the validation of the models through well-designed and controlled experiments.

The BFRL is making important contributions to the reduction of the risk of fire spread in buildings, to the safety of buildings and first responders, and the understanding of fire spread at the wildland-urban interface. The staff and facilities within the BFRL are a national resource for retrospective studies of fire accidents, which is superbly demonstrated in the studies of the fires at the World Trade Center and the Warwick, Rhode Island, Station nightclub. Lessons from fire investigations are aided by the ability to conduct tests, often at full scale in the Large Fire Laboratory (LFL), mainly for accidents, such as the nightclub fire. The LFL can also be used to obtain the heat-release rate (HRR) for furnishings to be used in the Fire Dynamics Simulator (FDS) of building fires with full allowance for furnishings, which are often the main source of fuel for the fire. The BFRL facilities for metrology are state of the art for providing unbiased performance assessment of products vital to the first responder such as respirators, smoke detectors, infrared cameras, and personal alert safety systems (PASS). Industry is not equipped to provide dependable assessment data for these products.

The projects in this strategic area reviewed by the panel showed a clear commitment to developing physics-based, predictive, computational, and validated mathematical models. The BFRL has core competencies in fire modeling (the

Consolidated Model of Fire and Smoke Transport [CFAST] and the Fire Dynamics Simulator), in which the laboratory has invested with outstanding results. The work is fundamental, has been peer-reviewed, has been leading in its field, and demonstrates unique capabilities. There are examples of new computational methodology being sought to address problems in fire protection (melt pool modeling).

There are excellent programs in this strategic area to support progress in addressing the U.S. fire problem for risk reduction and the effective development of codes and standards. The work that was reviewed covered a wide range of topics in support of this mission, and the evaluation of these programs within the BFRL by the leadership appears to be very rigorous. The reviewed work in the areas of high-rise building fires, wind-driven fires, and positive-pressure ventilation coupled with work on thermal imaging can have immediate positive impact for the effectiveness and safety of the firefighter. The work on egress in tall buildings that is a follow-on to the WTC study was well formulated. This work needs to be expanded with more attention given to the makeup of the team. The fact that a workshop has been organized to consider rethinking egress is a very positive step toward the creation of technology roadmaps that can give multiyear direction to the research efforts and serve as a foundation for increased support to the BFRL. Work on wildland-urban interface fires is critically needed as construction develops at these interfaces; the program that was reviewed holds promise for strategically addressing this issue. Smoke alarm performance research is critical and may enable the safety community to address a crucial aspect of smoke detector reliability. The thermal imaging camera issue is one of great promise, once again for the effectiveness and safety of the firefighter. The thermal imaging camera may be the biggest advancement for firefighter safety since the development of the self-contained breathing apparatus. The program balance from the standpoint of a practical fire service is definitely on track. Programs in toxicity measurement to aid in escape from burning buildings, firefighter safety and effectiveness, and emergency escape management address crucial aspects of the fire problem today.

The Reduced Risk of Fire Spread in Buildings Program addresses the important issue of the propagation of fires as it is influenced by different materials, a problem that is of major importance, as synthetic materials often have a higher energy-release rate than that of the natural materials that they replace. Good progress is being made in developing experimental and modeling capability for assessing the propagation of fires involving foams on real objects, which is a problem that is complicated by the formation of melts that flow and can form pool fires. Studies are also being conducted on reducing deaths resulting from fire propagation and the smoke that it generates. Technical merit in this area is rated excellent based on the following:

- The selection of problems based on good contacts with the customers in the fire community and on an appreciation of the mechanisms controlling fire spread and fire mitigation;
- Facilities that provide precise data on HRR ranging in scale from bench scale to 15 MW, which is a range that enables the FRD to translate fundamentals to industrial practice;
- Analytical capabilities that provide critical information on temperatures, velocity, distributions, soot, concentration of major combustion products, and

- toxic gases; and
- A dedicated and very qualified staff.

The researchers reviewed did not always provide enough information to permit the panel to obtain a complete view of the assessment criteria presented in the charge to the panel from the Director of NIST. While a number of clear technological strengths were presented, a number of gaps apparently exist in the competencies that the BFRL is bringing to the overall problem set. From an academic perspective the research is well managed and productive, but it does not contain the industrial perspective of gates for moving to the next level or Stage Gates for arriving at decisions to accelerate (or terminate) specific projects.

The researchers discussed systems in different ways: the need to look at coupling in experiments, the need to couple different computational approaches, the need to look at overall uncertainty effects. While the need is clear and to some degree was articulated well by the researchers to the panel, there was no systematic description of the construct of “systems” for projects or with respect to skill sets in the area of systems engineering. The industrial use of methodology and tools along the lines of Design for Six Sigma⁷ (a method for eliminating defects in processes) should be examined in the area of fire protection and appears to be appropriate for this environment (with obvious emphases and modifications as needed).

There is a clear set of strengths in physics-based modeling and in simulation in the programs reviewed. There was no clear capability in the areas of analysis of the resulting models. In particular, a great deal of the work at the BFRL addresses systems and temporally evolving situations of interest; there is an apparent need for added competence in the area of dynamical systems that involves a qualitative and quantitative understanding of the dynamics in order to fully utilize modern methods of nonlinear dynamical systems for qualitative understanding and for designing appropriate algorithms and focusing the computational efforts.

There was a great deal of discussion on uncertainty but almost no technical discussion or presentation on what is necessary to have competence in this area. Given the focus in numerous professional communities as well as ongoing projects in this area (e.g. ongoing efforts resourced by the Defense Advanced Research Projects Agency [DARPA] to provide effective computational tools for the propagation of uncertainty in large-scale interconnected, dynamical systems), the lack of understanding of the state of the art in this area should be actively addressed.

The President’s Committee of Advisors on Science and Technology (PCAST) recently published findings⁸ that stress the need to develop technology for networked systems connected to the physical world or to fully develop the technology known as cyber-physical systems. Without doubt, one institution where this R&D agenda is relevant and should be developed with intensity is the BFRL. In the area of fire safety as well as that of energy efficiency, the use of new technologies, particularly information

⁷ K.N. Otto and K.L. Wood, 2001, *Product Design*, Upper Saddle River, N.J.: Prentice Hall.

⁸ President’s Committee of Advisors on Science and Technology (PCAST), 2007, *Leadership Under Challenge: Information Technology R&D in a Competitive World*, Technical Report, August, Washington, D.C.: Executive Office of the President.

technology-based, was missing from the project reviews, the strategic objectives, and the overall discussions.

ADEQUACY OF INFRASTRUCTURE

The Large Fire Laboratory (LFL) is able to facilitate the study of fires with the precise measurement of the heat-release rate at three different scales for fires in the ranges of 10 kW to 750 kW, 100 kW to 3 MW, and 200 kW to 15 MW. The LFL is designed to evaluate large fires; this facility is different from the proposed Structural Fire Endurance Laboratory, which will involve the testing of the mechanical performance of structures subjected to fires and will necessarily involve both the fire and material research experts in the BFRL. The LFL has added greatly to the ability of NIST to carry out a broad range of experiments on the validation of models, the reconstruction of major accidental fires, and the quantitative evaluation of the HRR for fires burning a wide range of objects, including furnishings, trees, and entire enclosures. The distinguishing features of the LFL are the precision with which the HRR is measured and the availability of diagnostic tools for obtaining gas species composition and soot, temperature, and velocity profiles. Some of the problems that have been addressed using the LFL are the measurement of the HRR of furnishings to provide data inputs regarding building fires and the measurement of the HRR of large trees to provide inputs for computer simulation of WUI fires.

The competency of the staff supporting this Strategic Priority Area is high, and the excitement for their work is palpable. The stimulation promoted by the WTC investigation program is still evident and is being amplified by new programs on WUI fires and hydrogen funded through the America COMPETES Act. With the retirement of some renowned staff members, it is important to mentor the younger staff to help them exploit the benefits of collaboration of other laboratories with NIST, to guide them to appropriate forums for technological exchanges and journals for their publications, and to help them manage their time.

Restoring the funding of the University Grants Program to the level, corrected for inflation, that it had when it was transferred to NIST from the National Science Foundation would strengthen the national fire capabilities as well as increase the pool of potential employees for the fire program in the future. The following excerpt from a National Research Council report on fire safety⁹ provides the history of the grant program:

In the early 1970s, the National Science Foundation (NSF) supported fire research at a level of approximately \$2.2 million every year (\$9.6 million in today's dollars) through a program known as Research Applied to National Needs (RANN). The RANN program was terminated in 1977. Subsequently, a fire research grants program at the National Bureau of Standards (now NIST) was funded at about \$2 million annually (\$8.7 million in today's dollars). However, by 2002, the NIST fire research grants program had declined to only \$1.4 million, a decrease of 85 percent from the 1973 level when adjusted for

⁹ National Research Council, 2003, *Making the Nation Safe from Fire: A Path Forward in Research*, The National Academies Press, Washington, D.C.

inflation. As a consequence of the limited funding that has been made available, the scope and breadth of university fire research in the United States have declined dramatically over the past 30 years.

Program balance from the standpoint of a practical fire service is on track. Programs in toxicity measurement for escape from burning buildings, firefighter safety and effectiveness, and emergency escape management address crucial aspects of the fire problem today. Both the Toxicity Laboratory and the LFL are impressive. The reasoning behind the expansion plans for the large-fire test facility, including the construction of the Structural Fire Endurance Laboratory, is sound. Research intent and commitment are excellent. Staffing appears to be well thought out in the fire service area. There is an excellent balance of researchers, and there are plans to fill two current vacancies in the Fire Research Division.

The technical staff is the lifeblood of NIST. The staff members were articulate and, on the whole, knowledgeable of the technical areas. The staff appeared technically strong. However, the level of stature of the technical staff in the field was not clear. Publications alone do not indicate the leadership of the staff. Collaborations, which are occurring, also do not paint a complete picture. There were not clear indications that the staff are leading the field in some of the technical areas in which the BFRL participates, and staffing and staff development efforts should be undertaken to address the issue of leadership.

Biographies of the staff were not available to the panel; hence the evaluation of the BFRL staff backgrounds was incomplete in terms of understanding the current staff profile and the changes that are occurring (beyond the number of Ph.D. and M.S. staff members in the laboratory). The development of staff in terms of what is required at different levels and what is done in terms of assignments, training, or mentoring to enable staff to achieve higher levels of performance was unclear.

The staff includes pockets of significant excellence, but insufficient staff background data prevented an assessment of the overall level of staff qualifications. The laboratory infrastructure—facilities and people—needs additional focus to be able to complete the mission and particularly to achieve the strategic goals set by the BFRL management.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

The overarching Advanced Fire Service Technologies Program goes a long way toward balancing research for the built environment and research for firefighters who respond to fires in the built environment. Researchers in this area have a good understanding of the work going on in other laboratories, both in the United States and internationally. Overall, the BFRL has an excellent grasp of the fire problem in the United States. This work appears to be in support of America COMPETES Act of 2007. The work being done in both of the laboratories and in the programs across the board is extremely relevant to the needs that should be addressed for the fire problem in general.

The BFRL develops an unbiased evaluation of fire detection to help in the formulation of codes and standards (now prescriptive, in the future, performance-based) that will place the United States in a leadership position with regard to sensors, building materials, and building technologies. The BFRL has been very successful in working

with sensor manufacturers as well as with the fire service community in providing critical testing of the products that are manufactured and in use. The laboratory appears to have had less interaction with the building industry. At present, the industry relies on standard testing laboratories such as Underwriters Laboratories, Inc. (UL), which provide results on the performance of individual materials or components, but not on systems. The BFRL can, by testing systems, provide the data that the ultimate customer, the builder, needs. The proposed Structural Fire Resistance Laboratory will provide the ability to test the structural systems that are needed for the assessment of systems that involve multiple elements and joints.

BFRL researchers are active participants in major committees relating to fire safety and the protection of first responders, and they currently play a major leadership role in standards and code-setting committees. The results of the research efforts are disseminated through the preparation of CDs of fire scenarios, test burns, and training manuals for first responders, universities, and the public; and the sponsoring of an Annual Fire Conference as well as topical workshops, and outreach provided by the Web site Fire.Gov. The widespread adoption of FDS—the code of choice for the fire community—has established a Web-based access to the user community. In the Fire Research Division, researchers have been recognized by multiple awards including a Gold, a Silver, and three Bronze Medals of the Department of Commerce during the 2005-2007 period. Publication in peer-reviewed publications should be encouraged and strengthened. This output of the research provides the widest dissemination of the FRD results and is important for the development of visibility, particularly for the younger members of the FRD staff.

There is excellent balance in the work in this area between anticipatory, longer-term research and activities that respond to immediate customer needs. The WUI program provides an excellent example of longer-term research covering fires on multiple scales and at new interfaces. This work also tackles the complex problem of fire brands, which draw on the specialized facilities of the Large Fire Laboratory at NIST to determine fire brand generation by burning Douglas firs, and the large wind tunnel at the Building Research Institute in Japan to determine the impact of fire brands on a variety of common roof materials. The WTC and Rhode Island nightclub fire investigations are excellent examples of responsiveness of the BFRL to short-term needs through the use of multidisciplinary teams that enable both the understanding of the event and the systemic understanding of root cause that leads to changes in codes and standards. The determination of the adequacy of a variety of protection equipment (PASS, heat shields, radios, thermal imaging, and respiratory gear) for first responders is of enormous value to firefighters.

There was clear articulation of the mission and of the strategic directions for the BFRL. However, this strategic vision was not always complemented by detailed roadmaps and associated metrics that could be used to evaluate progress. This lack of portfolio management exemplifies an area in which project management techniques used widely in industry should be adopted by the BFRL.

There was clear use in the Fire strategic area of the “Heilmeier criteria”¹⁰ that

¹⁰ G. Heilmeier, 1992, “Some Reflections on Innovation and Invention,” *The Bridge*, Vol. 22 (No. 4): pp. 12-16.

have been adopted from DARPA¹¹ for project selection (investment criterion). However, these criteria are not implemented as rigorously as they have been by DARPA.

The areas of WUI fires and the World Trade Center investigation were presented to the panel in detail. These areas have had a clear and very positive focusing effect on the BFRL, and the response of the entire BFRL organization has been admirable during these investigations. The strengths of the diversity of expertise and the collaborative teaming among the contributors at the BFRL and elsewhere are evident in these investigations. It is not apparent, however, that clear lessons learned are being derived from these investigations and that upstream research is being developed systematically to address issues that arise from the studies on episodic events. These issues include the use of adequately sized and multidisciplinary teams. Smaller research efforts, especially without the use of technology roadmaps, can have a diffusing effect on research.

A role for NIST is the development of technology to enable performance-based codes. This leadership role was communicated to the panel by most presentations in a consistent manner. However, the leadership did not clearly show transition or impact on stakeholders to increase innovation or to increase performance in the building stock. The measurement of transitions to industrial use or to codes and standards, part of the R&D process, is not clearly being tracked at the BFRL.

Making use of technology maturation metrics such as technology readiness levels (TRLs) should be present, but in the projects reviewed there was no discernable process for understanding and measuring the state of technology readiness, particularly in the technology areas that underlie the Strategic Priority Areas. NASA, the Department of Defense, and others have adopted TRLs that quantify the maturity level but also give indications of what the gates are for moving to the next level. Without some sort of maturity index at the BFRL, it is not clear how the investments are being used to increase the levels or to get to transitions and impact. In addition to but different from using TRLs would be the use of project management strategies such as the Stage-Gate methodology, but there is no clear use of such an approach at the BFRL. There is a clear sense of the objective and milestones of the projects under review, but the methodology and criteria for arriving at a decision to accelerate (or to terminate) specific projects are not present. The projects that were selected to be reviewed appear to fall into several areas, but the choice was not explicit. There were projects that were long-standing (CFAST and FDS), projects that were driven by events or crises (WUI post-fire analysis, WTC investigation), and some newly emerging areas (egress, hydrogen fire safety). These could be put into a clearer project management format and the investments over the portfolio clarified if such processes were adopted.

CONCLUSIONS

The BFRL continues to demonstrate a core competence in the Fire Strategic Priority Area, particularly in the design and execution of experiments and the consistent coupling of experiments to validate predictive, physics-based computational tools. The work on the World Trade Center investigation is a very strong indicator of the

¹¹ Defense Advanced Research Projects Agency, 2007, *Strategic Plan: Defense Advanced Research Projects Agency*, Technical Report, Washington, D.C.

fundamental quality that the BFRL has and the value of the laboratory to the United States.

The BFRL has begun to outline strategic areas in which to focus R&D efforts and to make investments, and it is beginning to employ some tools to characterize the investments in the programs that make up the research portfolio. The general area of project execution requires some focus beyond the work done to date.

The staff has pockets of excellence, but insufficient data were presented to permit an assessment of overall staff qualifications. The laboratory infrastructure—the facilities and people—need additional focus to complete the mission and particularly to achieve the strategic goals set by the BFRL management.

The key recommendations are made relative to the strengthening of the core mission of developing measurement science. In the area of technology, the skill sets need to be both augmented and strengthened to execute against what are increasingly systems issues—there is little application in the teams for the projects reviewed of systems engineering, dynamical systems, and more broadly the much deeper use of information technology. Improved processes and metrics to characterize the research portfolio and to track project execution should be applied. The output of NIST is critically dependent on the staff. Recruiting and staff development need much stronger focus to ensure that the NIST mission can continue to be applied to new areas.

Specific recommendations in the area of technology include the following: increasing skill sets in systems engineering and dynamics, making explicit the ability to quantify uncertainty, and maintaining the core competence in fire systems that is founded on developing advanced experimentation capability coupled to validated computational tools. Investments should continue to be made in the experimental facilities as well as in making use of the facilities for the validation of mathematical models. The construction of a Structural Fire Endurance Laboratory is very desirable. The BFRL should prepare detailed schematic designs and obtain cost estimates for the proposed new large-scale fire test facility. The BFRL should also contact end users of the BFRL research as partners in developing the facility.

One recommendation in the area of the R&D process is for the adoption of project management tools (e.g., the Stage-Gate processes and some form of technology readiness levels) to quantify the technology maturity and to identify the overall investments in the R&D portfolio. Another recommendation is for the creation of roadmaps for the strategic areas that identify the sequencing of technology development and the timing that is needed for the identified stakeholders.

In future reviews, the BRFL should make explicit the biographical background of the current staff, the strategic hiring plans for competency levels, and individual staff development plans. Considerable motivation and focusing evolved from the work on fire problems with clear objectives, specifically, the WUI and WTC investigations. The BFRL should derive from these focusing-event investigations clear lessons learned and processes to use both in deriving research programs and in developing project planning methods that can be used in situations that do not have such clarity in the objectives.

Programs Funded Under the America COMPETES Act

DISASTER RESILIENT STRUCTURES AND COMMUNITIES (HURRICANES AND EARTHQUAKES)

The BFRL sees Disaster Resilient Structures and Communities (Hurricanes and Earthquakes) as a key focus area for addressing the goals of the America COMPETES Act of 2007 and the American Competitiveness Initiative. The Disaster Resilient Structures and Communities program has the following five stated research thrust areas: (1) develop validated tools that predict performance to failure under extreme loading conditions, (2) develop community-scale loss estimation tools to predict disaster resilience, (3) develop validated tools to assess and evaluate the capabilities of existing structures to withstand extreme loads, (4) develop performance-based guidelines for the cost-effective design of new buildings and the rehabilitation of existing buildings, and (5) derive lessons learned from disasters and failures involving structures. The BFRL Structures Group has mapped its existing program deliverables to these research thrust areas associated with ACI. The Structures Group received funding for a 5-year (FY 2003 to FY 2008) NIST Competence project to develop capabilities in analyzing the failure of complex systems. In FY 2008, the America COMPETES Act funding levels in the BFRL were not increased as had been anticipated. As a result, these programs have suffered from lack of adequate support. The President's FY 2009 budget includes the funding requests that had been made as part of the FY 2008 budget.

National Earthquake Hazards Reduction Program

NIST assumed leadership of the NEHRP in 2005, but the program appears to be early in its development stages within NIST. In 2006, the secretariat for the program was formally created. After that time (i.e., in FY 2006 and FY 2007), the primary activities of the program were associated with the start-up of the secretariat and with statutory compliance activities.

The NEHRP has strong leadership and good overall perspective on direction, objectives, and management. There has been limited technical progress on earthquake-related issues within NIST. Staffing and integration with other BFRL projects (multi-hazard) still need to be addressed. The NEHRP is a multi-agency partnership: the partners are the Federal Emergency Management Agency (FEMA), NIST, the NSF, and the U.S. Geological Survey (USGS). Since the lead agency role was assigned to NIST, the following activities have taken place:

- The establishment of the Interagency Coordinated Committee (ICC), which consists of the Directors of FEMA, NIST (Chair), NSF, USGS, the Office of Science and Technology Policy, and the Office of Management and Budget;
- The establishment of an Advisory Committee on Earthquake Hazards Reduction (ACEHR) that reports to the NIST Director;
- Initiation of the development of an updated strategic plan (a draft of the plan is to be reviewed by ACEHR in 2008); as directed by the ICC, performance of a gap analysis of the current 2001-2005 Strategic Plan, on the basis of

stakeholder comments received in the spring of 2006 and on feedback from ACEHR; this effort resulted in nine areas of added emphasis for the plan identified with particular lead agencies;

- Development of coordinated NEHRP agency budgets (although NEHRP itself has no control over budgets of other agencies); and
- Preparation and submission of annual NEHRP reports to Congress. The annual resources associated with the NEHRP secretariat office within the BFRL are currently \$750,000 (redirected from BFRL research funds) and \$85,000 from each of the partner institutions (FEMA, NSF, and USGS). In addition, the BFRL provides administrative support to the NEHRP.

Care should be taken that the role of the overall management of the NEHRP does not interfere with the BFRL technical programs associated with earthquake engineering.

DISASTER RESILIENT STRUCTURES AND COMMUNITIES (FIRES)

The extent of damage from wildland-urban interface fires has grown as a result of increased construction at that interface, which in turn has been aggravated where the weather has become hotter and drier. The problem area provides new technical challenges with the need to cover spatial scales ranging from submeter (to define fuel elements) to the regional scales (governing the terrain and winds that determine the propagation of the wildland fires). The problem requires an interdisciplinary approach to take into account socioeconomic factors that determine the type of construction and spatial distribution of the homes impacted by the fires. The BFRL is uniquely qualified to address the many facets of the wildland fires, drawing on its competencies in characterizing and modeling fire spread in buildings, its large-scale fire facilities for testing at multiple scales, its extensive connections in the fire community internationally, and its expertise in deriving lessons from fire investigations—particularly the skills demonstrated in the WTC and the Rhode Island Station nightclub fire investigations.

The WUI technical plan includes (1) the development of databases of fuels at the WUI; (2) the development of predictive tools bridging the multiple scales in communities at risk, extending the capabilities of the Wildland Fire Dynamic Simulator (WFDS); (3) the measurement of the fire resilience of WUI economies at the community scale; and (4) the development of risk-reduction strategies. Impressive progress has been made toward achieving these goals in a relatively short time with the resources provided under the America COMPETES Act and with extensive collaborations such as those with the U.S. Forest Service, the University of California at Riverside, San Diego State University, the California Department of Forestry and Fire Protection, the City of San Diego Fire Department, Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Forest Engineering Institute in Canada, and the Building Research Institute in Japan. Using facilities at NIST, models are being tested with data on the fires involving the following: single Douglas fir trees, the initiation of crown fires, grass fires, and fires in forest stands. The applicability of the WFDS to model community-scale fires has been demonstrated, but there is need for a controlled experiment involving a community fire. Fire investigations have been conducted on the October 2007 fires in San Diego County, employing post-fire analyses of both structure

ignitions and the fire spread travel through the wildland to the urban interface. A major innovation of the program is the systematic treatment of the role of so-called fire brands as a source of ignition, including study of the vulnerabilities of building elements such as roof structure and materials of construction, based on both wind tunnel tests conducted at the BRI in Japan and the post-fire investigation of the October 2007 San Diego WUI fire.

The BFRL should prepare technology roadmaps that clearly indicate the use of additional funding for the BFRL and indicate with precision and rigor the milestones being targeted and the affected stakeholders. The BFRL should fully embrace portfolio management tools and processes for the totality of the research programs being conducted across the laboratory. The laboratory should also move beyond the characterization of components to that of systems, as exemplified by work for the WTC and what is clearly emerging for WUI work. The focus on systems is critical to the science of measurement and U.S. competitiveness. New technologies from systems engineering, dynamical systems, and information technology should be examined and applied where appropriate.

Overall Conclusions

The technical merit of the programs reviewed within the BFRL overall is very high and in several instances at a state-of-the-art level; these programs have clear ties to the overall BFRL Strategic Priority Areas and are well aligned with the mission of NIST. With few exceptions the BFRL staff whose work was reviewed are fully aware of work being done elsewhere and have exceptional links with the external community. There is good balance in the BFRL work between anticipatory longer-term research and activities that respond to the immediate needs of customers.

Equipment and facilities supporting current BFRL work are excellent and, except in noted cases, do not appear to be a limiting factor with respect to research efforts. The updating and modernizing of related BFRL test equipment and procedures must continuously be considered, as such equipment is central to the mission of NIST. The BFRL staff has a critical mass of scientific and technical competencies and is well qualified to conduct the programs now underway. The panel has serious concerns relative to the attracting, recruiting, training, and retaining of staff for future needs. The BFRL needs to develop a plan to address present and future staffing needs, mentoring and staff development, retention strategies, technical and project management training, and the provision of the human resources support necessary to implement the plan without unduly taxing the time of scientific personnel. Available funding, at least prospectively, appears adequate for success in most current areas of work if the funding materializes. National economic opportunities and global environmental threats justify considerably more funding on energy-related work.

The BFRL has a strong foundation and record of excellent results in achieving program objectives and disseminating results and products into practice. The panel was presented with a clear articulation of the mission and of the strategic directions for the BFRL. However, this strategic vision is not always complemented by detailed roadmaps and associated metrics that could be used to evaluate progress. The current process may be effective on a project-by-project basis but may be insufficient as an effective methodology for assessing a group of projects with related objectives.

The BFRL sees Disaster Resilient Structures and Communities (Hurricanes and Earthquakes) as a key focus area for addressing the goals of the America COMPETES Act and the American Competitiveness Initiative. In FY 2008, the BFRL's funding levels under the America COMPETES Act were not increased as had been anticipated. As a result, the programs under this area have suffered from lack of adequate support. These programs are just now taking shape. The panel's recommendations relative to the wildland-urban interface fire research in support of the America COMPETES Act and the ACI are twofold: (1) the BFRL should fully embrace technical portfolio management tools and processes, and (2) the BFRL should utilize new technologies from systems engineering, dynamical systems, and information technology to take advantage of new technologies that complement its existing strengths in physics-based modeling and testing.