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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:

Randy Bruegman, Fresno Fire Department, California,
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E. Sarah Slaughter, Massachusetts Institute of Technology.

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 D. 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

The Panel on Building and Fire Research, a panel of experts appointed by the National Research Council (NRC), 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 on March 9-11, 2010, and reviewed its activities. As requested by the Director of NIST, the panel assessed the following: (1) the technical merit of the current laboratory programs relative to current state-of-the-art programs worldwide; (2) the adequacy of the laboratory's budget, facilities, equipment, and human resources, as they affect the quality of the laboratory's technical programs; and (3) the degree to which laboratory programs in measurement science, standards, and services achieve their stated objectives and desired impact. Following is a summary of the panel's conclusions addressing its charge.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

Overall, the technical merit of the programs within the BFRL is excellent and at the state of the art, although progress is sometimes hampered by factors beyond NIST's control. The BFRL's ability to stimulate new scientific and technological advances in high-performance buildings is constrained by major uncertainties about policy changes or by the presence of conflicting policies at the national, state, or local level. For example, countries with building energy performance standards more stringent than those in the United States have assumed leadership in this area, a position governed more by policy than by advances in technology or metrology. Barring this exception, the BFRL's Strategic Priority Areas are well aligned with the NIST mission to promote U.S. innovation and industrial competitiveness through the development of measurement science, standards, and technology. Members of the BFRL staff are internationally recognized and are the recipients of prestigious awards within NIST, nationally, and internationally. The BFRL is conducting groundbreaking research in critical areas.

The BFRL researchers generally have long-standing and active relationships with other research facilities and organizations around the world. The ties to the external community are extensive and uniformly strong with industry and other-agency partners. Industrial engagement is through a deliberate organization of forums and workshops. BFRL staff is, with some exceptions, well informed with respect to work taking place in other national laboratories, at universities, in private industry, and in other nations. The BFRL does an excellent job of interacting with customers, and its staff participate actively in professional and trade committees on codes and standards.

The BFRL has performed a major roadmapping activity during the past 2 years, part of which involved preparing planned outcomes for the near term (within 3 years), medium term (3 to 8 years), and long term (beyond 8 years). Further, the BFRL balances the need for measurement science to support short-term labeling and prescriptive standards with the longer-term goal of anticipating the transition to performance-based codes and standards.

ADEQUACY OF INFRASTRUCTURE

The equipment and facilities of the BFRL are generally excellent. Specific equipment deficiencies have been largely resolved with American Recovery and Reinvestment Act of 2009 funding (Public Law 111-5; ARRA, or stimulus, funds), and plans for the addition of two major new facilities are well underway. The National Structural Fire Resistance Laboratory (NSFRL) has been designed, and construction is planned for the fall of 2010. The NSFRL fills an important gap in the fire test facilities at the BFRL.

Also coming to the NIST site is a new residential test facility for evaluating methods of design and construction targeted at achieving net-zero energy buildings. This facility will allow the BFRL to measure the performance of various energy conservation technologies and techniques and that of local energy generation technologies. The facility will allow reconfiguration of many of its component parts to facilitate the installation of new technologies and test protocols as they are developed.

There has been a long-term area of competence in fire at NIST, and the activities in fire-resistant structural design have accelerated in the years since the World Trade Center (WTC) investigations. With the plans for the construction of the NSFRL, the activities are now at the point of making the BFRL a unique international resource in this area. The technical caliber of the research being performed is exceptionally high, highly relevant to national needs in the area of risk mitigation, and interdisciplinary. It provides the general public and decision makers with highly favorable exposure to NIST research, generating enthusiastic support for the role of NIST in building technology. Moreover, the expansion of the laboratories will have a major impact on the entire BFRL program. However, this expansion will require considerable new managerial resources and a business plan for the operation of the facility over the next several years.

Additional resources are also needed to support the wind program. Although recognized internationally, this program continues to be handicapped by the lack of a wind tunnel.

The BFRL professional and support staff are highly qualified and motivated. Since the previous panel review 2 years ago, the BFRL has been successful in filling vacant positions with well-qualified individuals through extensive informational and recruiting activities. Since 2006, the full-time staff additions (36) have exceeded the departures (29). Concerns remain about the recruiting and retaining of staff for future projects. Difficulties are exacerbated by the requirement to hire U.S. citizens and the difficulty of finding candidates with the necessary interdisciplinary skills for the Office of Applied Economics. Outreach and partnerships with universities (e.g., internships, contract research) could increase the pool of potential new talent for needed competencies.

A number of the key personnel in high-visibility programs are likely to retire within the next 3 to 5 years. To the extent that certain of these programs are strongly dependent on the capabilities and leadership of single individuals, it is imperative to develop a plan for maintaining the momentum of the affected programs. BFRL management should consider developing a formal succession planning program for technical staff in key programmatic areas. On the plus side, there are leadership training and staff development programs in place to develop new technical expertise and technical managers. The hiring of a new manager of codes and standards will fill an important gap in the organization and staffing of the BFRL.

The current budget plan appears to be adequate for immediate facility, equipment, and programmatic needs. Recent budget increases provide opportunities for benchmarking BFRL facilities and equipment against international facilities and for carefully choosing investments in facilities and equipment in order for the BFRL to remain in a leadership position internationally. Across the BFRL, the balance of funding provided from in-house work and work for other agencies is well aligned with that for NIST as a whole, although some more-applied programs understandably have a higher portion of support from work for others. The ratio of the support for work from other agencies to the in-house funds (Science and Technology Research Services, or STRS, funds) for the BFRL and NIST as a whole is about the same ($10.5 million and $37.3 million for the BFRL and $101.5 million and $504.5 million for NIST in 2010). Discussions with staff indicated strong support for having a relatively large fraction of external funding in some programs because of the interactions with clients that this fosters. A question is raised in Chapter 5 on whether the future funding of research in the National Structural Fire Resistance Laboratory would be a problem. The budget and effort devoted to a safety upgrade of facilities were provided and conducted thoroughly, with strong leadership and support from the BFRL management.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

Since the panel review in 2008, the roadmap planning process has led to increased consistency and cohesion across the BFRL (see discussions on the application of the Stage-Gate process in Chapter 7). It has also assisted in the targeting of resources toward a focus on high-impact areas. The most evident roadmapping process was that of goal setting to prioritize work. The roadmap process is still in a state of rollout, and several areas should be considered as next steps. The roadmap presented by the BFRL did not include clear milestones with specific time frames. The BFRL has implemented a Stage-Gate process for project planning.[1] The staff should continue to manage and prioritize projects using this tool. The staff should also refine the metrics of the tool based on experience with project outcomes and should do postmortem analyses of projects to learn from the use of the process.

A major impact of the research of the BFRL is in guiding the development of codes and standards. The BFRL has been very active in setting up workshops with all stakeholder groups—industry, and standards and codes organizations—both for establishing national standards and for discussing how industry can use standards to advantage to compete globally. These workshops have played an important role, both in the setting up of roadmaps and in the development of measurement science in support of national efforts on codes and standards. A noteworthy accomplishment of the BFRL effort is the far-reaching safety improvements resulting from the adoption of recommendations of the World Trade Center investigation in modifying key building and fire codes and standards. The building program would benefit from the development of new measurement science in construction at both the component and the systems level.

[1] Additional information about the Stage-Gate process can be found at http://www.stage-gate.com/knowledge_pipwhat.php. Accessed August 19, 2010.

The dissemination of results to the research and customer community is excellent, occurring through conferences, workshops, NIST technical publications, peer-reviewed papers, and open-source software. The BFRL Web site (http://www.nist.gov/bfrl/) provides excellent access to NIST products. Interest has been shown by industry in commercializing or utilizing testing equipment developed by the BFRL (e.g., the modified cone calorimeter, the integrating sphere weatherability testing equipment, the Virtual Cement and Concrete Test Laboratory). Measurement science at the BFRL is ahead of the adopted codes and standards in the construction, building, and fire industries. This is the proper role for the BFRL to play. By aspiring to create new measurement standards, the BFRL creates "proto-standards," which lead in turn to widely used codes and standards.

RECOMMENDATIONS

The recommendations of the panel based on its assessment of the Building and Fire Research Laboratory are as follows:

- The BFRL staff should continue to manage and prioritize projects using the Stage-Gate process, to refine the metrics of this tool based on experience with project outcomes, to do postmortem analyses of projects to learn from the use of the process, and to incorporate clear milestones with specific time frames into the resulting roadmap.
- Now that some evaluation standards related to codes and standards development have been in place for a number of years, the BFRL should compare actual performance and outcomes with those estimated using these methodological standards.
- Efforts should continue to focus on implementing performance-based standards and integrating life-cycle concepts into building design and construction practices.
- The BFRL needs to develop a model for sustained operation of the National Structural Fire Resistance Laboratory involving the coordination of in-house and extramural activities, and it needs to develop a protocol for the selection of extramural projects and collaborative activities.
- The BFRL should work to ensure that the planning and maintenance of the mandated Disaster and Failure Events Studies and Data Archiving activity do not impair the professional staff's ability to discharge ongoing programmatic responsibilities in the BFRL effectively.
- In the area of staffing, outreach programs to and partnerships with universities should be continued in order to recruit young talent and to provide postdoctoral fellowships to handle the increased workload as well as to increase the pool of potential new talent for the interdisciplinary competencies needed for the Office of Applied Economics. Staffing difficulties are exacerbated by the requirement to hire U.S. citizens.
- BFRL management should consider developing a formal succession planning program for technical staff in key programmatic areas.

- The building program would benefit from the development of new measurement science in construction at both the component and the systems levels.
- The BFRL should pursue the spectrum of opportunities and potentials available to it, including the following, to expand its scope of inquiry and analysis in building and fire safety: the addition of staff with leadership potential in flame-heat-transfer modeling; the definition of an appropriate role for the BFRL with respect to the growing nuclear power industry; the integration of life-cycle analysis and sustainability into building performance assessment; anticipation of the measurement science needed to support the transition to performance-based standards and the Smart Grid, as well as the multidimensional nature of building performance.
- Additional resources are needed to support the wind program; the program continues to be handicapped by the lack of a wind tunnel.

Recommendations applicable to each of the BFRL Strategic Priority Areas are presented in their respective chapters.

1

The Charge to the Panel and the Assessment Process

At the request of the National Institute of Standards and Technology, 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 2010, 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 of these 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 fiscal year (FY) 2010 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 current state-of-the-art programs worldwide;
2. The adequacy of the laboratory budget, facilities, equipment, and human resources, as they affect the quality of the laboratory's technical programs; and
3. The degree to which laboratory programs in measurement science, standards, and services 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 current state-of-the-art programs worldwide.
   - *Relative Technical Caliber:* How does the technical quality of the laboratory programs compare to current state-of-the-art programs 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?

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[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.

2. The adequacy of the laboratory budget, facilities, equipment, and human resources, as they affect the quality of the laboratory's 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 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, standards, and services 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?

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.

In order to accomplish the assessment, the NRC assembled a panel of 22 volunteers, whose expertise matches that of the work performed by the BFRL staff.[3] The panel members were also assigned to five subgroups (Strategic Priority Area review teams), whose expertise matched that of the work performed in the BFRL's five Strategic Priority Goal Areas of Measurement Science for (1) Net-Zero Energy, High-Performance Buildings; (2) Advancing Infrastructure Delivery; (3) Sustainable Infrastructure Materials; (4) Disaster-Resilient Structures and Communities; and (5) Innovative Fire Protection.

The panel met at the NIST facilities in Gaithersburg, Maryland, on March 9-11, 2010. After the full panel met for a session of welcoming remarks from the NIST Director's representative, the Acting Coordinator for Laboratory Programs, and an overview presentation on the BFRL by the BFRL management, the panel divided into its five review teams, and each (led by a team leader chosen from within the panel) then visited with the staff of its respective BFRL Strategic Priority Goal Area for about a day. During these visits, the review team members attended presentations, tours, demonstrations, and interactive sessions with the BFRL staff. Subsequently, the entire panel assembled for about a day-and-a-half meeting, during which it interacted with

[3] See http://www.nist.gov/bfrl/ for more information on BFRL programs. Accessed May 1, 2010.

BFRL and NIST management and also met in a closed session to deliberate on its findings and to define and draft the contents of this assessment report.

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 of BFRL activities. The panel reviewed selected examples of the research covered by the BFRL; because of time constraints, it was not possible to review the BFRL programs and projects exhaustively. The examples reviewed by the panel were selected by the BFRL. The panel's goal was to identify and report salient examples of accomplishments and opportunities for further improvement with respect to the following: the technical merit of the BFRL work, its perceived relevance to NIST's own definition of its mission in support of national priorities, and specific elements of the BFRL's resource infrastructure that are intended to support the technical work. These examples are intended collectively to portray an overall impression of the laboratory, while preserving useful suggestions specific to projects and programs that the panel examined. The assessment is currently scheduled to be repeated biennially, which will allow, over time, exposure to the broad spectrum of BFRL activity. 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. The omission of any particular BFRL program or project should not be interpreted as a negative reflection on the omitted program or project.

2

Measurement Science for Net-Zero Energy, High-Performance Buildings

The primary core competency for the Measurement Science for Net-Zero Energy, High-Performance Buildings 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 and procedures to aid the designer in evaluating and making decisions about trade-offs.

Areas of expertise within this Strategic Priority Area include energy efficiency, renewable and distributed energy sources, indoor air quality, building controls, alternative refrigerants, ventilation strategies, economics, and codes and standards. The BFRL divisions that are active in this Strategic Priority Area are the Building Environment Division (BED), the Office of Applied Economics (OAE), and the Fire Research Division (FRD). 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, Computer-Integrated Building Processes, and Indoor Air Quality and Ventilation.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

The high level of expertise and knowledge of the staff working in this Strategic Priority Area is apparent. For example, the volatile organic compound emission measurement and carbon monoxide emission from emergency power generation measurement projects and the Net-Zero Energy Residential Test Facility (NZERTF) in Gaithersburg, Maryland, are good examples of groundbreaking measurement science research. Also, the application of airflow laser velocimetry and computational fluid dynamics (CFD) to expand the capabilities of heat exchanger simulation models is state of the art.

Even though the work within this Strategic Priority Goal Area is of high quality, especially in the areas noted above, additional steps can be taken to enhance the effectiveness of some activities. For example, the work on solar photovoltaic panel performance mapping could be groundbreaking if the appropriate solar spectrum for various typical seasonal and geographical locations can be simulated. In addition, the research in wireless data communications does not seem well connected to other current work outside the laboratory. These two areas are examples of how the work of the BFRL could benefit from more collaboration with work outside the laboratory, with federal agencies, academia, and nongovernmental organizations.

Work in the Measurement Science for Net-Zero Energy, High-Performance Buildings goal area is becoming better coordinated with that of other federal agencies. BFRL staff were heavily involved in the development of the 2008 report *Federal Research and Development Agenda for Net-Zero Energy, High-Performance Green*

Buildings.[4] The BFRL's 2009 priority-setting Workshop on Measurement Science for Net-Zero Energy Buildings included invited participants from the private sector, industry trade organizations, universities, the relevant national laboratories, and other federal agencies. Not only did these activities provide a solid foundation for future programs, they also improved the BFRL team's understanding of what is going on at other national laboratories.

The staff members are expanding their knowledge of international standards and measurement technologies, not only through participation in international standard-setting committees but also by participating in cooperative research projects through the International Energy Agency (e.g., developing ways to measure the performance of whole buildings and various subsystems). The staff is generally aware of relevant information from outside sources and has made numerous visits to laboratories in other countries. However, the limited scope of the panel's review did not permit an assessment of the results of the visits, nor did it reveal the extent to which they are strategically planned—for example, to share best practices, to gather intelligence, or to negotiate access to unique facilities. Overall the programs in this Strategic Priority Area apply interdisciplinary methods and insights to estimate multidimensional impacts and the effectiveness of particular measures and standards.

The past few decades have marked a shift from prescriptive standards to performance standards, the latter enabled by modern information and control technologies. In the case of energy-efficient buildings, BFRL's programmatic emphasis is therefore focusing more on measuring the performance of entire buildings and their increasingly complex subsystems (e.g., cogeneration systems that produce both heat and on-site power) as compared to the performance of individual components. Therefore, simulation modeling appears as an element of many of the projects related to building energy efficiency. Such models can provide insight into the design of test procedures and the selection of test conditions to support labeling of seasonal or annual performance. For example, some NIST projects aim to add functionality to existing simulation programs: for example by understanding how natural or forced ventilation can affect energy efficiency or pollutant distributions within a building. For other projects, complex whole-building-system simulation models that already exist must be simplified to enable real-time fault detection, which requires a continuous comparison of measured performance to simulated performance of individual components or the whole building.

ADEQUACY OF INFRASTRUCTURE

The current budget plan for this Strategic Priority Area appears adequate for immediate facility and equipment needs. Recent budget increases provide opportunities for benchmarking BFRL facilities and equipment against international facilities and for carefully choosing to invest in the kinds of facilities and equipment required for the BFRL to remain in a leadership position internationally. The construction of the Net-Zero Energy Residential Test Facility at NIST will help the BFRL achieve this objective.

[4] Executive Office of the President, National Science and Technology Council, Committee on Technology, *Federal Research and Development Agenda for Net-Zero Energy, High-Performance Green Buildings,* Report of the Subcommittee on Buildings Technology Research and Development, Washington, D.C., October 2008.

In general, the funding is adequate to achieve success. Recruiting, however, is impaired by the inability of NIST to hire non-U.S. citizens. Hiring procedures that focus on narrow disciplinary-based areas of expertise also inhibit the ability to hire new Ph.D.'s and other candidates having the desired combination of interdisciplinary skills. Outreach and partnerships with universities (e.g., internships, contract research, etc.) could increase the pool of potential new talent for needed competencies.

The BFRL is currently able to meet existing needs, but as more senior researchers retire, replacing them may be difficult. The lack of replacement of key staff may lead to deficiencies in core competencies. On the plus side, there are leadership training and staff development programs in place to develop new technical expertise and technical managers. Outreach programs to students at universities to recruit young talent and handle an increased workload should be continued. Leadership training and staff development programs to improve the level of expertise on the staff should be continued.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

The BFRL has implemented a Stage-Gate process for project planning. The staff should to continue to manage and prioritize projects using this tool. The staff should refine the metrics of the tool on the basis of experience with project outcomes, and they should do postmortem analyses of projects to learn from the use of the process.

Critical solution-enabling tools are being developed to support the energy-efficient operation of buildings. An example is in the area of system simulations and fault detection and diagnosis (FDD). FDD tools developed by NIST have been incorporated into Honeywell's Alerton line of variable-air-volume-box controllers.

The program milestones appear feasible, but priority setting is unclear. To maximize programmatic impact and promote innovation, the net-zero energy buildings group must anticipate and stay ahead of developments in this rapidly changing area. Advances in measurement science are required to support the transition to performance-based standards and intelligent building controls that detect equipment faults. The performance of components, equipment, and whole buildings must be measured across their entire operating envelopes, not simply a single rating point. In addition, protocols are required for communicating performance data from components to equipment to building energy management systems and to the Smart Grid.

Anticipating such future needs is not easy. Decades ago, NIST pioneered the development of building simulation models, but today they are far too complex for any single institution to bear the ongoing cost of model development and validation. Yet NIST can and should anticipate needs for adding functionality to simulation models—for example, to understand how natural or forced ventilation can affect energy efficiency and pollutant distributions within a building. Such algorithms should be validated by careful measurements in well-designed experiments, as they have been in NIST's residential test facilities. Anticipating such needs, however, also requires the construction of new facilities to be as modular and flexible as possible (e.g., movable walls, thermal mass placement), in addition to the exploration of cooperative arrangements with other laboratories that are capable of producing the necessary data. The new NZERTF will have some of these capabilities, which should be included to maximize the flexibility of the facility.

The software tool Loop Design and Analysis (LoopDA) for natural-ventilation design is a good example of a need that was anticipated with ample lead time. However, customer needs are not always anticipated in a timely manner or at a time when adequate resources are available. For example, the production of residential and commercial indoor air cleaners had developed into a half-billion-dollar industry that was making unsupported claims before the need for standardized test procedures and labeling was recognized.

New funding and net-zero-building goals may provide the BFRL with the opportunity to develop strategies for anticipating the kinds of measurement science needed to support the transition to performance-based standards and the Smart Grid as well as the multidimensional nature of building performance (the factors of energy, air quality, comfort, and electronic noise). It is also time to consider how the BFRL can exploit its unique position within the Department of Commerce to access the massive U.S. Census Bureau databases needed to calculate carbon footprints and other indirect economic effects of model building codes. The cost of adding such capacity may be substantial, but it could yield great long-term benefit.

Dissemination of this important work is effectively handled through conference papers and journal articles, Web site publications, seminars, workshops, and software tools. The close working relationships of the BFRL staff with industrial users of the Reference Fluid Thermodynamic and Transport Properties Database (REFPROP) not only facilitate the dissemination of these important data on thermodynamic and transport properties of refrigerants, but also provide opportunities to help NIST's Chemical Science and Technology Laboratory anticipate needs for data on new types of fluids.

Staff participation in numerous standards development processes contributes to the effectiveness of the laboratory's work. These include activities of the following: the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE); ASTM International (formerly known as the American Society for Testing and Materials); the American Society of Mechanical Engineers (ASME); the U.S. Green Building Council (USGBC); the International Energy Agency (IEA); and the International Organization for Standardization (ISO).

CONCLUSIONS

While NIST's capabilities for conducting research on future metrology and standards needs are high, its ability to efficiently stimulate and complement private-sector scientific and technological advances is constrained by other national, state, and local policies. Major uncertainties about likely policy changes in the pricing of carbon emissions or energy (e.g., portfolio standards or feed-in tariffs for renewable energy), and/or the willingness to use regulatory policies to guide the development of technologies significantly more costly than current market forces dictate, continue to complicate targeting and limit the application of NIST's contributions to high-performance buildings technology. Increased emphasis on measurement science for integrated systems and whole-building performance standards instead of for components alone is necessary, but not sufficient, to enhance U.S. competitiveness.

The BFRL has seen significant funding growth in some program areas within the Measurement Science for Net-Zero Energy, High-Performance Buildings Strategic Priority Area and has implemented a Stage-Gate process for project planning. Looking forward, it is important to make management quality a high enough priority to ensure that new facilities are established successfully and safely and that the processes for setting research and development (R&D) priorities, selecting projects, and Stage-Gate oversight are effective and robust.

The high level of expertise and knowledge of the staff in this Strategic Priority Area is apparent. Interdisciplinary methods and insights to estimate multidimensional impacts and the effectiveness of particular measures and standards are leveraged across programs. BFRL's programmatic emphasis is staying ahead of the requirement of the shift from prescriptive standards to performance standards by focusing more on measuring the performance of entire buildings and their increasingly complex subsystems and model developments as an element of many of the projects related to building energy efficiency.

Staff members are generally aware of relevant information from external organizations and have made visits to laboratories in other countries. It is not clear whether sufficient efforts are being undertaken to learn from other countries in which high-performance building technologies are far more advanced.

Overall, the current budget plan appears adequate for immediate facility and equipment needs, and funding is adequate to achieve success. Recruiting, however, is impaired by the inability of NIST to hire non-U.S. citizens. Outreach and partnerships with universities (e.g., internships, contract research, etc.) could increase the pool of potential new talent for needed competencies.

Within the Stage-Gate process, the staff is encouraged to continue to manage and prioritize projects using this tool and also to do and learn from postmortem analyses of projects, as experience and metrics refinements usually prove beneficial. The area of energy use in buildings is very dynamic, and the BFRL group must anticipate developments and stay ahead of them. However, new funding and net-zero energy building goals ought to provide the BFRL with the opportunity to develop strategies for anticipating the kinds of measurement science needed to support the transition to performance-based standards and the Smart Grid, and to addressing the multidimensional nature of building performance. It is also time to consider how the BFRL can exploit its unique position within the Department of Commerce to access the massive U.S. Census Bureau databases needed to calculate carbon footprints and other indirect economic effects of model building codes.

Dissemination is effectively handled through conference papers and journal articles, Web site publications, seminars, workshops, and software tools. The close working relationships of the BFRL staff with industry not only facilitate the dissemination of this important work, but also must provide windows to anticipate opportunities, such as the very urgent need to understand the characteristics of the next generation of non-ozone-depleting, low-global-warming refrigerants. Finally, staff participation in numerous standards development processes contributes to maximizing programmatic impact and promoting innovation, such as in the Net-Zero Energy Buildings program.

RECOMMENDATIONS

The recommendations of the panel based on its assessment of the Measurement Science for Net-Zero Energy, High-Performance Buildings Strategic Priority Area are as follows:

- The BFRL should make management quality a high enough priority to ensure that new facilities are established successfully and safely, and that the processes for setting R&D priorities, selecting projects, and Stage-Gate oversight are effective and robust.
- With respect to staffing, hiring procedures that focus on narrow, disciplinary-based areas of expertise inhibit the ability to hire candidates with the desired combination of interdisciplinary skills, and they should be reconsidered. Outreach to and partnerships with universities should be pursued to increase the pool of potential new talent for needed competencies and to recruit young talent to handle the increased workload. Leadership training and staff development programs to improve the staff's level of expertise should be continued. The BFRL should work to prevent the retirement of senior researchers from creating deficiencies in core competencies.
- The staff should continue to manage and prioritize projects using the Stage-Gate process and to refine the metrics of this tool based on experience with project outcomes, and they should do postmortem analyses of projects to learn from the use of the process.
- The net-zero energy buildings staff must anticipate developments in this rapidly changing area and stay ahead of them.
- BFRL staff's close working relationships with industry must provide windows to anticipate opportunities, such as the very urgent need to understand the characteristics of the next generation of non-ozone-depleting, low-global-warming refrigerants.
- The BFRL should consider how it can exploit its unique position within the Department of Commerce to access the massive Census Bureau databases needed to calculate carbon footprints and other indirect economic effects of model building codes.
- The BFRL should pursue the benchmarking of its facilities and equipment against international facilities, and it should pursue the careful selection of investments in the kinds of facilities and equipment required for the BFRL to remain in a leadership position internationally.
- For the work on solar photovoltaic panel performance mapping and on wireless data communications, more collaboration with outside organizations should be sought.
- The performance of components, equipment, and whole buildings must be measured across their entire operating envelopes, not simply a single rating point, and protocols are required for communicating performance data from components to equipment to building energy management systems and to the Smart Grid.

- NIST can and should anticipate needs for adding functionality to simulation models. Algorithms should be validated by careful measurements in well-designed experiments. New facilities should be constructed to be as modular and flexible as possible—the new Net-Zero Energy Residential Test Facility will have some of these capabilities, which should be included to maximize the flexibility of the facility. Cooperative arrangements with other laboratories that are capable of producing necessary data should be pursued.

3

Measurement Science for Advancing Infrastructure Delivery

The primary core competencies for the Measurement Science for Advancing Infrastructure Delivery (MS-AID) Strategic Priority Area are consistent with those in the panel's 2008 report, but they have been adjusted to reflect refinements in the nation's needs and NIST capabilities.

Areas of expertise within this Strategic Priority Area include the following: information, communication, and automation technologies for the intelligent integration of building and infrastructure design, construction, and operations; 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, and the Office of Applied Economics. The active groups include the Construction Metrology and Automation Group in the MCRD and the Computer Integrated Building Processes Group in the BED. The MS-AID Strategic Priority Area focus is on developing "measurement science" and thus inherently involves interfaces among the MCRD, BED, and OAE.

This Strategic Priority Area has identified the following five key drivers for change:

1. Energy independence, environmental security, and sustainability;
2. Renewal of the nation's aging physical infrastructure;
3. Demand for better-quality, faster, and less expensive construction;
4. Competition due to globalization and offshoring; and
5. Homeland security and disaster resilience.

This Strategic Priority Area is addressing the second and third of these key drivers for change in U.S. construction.

The MS-AID Strategic Priority Area has also appropriately identified barriers to change, which are largely related to the size, complexity, and fragmentation of the industry. The challenges accompanying those barriers are compounded by prescriptive codes and standards and the low profit margins, resulting in a low level of R&D investment.

The stock of U.S. infrastructure is enormous, and much of it has exceeded its design life. The American Society of Civil Engineers (ASCE) estimates that the cost for the renewal of existing critical infrastructure exceeds $2 trillion. In addition to buildings, other areas identified in the ASCE 2009 *Report Card for America's Infrastructure*[5] (i.e., bridges, drinking water, energy, and wastewater) are closely related to the BFRL mission. Another study, commissioned by the BFRL in 2009 and conducted through the National

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[5] The ASCE 2009 *Report Card for America's Infrastructure* reported the condition (in terms of "grades") of the range of infrastructure sectors in the United States. See http://www.infrastructurereportcard.org/; accessed June 1, 2010.

Research Council, identified specific challenges and offered recommendations for advancing the productivity and competitiveness of the capital facilities sector.[6]

The goal of the MS-AID Strategic Priority Area is to achieve significant improvements in the construction and operation of the nation's physical infrastructure through the development of measurement science that enables the assessment and integration of information, communication, automation, and sensing technologies. The key MS-AID program is the Automated and Integrated Infrastructure Construction Processes Program.

The construction industry is large, complex, and fragmented. Even individual projects involve three major phases—planning, design, and construction—that are traditionally performed by different organizations at sequentially different times. Communications among groups and individuals are difficult. (For example, a $100 million project will, over time, typically involve about 10,000 different individuals, resulting in 50 million potential communications channels!) The industry has traditionally managed itself by emphasizing experience and standardized procedures that vary among differing organizations. Recent advancements in communications, computers, and other technologies provide opportunities for significant improvements in project delivery methods. The MS-AID Strategic Priority Area is intended to develop a "measurement science" for assessing the effectiveness of improvements and quantify "cause-and-effect" relationships between activities in various project phases, and to correlate those with project results. The BFRL has appropriately chosen to select objectives that exploit the technical expertise of the laboratories and interface that expertise with other organizations, such as the Construction Industry Institute, ASCE, NRC, and universities.

The word "productivity" appears in many MS-AID documents and is the basic driver for many MS-AID goals and activities. Although economists, including those in the Office of Applied Economics, recognize differentiating adjectives, such as "capital" productivity or "worker" productivity, MS-AID has properly used the term categorically as relating to construction industry improvement. Thus, the goal of improved productivity would relate to better designs, better schedules,, better quality of conformance and performance, improved safety, and lower costs. More so, the MS-AID Strategic Priority Area emphasizes the development of the "management science" to support and measure the effects of such improvements.

The program objectives of the MS-AID Strategic Priority Area are to develop the measurement science to:

- Enable automated access and integration of diverse information systems;
- Enable real-time construction and process sensing and control of construction;
- Determine productivity at discrete and aggregate levels;
- Evaluate performance of promising automation and integration technologies; and
- Develop standard criteria for the measurement of the accuracy of the transfer of electronic engineering and construction data.

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[6] National Research Council, *Advancing the Competitiveness and Efficiency of the U.S. Construction Industry,* Washington, D.C.: The National Academies Press, 2009.

The key drivers for change are widely recognized and accepted within the industry. The size and complexity of the industry make it impossible for any single agency to address everything immediately. The MS-AID program objectives are consistent with a selective approach that utilizes the expertise within the BFRL to have maximum impact in developing the measurement science.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

Activities in the MS-AID Strategic Priority Area are compatible with programs conducted by other laboratories and universities throughout the world, but they provide a unique perspective on addressing these issues. The BFRL has long addressed specific technical issues in a thorough and methodical manner. The BFRL has more recently begun to apply its expertise and methodologies to its management science initiative.

Program staff interfaces effectively with national and international counterparts, and it collaborates with key stakeholders. The BFRL has funded and has been heavily involved with CII's Benchmarking and Metrics Program, particularly with regard to homeland security applications. It also funded the recent study, referred to above, by the National Research Council, *Advancing the Competitiveness and Efficiency of the U.S. Construction Industry*. It has funded construction robotics research at the University of Texas, and it was a principal sponsor a few years ago of an international ASCE Research Foundation Workshop on Sustainable Construction.

The MS-AID Strategic Priority Area has related its program objectives to desired outcomes for the near term (FY 2010–FY 2013), medium term (FY 2013–FY 2018) and long term (FY 2018 and beyond). Each program objective includes multiple activities, some of which appear in each of the time frames.

Ongoing activities in the MS-AID Strategic Priority Area include the Automated and Integrated Infrastructure Construction Processes Program and the following projects:

- Metrics and Tools for Measuring Construction Productivity,
- Performance and Use of 3D Imaging Systems,
- Construction Control Using 3D Imaging and Building Information Models,
- Development of an Indoor Intelligent and Automated Construction Job Site Testbed,
- Methods and Metrics for Conformance Testing of Construction Project Data Standards, and
- Virtual Project Data Integration Testbed.

The ongoing activities utilize the expertise and abilities of the MS-AID group and are within the context of the objectives. They identify the development of metrics and tools, use of three-dimensional and automated systems, Project Data Standards, and Project Data Integration, which will all add to the industry's productivity.

Some of these activities—for example, the use of three-dimensional imaging systems, the Job Site Testbed, and the Virtual Project Data Integration Testbed—are internally driven, having interfaces with outside firms and agencies as necessary and appropriate. Other activities are more integrated with outside organizations, such as activities undertaken in cooperation with the Construction Industry Institute. All activities are coordinated or integrated with outside organizations, such as the

Construction Industry Institute, the Construction Users Roundtable, the Electric Power Research Institute, FIATECH, and the ASTM.

The MS-AID Strategic Priority Area is also pursuing the development of measurement science for quantifying cause-and-effect relationships between activities in various project phases and correlating those with project results. Many examples of cause-and-effect relationships are possible, such as using the results of a “Project Definition Rating Index” during the planning phase of a project prior to entering the design or construction phases, or using “Constructability” tools during the design phase. In recent years, much implementation of new management tools and techniques has taken place, but with a mostly anecdotal reporting of results. The only public database for correlating such uses with project outcomes is that of the Construction Industry Institute, which is heavily oriented toward industrial projects. (As an example, the CII companies’ safety records are an order-of-magnitude better than those of the overall industry, partly because of correlations of cause-and-effect studies using its database.) The metrics and tools for measuring construction productivity developed by BFRL’s Office of Applied Economics should be expanded to examine a variety of cause-and-effect relationships.

ADEQUACY OF INFRASTRUCTURE

Personnel within this Strategic Priority Area are distinguished both by their technical competence and their passion for their work. The priority area involves staff with advanced degrees and industry experience. It has produced numerous publications and presentations at professional meetings and is active in appropriate interfaces with other agencies. However, current staffing levels may not be adequate to achieve program objectives, and consideration should be given to increasing the staffing level consistent with overall BFRL priorities. In particular, it would be appropriate to add staff with advanced degrees from the many developing graduate programs in project management, construction management, and facilities management that are at the forefront of developing new management science tools.

Laboratory space for this priority area had been limited during previous evaluations, but this appears to have been rectified by the provision of space for the Indoor Intelligent and Automated Construction Job Site Testbed, which is currently being renovated.

Computing capacity and speed are critical to the successful performance of activities within this priority area. Efforts should be made to ensure that state-of-the-art computing capability is available and continuously upgraded.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

Feasible milestones have been identified and incorporated in MS-AID project plans, and the MS-AID program is managed to achieve these performance targets.

Extensive interfaces with all stakeholder groups, including codes and standards organizations, have been established, and the incorporation of program outputs into codes and standards development is inherent in all program activities. Program results are made available through conferences, workshops, and NIST technical publications and journal articles.

The program has made progress toward addressing current and emerging priority area needs through the sponsorship of workshops, conferences, and independent assessments by the National Research Council.

Figure 3.1 illustrates the potential for MS-AID activities to have a significant impact on project delivery. The cost-influence curve (shown in the figure) has long been recognized by construction industry practitioners and researchers. The timing of total expenditures on a project is represented by a typical S-curve that shows a relatively low level of expenditures in the planning and design stages, with the majority of expenditures occurring in the construction stage. However, the activities and decisions made early in a project's planning and design stages are increasingly recognized as having a dominant influence on a project's cost, as well as on its quality, safety, and delivery schedule. The unique modeling and measurement capabilities of the MS-AID program could be used to identify and exploit cost savings and other benefits that could accrue from a better understanding of the earlier phases of the construction process.

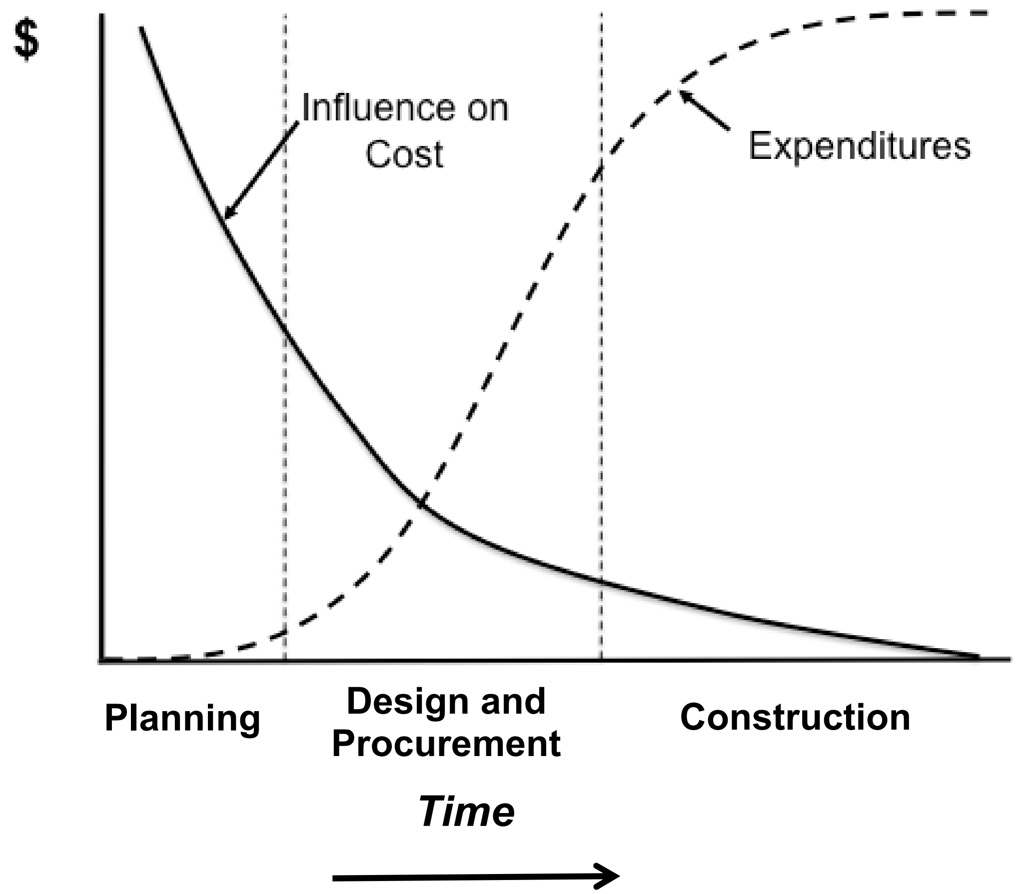

FIGURE 3.1 Cost-influence curve for phases of the construction process.

CONCLUSIONS

Opportunities and Recommendations

Following are opportunities identified and recommendations made by the panel on the basis of its assessment of the Measurement Science for Advancing Infrastructure Delivery Strategic Priority Area:

- The valuable metrics and tools for measuring construction productivity developed by BFRL's Office of Applied Economics should be expanded to examine a variety of cause-and-effect relationships. Examples include using the results of a "Project Definition Rating Index" during the planning phase of a project prior to entering the design or construction phases, or using "Constructability" tools during the design phase.
- Worker safety offers an excellent opportunity to launch this cause-and-effect initiative by the OAE.
- The MS-AID staff should maintain its strong relationships with the construction community in order to identify new opportunities to add value.
- Current staffing levels may not be adequate to achieve program objectives, and consideration should be given to increasing the staffing level consistent with overall BFRL priorities.
- Efforts should be made to ensure that state-of-the-art computing capability is available and continuously upgraded.
- The MS-AID Strategic Priority Area has the potential to have significant additional impact by expanding its scope to include other phases of project delivery.

Conclusions

Following are the conclusions of the panel based on its assessment of the BFRL's MS-AID Strategic Priority Area:

- The work conducted by the Measurement Science for Advancing Infrastructure Delivery (MS-AID) Strategic Priority Area is supportive of broader BFRL goals for measurement science.
- The work conducted within this Strategic Priority Area is consistent with the BFRL definition of the scope of measurement science.
- The outcome of this work will be significant progress toward achieving the following:
  —Renewal of the nation's physical infrastructure;
  —Better-quality, faster, safer, and less costly construction; and
  —Improved global competitiveness.
- MS-AID has a broad spectrum of opportunities and the potential to expand its scope of inquiry and analysis.

4

Measurement Science for Sustainable Infrastructure Materials

The primary core competencies for the Strategic Priority Area of Measurement Science for Sustainable Infrastructure Materials are performance, durability, and the service-life prediction of building materials. A secondary core competency involves fire protection and fire spread within buildings and communities.

The areas of expertise in this Strategic Priority Area are materials-based and include polymers, concrete and associated inorganic materials, and flammability, with an emphasis on polymeric materials. This subject area covers three primary topics, involving three groups, in the overall area of building and fire research. The BFRL divisions involved with this priority are the Fire Research Division and the Materials and Construction Research Division. The specific groups are the Polymeric Materials Group and the Inorganic Materials Group in the MCRD and the Materials Flammability Group in the FRD.

The major change in these topics since the previous review is the transition from an emphasis on nanotechnology to an emphasis on sustainability. The prediction of the life cycle of high-performance polymers and composites, including nanocomposites, is an area that is now embracing sustainability concerns relative to the choice of materials selected for present and emerging applications. An area of increasing interest relative to sustainability involves predicting the service-life performance of concrete building and infrastructure materials. Another project involves the reduction of the flammability of materials as halogenated flame retardants become less accessible to the material suppliers for use in flame-retardant compositions. The areas reviewed have done an excellent job of making the transition from an emphasis on nanotechnology to an emphasis on sustainability, and there are overlapping goals for each emphasis.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

In the study of the life cycle of high-performance polymers and composites, several topics are being investigated, including outdoor and accelerated aging of nanostructured polymeric systems, multiscale mechanical properties of polymeric materials, and nanoparticle release during the life cycle of nanostructured materials. The outdoor accelerated aging of nanostructured polymeric materials is a research thrust of national importance. Using reliability principles to establish a relationship between accelerated and real-time aging using cumulative damage models appears to be an appropriate approach. More information on the successes of this model in relating the accelerated test results with outdoor weathering data would be helpful in assessing the results of this effort. The multiscale study of the properties of polymeric composite materials is focused on nano-reinforced polymers using nano-indention to determine elastic modulus. Although modulus is an important measure, other measures such as glass transition temperature, coefficient of thermal expansion, and cure shrinkage are important properties influenced by reinforcement characteristics. The application of other approaches such as Dynamic Mechanical Analysis and Differential Scanning Calorimetry can be helpful in understanding resulting properties. Non-invasive characterization of dispersion in polymeric composites is a grand challenge that will benefit the field of nanocomposites enormously, but progress has been slow. Dispersion of nanoparticles is a critical issue. The measurement of dispersion using angular optical scattering should be complemented by using laser scattering, x-ray scattering, and microtomography imaging.

The nanoparticle life-cycle study focused on the release of carbon nanostructures from polymer nanocomposites subjected to ultraviolet radiation. This project is in response to a major concern on the potential toxicity of nanoparticles employed in materials that may be released to the environment in their life cycle. The development of a system for the detection and collection of released products is the primary objective of this study. It is important that the study establish test samples with appropriate degrees of dispersion, since poorly dispersed systems are likely to show high levels of carbon nanotube release that may not be characteristic of well-dispersed systems.

The development of measurement science for sustainable cement-based materials is of great importance to the civil infrastructure in the United States. Research currently being conducted in the Inorganic Materials Group in sustainable cement-based materials will retain, strengthen, and extend the historic global leadership of the BFRL in microstructure modeling and characterization tools. This research is well aligned with its core mission in regard to performance, durability, and service-life predictions of building materials.

There is a strong urgency to extend the service life of the U.S. infrastructure while utilizing cements with a low carbon footprint by substituting cements with industrial waste products such as fly ash or slag. The research being conducted at the BFRL is at the forefront in regard to developing rheology-based models and measurement and characterization tools that will enable the routine commercial use of high volumes of fly ash and slag in concrete, which are essential for producing more durable and sustainable concrete structures. The BFRL approach in characterizing fly ash and relating it to its performance is unique, and no such projects are currently being conducted in or outside the United States. Major accomplishments in this area are evidenced by the receipt of the ASTM P.H. Bates Memorial Award (2008) and the NIST Bronze Medal (2007) for the development of a new ASTM x-ray diffraction (XRD) standard method.

In addition, the mitigation of early age cracking is essential in enhancing the durability of concrete structures. The BFRL is currently working on guidelines for measuring the concrete properties that contribute to early age cracking and on mitigation strategies. The BFRL's impact in this area is evidenced by the receipt of the prestigious American Concrete Institute (ACI) Wason Medal and the Frank G. Erskine Award.

The BFRL should continue the microstructure modeling with the emphasis on molecular dynamic modeling in collaboration with the efforts currently underway in Europe.

NIST is a global leader in the realm of understanding material flammability. Over the past several years, the BFRL team has been very instrumental in providing critical scientific data that help in understanding fire protection, durability, and service-life prediction. The objective of the Reduced Flammability of Materials Program is to develop measurement science tools to help the material industry in producing sustainable, cost-effective, and fire-safe materials. The team has made a concerted effort in focusing on sustainability. A roadmap was established after an innovative fire protection workshop was conducted, which involved experts from academia and industry. As a result of the workshop, changes were made to strategic goals and programs. The three specific thrusts that were identified are (1) the development of bench-scale flammability measurement methods, (2) the evaluation of new models and materials for fire-safe products, and (3) the development of data and methods to enable a critical assessment of the sustainability of new fire-safe technologies. The goal of the thrusts is fully aligned with the BFRL mission and vision.

One of the program goals is to design and implement measurement science tools that enable the development of fire-safe products. The compilation of a database of materials with promising sustainability attributes and the development of tools to evaluate these materials for their effectiveness as sustainable flame retardants in a series of polymer systems have already been started. The team has done an excellent job in working with a number of agencies and partners, both domestic and international, as this effort will require the tools and expertise from different disciplines such as environmental science, nanotechnology, flame retardancy, and life-cycle assessment.

One of the major practical issues is the flammability of polyurethane foam. According to National Fire Protection Association (NFPA) reports,[7,8,9] reducing the flammability of materials used in products found in homes, automobiles, and building insulation could reduce the total core cost of fire to the U.S. economy. This would also significantly enhance public safety. U.S. fire deaths attributed to the burning of polyurethane foam products remain a major fraction of the total fatalities recorded in home fires. Development of the measurement science to enable industry to produce fire-safe foam products requires the development of an extensive knowledge base for several complex technologies. The BFRL team had taken this as a goal several years ago and was able to develop a vertical cone calorimeter test method. In the past 2 years, the team has been able to show the utility of this test method as a possible screening tool that will take dripping into consideration. This test method has already gained traction, as some laboratories have started using it. The next step will have to be that of working with regulatory bodies to show the relevance as a test method and to incorporate it into a standard test.

NIST has made major contributions to the understanding and use of nanocomposites to reduce flammability in polymers. One of the concerns that the industry has regarding nanocomposites is the release of nanoparticles into the environment. The BFRL team has been working on a project to develop techniques to quantify the yields, chemical compositions, morphologies, and size distributions of nanoparticles released into the environment. This is not an easy problem. The challenge is that of making measurements of nanoparticle release while still considering the potential health hazards. The developments in this area will be critical in answering the question of nanoparticle release in terms of actual quantifiable data.

[7] John R. Hall, Jr., "The Total Cost of Fire in the United States," Fire Analysis and Research Division, National Fire Protection Association, February 2008.

[8] Michael J. Karter, Jr., "U.S. Fire Loss for 2006," *NFPA Journal* 101(5):64, 2007.

[9] Marty Ahrens, "Home Fires That Began with Upholstered Furniture," National Fire Protection Association, Quincy, Mass., May 2008.

ADEQUACY OF INFRASTRUCTURE

The equipment and personnel necessary to carry out the goals and objectives of the projects in place appear to be adequate. Specific equipment deficiencies have been partially resolved with ARRA stimulus funds obtained in the past year. Additional equipment and capital items could, however, advance the performance of this division as it focuses on critical sustainability issues involving key materials.

The concrete area appears to be one in which the Inorganic Materials Group offers a unique service to the huge (and energy-consuming) concrete industry by conducting more fundamental research and establishing measurement standards for more-sustainable concrete products. This area could benefit from a state-of-the-art testing facility for future cement-based materials (such as fly-ash-modified concrete) and for the potentially huge concrete market in the re-emerging nuclear power market.

A need was expressed for a polymer materials scientist with modeling skills and also for life-cycle analysis expertise for the flame-retardant materials area. Succession planning was discussed with the panel; the plans should be reviewed as needed, because several retirements may occur in the next several years.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

The change in priority emphasis from nanotechnology to sustainability obviously modifies the objectives and desired impacts of each specific project. The Sustainable Infrastructure Materials priority area has done an excellent job in making the proper changes in the priorities. This was quite helpful, as the projects in place also were directed toward goals consistent with sustainability issues. A review of the two major impact areas noted in the previous (2008) panel report demonstrated continued effort and success in implementing these measurement techniques into broader external use. The integrating sphere weatherability testing equipment has several companies seeking Small Business Innovation Research support for commercialization, and the modified cone calorimeter vertical flammability test apparatus is now used by several external laboratories for polyurethane foam.

The measurement science developed in the BFRL group for sustainable cement-based materials provides the fundamental understanding in developing standards and ASTM protocols, which allows the technology to be readily transferred to industry. For example, the XRD standard test method that was developed at the BFRL in the Inorganic Materials Group has recently been incorporated into a new ASTM standard. The BFRL was contacted by Roman Cement LLC to utilize the characterization tools developed in the Inorganic Materials Group. The Virtual Cement and Concrete Test Laboratory, resulting from its pioneering work in hydration modeling, is well recognized by national and international researchers and is in the process of being adopted by industrial partners. The inorganic cement group has an excellent record of publishing in peer-reviewed journals and of collaboration with universities, nationally and internationally.

The areas where achievements in the past several years should result in potential impact in areas of national interest include the fundamental measurement and characterization work conducted on fly-ash-modified concrete. The assessment of nanoparticle release into the environment was addressed as a concern several years ago, and meaningful progress has been achieved toward answering this environmental and health issue.

CONCLUSIONS

The Strategic Priority Area of Measurement Science for Sustainable Infrastructure Materials is focused on the measurement and characterization of materials for meeting the sustainability requirements of the future. The core competency is crucial to the infrastructural materials requirements of the future. The critical skills are present to meet the core competency requirements as well as to investigate the technical projects in progress. Overall, the laboratory is well equipped (except as noted), and changes in project execution made in the past several years have proven fruitful. These changes include the implementation of a more detailed safety review procedure and adaptation of the Stage-Gate process to ensure that projects are properly focused and not directed in a chaotic fashion. The publications and presentations by group members continue to be impressive, illustrating the technical impact that this area has on its external peer group.

One of the important missions of this Strategic Priority Area (as well as of most programs at NIST) is to ensure that other government agencies have the necessary information to make proper decisions. The material choices for present and future needs are sometimes dominated by other agencies (the Environmental Protection Agency as an example). Where material choices are impacted by sustainability issues, this group should be proactive with other government agencies to ensure that proper choices are made. Many of these decisions involve risk–reward analysis, which NIST is more equipped to determine than most other agencies are. The group is placing appropriate emphasis on utilizing the sustainability model developed at NIST (Building for Environmental and Economic Sustainability, or BEES). It would be useful if this model were specifically linked to infrastructure materials. Another emerging area, in which the Inorganic Materials Group involved with concrete should be actively engaged, is the emerging nuclear power plant construction. Codes and standards for these plants are more than 30 years old. This group is in a unique position to offer valuable expertise related to concrete utilization in this re-emerging industry.

RECOMMENDATIONS

The recommendations of the panel based on its assessment of the Strategic Priority Area of Measurement Science for Sustainable Infrastructure Materials are as follows:

- The measurement of the dispersion of nanoparticles using angular optical scattering should be complemented by the use of laser scattering, x-ray scattering, and microtomography imaging.
- It is important that the nanoparticle life-cycle study establish test samples with appropriate degrees of dispersion.
- The BFRL should continue the microstructure modeling, with the emphasis on molecular dynamic modeling, in collaboration with the efforts currently underway in Europe.

- The next steps for the vertical cone calorimeter test method will have to be those of working with regulatory bodies to show its relevance as a test method and incorporating it into a standard test.
- Additional equipment and capital items could advance the performance in the Measurement Science for Sustainable Infrastructure Materials Strategic Priority Area as the researchers focus on critical sustainability issues involving key materials.
- The concrete work could benefit from a state-of-the-art testing facility for future cement-based materials (such as fly-ash-modified concrete) and for the potentially huge concrete market in the re-emerging nuclear power market.
- The expressed needs for a polymer materials scientist with modeling skills and for life-cycle-analysis expertise for the flame-retardant materials area should be addressed.
- Staff succession plans should be reviewed as needed.
- The material choices for present and future needs are sometimes dominated by other agencies. Where material choices are impacted by sustainability issues, the staff in the Measurement Science for Sustainable Infrastructure Materials Strategic Priority Area should be proactive with other government agencies to ensure that proper choices are made.
- The sustainability model developed at NIST (Building for Environmental and Economic Sustainability) should be specifically linked to infrastructure materials.
- The Inorganic Materials Group involved with concrete should be actively engaged with the re-emerging nuclear power plant construction industry to offer its valuable expertise related to the use of concrete.

5

Measurement Science for Disaster-Resilient Structures and Communities

The primary activities within the Measurement Science for Disaster-Resilient Structures and Communities Strategic Priority Area relate to earthquake engineering and the performance of structures under multiple hazards. Within the earthquake area, there are three components: the mandated leadership in the National Earthquake Hazard Reduction Program (NEHRP), earthquake mitigation through in-house research, and earthquake mitigation through extramurally funded projects. Within the multiple hazards area, there are programs related to disproportionate collapse, fire-resistant design and retrofit of structures, and wind and multihazard engineering. An outgrowth of the fire program is the planned National Structural Fire Resistance Laboratory. An outgrowth of the National Construction Safety Team Act of 2002 (Public Law 107-231) is the new initiative related to a database for disaster and failure events. The panel reviewed extensive documentation made available prior to the meeting and heard comprehensive presentations by BFRL staff on approximately 15 research programs.

The BFRL divisions and offices active in this area are the Materials and Construction Research Division, the National Earthquake Hazards Reduction Program Office, and the Office of Applied Economics.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

Earthquake Engineering

Activities Mandated by NIST Leadership of the NEHRP

NIST assumed the leadership of the NEHRP in 2005. Since 2008, the Director of the NEHRP appears to have discharged on a timely basis all mandated requirements under this program and has strengthened institutional ties with other cognizant federal agencies, including the Federal Emergency Management Agency, the U.S. Geological Survey, and the National Science Foundation. New staff members hired for earthquake engineering research (see the following subsection) have played a critical role in assisting the director in discharging these responsibilities, allowing him time for strategic planning. This activity remains relevant to the need to reduce seismic risk in urban areas. The Director of NIST chairs the NEHRP Interagency Coordinating Committee and plays a key role in anticipating future research and implementation needs. The program is funded at an adequate level to meet its obligations under NEHRP.

Projects on Risk Mitigation

Earthquake-related research, both through internal and external projects, serves primarily to improve building codes and standards and construction practices. One of the most significant accomplishments of the past 2 years is in the hiring of six outstanding professional and support staff members.

In a relatively short period of time, the research staff has undertaken a broad range of projects, from the so-called ATC Roadmap[10] intended to bridge the gap between scientific earthquake analysis and engineering practice, to assessment of first-generation seismic design methods and the development of efficient nonlinear seismic measurement science tools. It is appropriate that the effort related to nonlinear measurement science tools will be subject to peer review in the coming year. Through the NEHRP Consultants Joint Venture, 12 contract task orders have been issued on projects related to quantification of the seismic performance of building and other civil infrastructure systems. The technical caliber of the in-house staff and the NEHRP consultants is very high; the projects are relevant owing to the involvement of practitioners in the work orders; and the BFRL has anticipated the research needs to implement performance-based earthquake engineering. The budget appears to be adequate to meet programmatic objectives. The stature of the NEHRP consultant group ensures that the work products are likely to be implemented in professional practice.

Performance of Structures Under Multiple Hazards

The programs within this Strategic Priority Area build on NIST expertise relating to the performance of structures subject to extreme events and deal with issues and behavior that the private sector has been reluctant to undertake. These activities are focused on progressive collapse and fire-resistant design, are exemplary of those types of projects, and are clearly within the NIST mission. The program in wind engineering is similarly internationally well recognized and has been a significant driver in the past 30 years in the advancement of wind load provisions in ASCE 7, *Minimum Design Loads for Buildings and Other Structures*.

The research program on disproportionate collapse has been in progress for a number of years, has both experimental and analytical components, and has resulted in a number of significant research projects that have been introduced to the code community. This program is quite mature. Although the ongoing work to implement these recommendations in design practice is commendable, effort should be devoted to anticipating the needs of the structural design community in setting the research goals and challenges that the program will address in the next 3 to 5 years.

There has been long-standing competence in the area of fire at NIST, and the activities in fire-resistant structural design have accelerated in the years since the investigations into the collapse of the World Trade Center buildings. With the plans for the construction of the new National Structural Fire Resistance Laboratory underway, the activities are now at the point of making the BFRL a unique international resource in this area. The technical caliber of the research being performed is exceptionally high, highly relevant to national needs in the area of risk mitigation, and interdisciplinary in the most positive sense of the word. It also provides the general public and decision makers with highly favorable exposure to NIST research, generating enthusiastic support for the role of NIST in building technology. The substantial commitment of funding through the ARRA for the NSFRL is a reflection of the high value that has been placed on the fire

[10] Applied Technology Council (ATC), *The Missing Piece: Improving Seismic Design and Construction Practices,* ATC-57, 2003. See http://www.ATCouncil.org. Accessed June 1, 2010.

program, but the one-time infusion of funds raises concern relative to the match between funding and sustained operation. These concerns are discussed in detail in the following subsection related to the new laboratory.

The Wind Engineering and Multi-Hazard Failure Analysis Program is managed by exceptionally well-qualified staff. While resources to perform analytical studies are adequate at the present time, the wind research program continues to be handicapped by the lack of a wind tunnel that might be used to validate some of the analytical studies with carefully designed experimental studies. Research partnerships with universities may provide a mechanism for supporting experimentation. The staff have well-established links to code and standards committees, are internationally well recognized, and are of the highest scientific quality. The long-term research to integrate wind and storm surge addresses a national risk-mitigation need.

National Structural Fire Resistance Laboratory

The NSFRL is being funded through the American Recovery and Reinvestment Act of 2009. The need for this world-class facility was identified at the time of the investigation of the collapse of the WTC buildings, and planning has been underway for the past several years. The design is now complete, and the construction contract is expected to be awarded in the fall of 2010, with construction planned for October 2010 to November 2011. This facility will be unique and will offer long-term support to structural fire engineering in the United States and internationally.

The prospect of having this facility at NIST is exciting. However, a number of operational issues on the horizon require attention. NIST management must recognize appropriately the burden that this construction project will place on NIST technical staff. An immediate priority will be the development and implementation of a staffing plan, including the hiring of a facility manager with the authority to conduct shakedown testing of the laboratory when it is completed. There is also need for the development of a model for the sustained operation of this significant capital investment, involving the coordination of in-house and extramural activities and a protocol for the selection of extramural projects and collaborative activities. The BFRL should develop its own model for the selection of extramural research projects and should not be guided by the criteria or preferences of any other federal agency or private concern. It will be necessary to have continued collaboration with the Fire Research Division of the BFRL.

Disaster and Failure Events Studies and Data Archiving

The initiative on Disaster and Failure Events Studies and Data Archiving is an outgrowth of the National Construction Safety Team Act of 2002, which authorizes NIST to establish and deploy teams to investigate building failures. This recent initiative builds on and organizes BFRL’s previous episodic involvement in post-incident disaster and failure studies over the past three decades and provides a formal structure for archiving the lessons learned from those studies. This program is still in the planning stages, and staff is working to establish criteria for performing initial reconnaissance, full reconnaissance, and technical investigations; to establish protocols for the collection and preservation of data; and to develop database management tools.

This program will be a high-visibility initiative of the BFRL, but at this stage of program development, several items require careful consideration. Perhaps most important is the impact that this mandated activity will have on the professional staff and on their ability to continue to discharge ongoing programmatic responsibilities at BFRL effectively, in view of the episodic nature of the investigations.

An office will be established to manage and coordinate the efforts of this program. Some investigations will be performed by existing BFRL technical staff, but others might be contracted out as needs dictate. These investigations may place burdens on existing technical staff, and the quality assurance for those investigations that are contracted out will ultimately receive close review by NIST.

An additional concern relates to the criteria for selecting the results of non-BFRL-coordinated investigations for inclusion in the database and the need for maintaining the integrity and credibility of such data over which the BFRL will have no control. A continuing concern will be the maintenance of the integrity and credibility of the database itself. A protocol must be developed for balancing the need for public access to the database and complying with the requirements of the Freedom of Information Act, while at the same time maintaining the security of potentially sensitive data.

The scope of the building performance data is structural failures, as mandated by Congress. The BFRL should consider collecting other data of interest to the building community and useful in the support of ongoing BFRL research programs, including information on the serviceability and durability of building products. The maintenance of this database should consider the context of the evolution of Building Information Management systems.

Summary

The work being done within the Measurement Science for Disaster-Resilient Structures and Communities Strategic Priority Area is at the state-of-the-art level. The quality of the work is demonstrated by the publication of the research in the archival literature and the recognition of research products in codes and standards. The work is relevant to the BFRL mission, and the ties to the external community are uniformly strong across the three major thrust areas.

ADEQUACY OF INFRASTRUCTURE

At the time of the 2008 panel review, the primary focus was the development of advanced computational models, and some hardware and software constraints were noted. In the past 2 years, the program has grown to include structural testing and the validation of models, and the issue of computational limitations was not raised. Computational resources appear to be adequate. The BFRL has made remarkable progress in the development of its National Structural Fire Resistance Laboratory which, on completion, will fill a huge void in the nation's capability for performing such fire testing. Priority should be given to completing this facility on schedule and to developing a management plan for its successful operation.

Current professional staff in the Materials and Construction Research Division is well qualified to conduct the projects envisioned or underway. The recent hiring progress in the earthquake program since the 2008 panel visit is encouraging. Concerns remain about the recruiting and retaining of staff for future projects. A number of the key personnel in high-visibility programs are likely to retire within the next 3 to 5 years. To the extent that certain of these programs are strongly dependent on the capabilities and leadership of single individuals, it is imperative that a plan be developed for maintaining the momentum of those projects. BFRL management should consider developing a formal succession planning program for technical staff in key programmatic areas.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

The Materials and Construction Research Division has excellent linkage with the BFRL mission. The work of the division's professional staff has achieved significant recognition in the building and codes and standards community, and the staff has been successful in moving research products into standards.

For continued success in achieving these impacts, efforts should continue to focus on implementing performance-based standards and integrating life-cycle concepts into building design and construction practices. An important issue is the development of metrics for performance-based engineering for a range of natural and human-made hazards. The earthquake program has accepted the performance metrics being developed by the Applied Technology Council for performance-based seismic design. Although this decision is appropriate, the application of these seismic-design-based metrics to other hazards is questionable. Moreover, in the general area of performance-based engineering, there are many levels of performance short of collapse that are significant issues for structural engineers, architects, and building occupants. The BFRL has the opportunity to take a leadership role in developing these more encompassing performance metrics. This effort will require nontraditional expertise. In the fire area, in particular, the move from prescriptive to performance-based standards will encounter significant resistance from current stakeholders. Nonetheless, BFRL staff should continue their efforts in this direction.

In the area of natural and human-made hazard mitigation, the issues of cost versus benefits and life-cycle analysis of alternate strategies are continuing concerns. During the current review, the BRFL staff did not evince recognition of these issues. For this work to be ultimately accepted in building codes, the issue of costs and benefits must be addressed. The BFRL research staff, in conjunction with BFRL's Office of Applied Economics, has the unique ability to address this problem in the public interest. (There is a more detailed description of the OAE in Chapter 7, "Overarching Issues.")

The validation of high-fidelity analytical models is an underlying theme in several of the high-visibility projects. There is need for validation, but reservations about validating one computational model against another should be considered. Moreover, there is no evidence that sources of epistemic uncertainty, inherent in any analytical model regardless of scale, have been properly incorporated into the validation process. The investigators in projects in which the validation of computational models is a major research thrust should be cautious in their approach. The renewed interest in experimental research, represented especially by the NSFRL, offers more important tools for performing this validation.

No nuclear plants have been designed in the United States for nearly 30 years, and codes and standards are out of date. Therefore, there is an opportunity for the BFRL to have a significant impact on the development of design and construction standards for nuclear energy facilities.

CONCLUSIONS

The primary activities in the Strategic Priority Area of Measurement Science for Disaster-Resilient Structures and Communities revolve around earthquake engineering and the performance of structures under multiple natural and human-made hazards. These programs build on BFRL technical achievements and contribute to a tradition of excellence sustained over a period of many years. They are widely recognized nationally and internationally, and their research products have had a significant impact on building codes and standards. The professional staff is highly capable, and the research products continue to maintain a level of technical excellence. However, there is need for a structured succession planning exercise in key areas to sustain program momentum as key staff members retire during the next several years.

Two recent initiatives will leverage the established expertise of the BFRL technical staff. The National Structural Fire Resistance Laboratory is a marvelous opportunity to create a unique, world-class testing facility to support improvements in fire engineering. The Disaster and Failure Events Studies and Data Archiving initiative undoubtedly will have high visibility and, if successful, will engender valuable public and political support for BFRL research programs. Both initiatives may place heavy demands on current BFRL staff, detracting from their traditional research responsibilities and accomplishments if not carefully managed. These initiatives should be carefully managed and scrutinized as they develop.

There is a proper balance between mandated programs, continuing research, and new initiatives. Within the general area of performance-based engineering, there is a need to better integrate concepts of life-cycle analysis and sustainability into building performance assessment. Attention should be given to the study of appropriate and encompassing performance metrics beyond those being developed in connection with performance-based earthquake engineering. The BFRL should examine and define its role with respect to the current and anticipated rebirth of nuclear power.

RECOMMENDATIONS

The recommendations of the panel based on its assessment of the Strategic Priority Area of Measurement Science for Disaster-Resilient Structures and Communities are as follows:

- BFRL management should develop a formal succession planning program for technical staff in key programmatic areas.
- For the NSFRL construction project, an immediate priority will be the development and implementation of a staffing plan, including the hiring of a facility manager with the authority to conduct shakedown testing of the laboratory when it is completed. A model for the sustained operation of the NSFRL should be developed, involving the coordination of in-house and extramural activities and a protocol for the selection of extramural projects and collaborative activities. The BFRL should develop its own model for the

selection of extramural research projects. Continued collaboration with the Fire Research Division of the BFRL will be needed.

- The outcomes of the Disaster and Failure Events Studies and Data Archiving program will need to be carefully managed to achieve its potential. A protocol must be developed for balancing the needs for public access to the database and compliance with the requirements of the Freedom of Information Act, with the need for maintaining the security of potentially sensitive data. The BFRL should consider collecting other data that are of interest to the building community and useful in the support of ongoing BFRL research programs, including information on the serviceability and durability of building products.
- Both of these activities may place heavy demands on current BFRL staff, detracting from their traditional research responsibilities and accomplishments, so these initiatives should be carefully managed and scrutinized as they develop, to avoid such problems.
- Within the general area of performance-based engineering, there is a need to better integrate concepts of life-cycle analysis and sustainability into building performance assessment. Attention should be given to the study of appropriate and encompassing performance metrics beyond those being developed in connection with performance-based earthquake engineering. The BFRL should examine and define its role with respect to the current and anticipated rebirth of nuclear power facilities—it could have a significant impact on the development of design and construction standards.
- Priority should be given to completing the National Structural Fire Resistance Laboratory on schedule and developing a management plan for its successful operation.
- The investigators in projects in which the validation of computational models is a major research thrust should be cautious in their approach. The renewed interest in experimental research, represented especially by the NSFRL, offers important tools for performing this validation.
- The wind research program continues to be handicapped by the lack of a wind tunnel. Consideration should be given to research partnerships with universities that may provide a mechanism for supporting experimentation.

6

Measurement Science for Innovative Fire Protection

The goal of BFRL's Fire Research Division is to reduce the impact of fire on communities, structures, building occupants, emergency responders, and the economy by providing the measurement science needed to reduce preventable fire losses. The areas of expertise within the division include all areas of fire science and fire protection engineering. More specifically, fire science includes flammability, computational fluid dynamics, heat transfer, fire growth modeling, and combustion chemistry and toxicity—whereas fire protection engineering includes hazard assessment; fire detection, suppression, and smoke control; building egress design (involving stairway and elevator technology and occupant behavior); fire service technologies; and codes and standards.

The NIST Fire Research Division ably serves the national needs and is clearly superior worldwide to other fire research centers for its breadth and excellence in fire research serving national needs. Other fire research centers target different areas of specialization. The modeling of the physics and chemistry of fire is the fundamental strength of the division. Its Fire Dynamics Simulator (FDS) model is used worldwide to evaluate the hazards of a specified fire. Maintaining and improving on this strength to predict fire growth is essential to the division's longer-term mission. The division is notable for its success in performing key research leading directly to the adoption of numerous standards and codes.

The FRD has four groups: Fire Fighting Technology, Fire Measurements, Engineered Fire Safety, and Materials Flammability.

The programs and their primary responsibilities supporting the fire protection goals are the following:

- *Reduced Risk of Fire Spread in the Wildland-Urban Interface (WUI) Program:* To improve the fire performance of structures and communities in the wildland-urban interface through the development of standard test methods for building materials and risk-assessment and risk-mitigation tools for use by community decision makers, homeowners, and fire officials.
- *Advanced Fire Service Technologies Program:* To increase the effectiveness and safety of emergency responders by enabling the development of improved protective equipment, situational awareness, and science-based tactics and training tools for the fire service.
- *Reduced Risk of Fire Hazard in Buildings Program:* To increase the safety of building occupants and the fire performance of structures and their contents by enabling the implementation of innovative, cost-effective fire protection technologies. This program includes the further development of NIST's well-known Fire Dynamics Simulator.
- *The Fire Grants Program:* To conduct measurement science that enables innovative fire protection and reduced flammability of materials through grants and contracts to appropriate institutions.

- *Reduced Flammability of Materials Program* (reviewed by the Sustainable Infrastructure Materials review team; see Chapter 4 in this report): To develop measurement science tools to aid the materials industry in producing sustainable, cost-effective, fire-safe products through the development of validated bench-scale flammability measurement methods, models, guidelines, and databases.

TECHNICAL MERIT RELATIVE TO STATE OF THE ART

The BRFL presented to the panel a sample of projects in each of the major research programs as described below.

Wildland-Urban Interface

Fire spread in the wildland-urban interface is an increasing problem caused by (1) more people living on the wildland-urban interface (second homes, etc.), (2) the increased buildup of vegetative and construction fuels that occurs at the interface, and (3) climate change—especially droughts in the southwestern United States. Wildland fires are spread by firebrands, radiative heat transfer, and direct flame contact. The WUI research program is very responsive and well thought out. The program has three parts aimed at technical progress:

1. To develop validated computer models for fire spread through WUI fuel (structures and vegetation), with model development including laboratory and field measurements of wind, vegetation, terrain, heat fluxes, and firebrands' generation and transport;
2. To develop a database characterizing the vulnerability of different structural materials and assemblies to ignition from firebrands, including roofing materials and firebrand penetration through openings and protective screens and vents; and
3. To perform on-site post-fire forensic studies of buildings in consultation with local firefighters to validate NIST's experience and expertise.

CFD modeling of fire spread is particularly challenging, as it involves the bridging of scales over eight orders of magnitude, ranging from millimeters for structural ignition and firebrand production, to hundreds of kilometers for regional-scale smoke transport. Three near-term standards are expected from this research. They are as follows:

1. Measurement of the vulnerability of building elements, including roofing, decking, siding, and vents, to ignition and/or penetration by firebrands;
2. Guidance for both homeowners and professionals regarding the vegetation and general landscaping surrounding homes at the WUI; and
3. Standard methods for reporting fire losses at the WUI that might eventually improve the defenses against wildfires by guiding building codes and standards improvements.

Fire Service Technologies

The Advanced Fire Service Technologies Program provides great help to firefighters by performing research ensuring their safety and effectiveness. A good example of the research is the study on the effective functioning of respirators for firefighters. The research represents a particularly good use of NIST's technical capabilities. It is customer-driven and requires a multidisciplinary team (involving CFD, toxicology, materials, etc.). Another example is the recently issued performance-based standard for thermal imaging cameras used by first responders to find victims in smoky conditions or fires hidden behind walls or ceilings. Performance-based testing of thermal imagers ensures that cameras work under actual-use conditions. In addition, science-based standards enable U.S. manufacturers to develop innovative and more effective technologies for both domestic and international customers.

Another problem in firefighting is the degradation of protective clothing by exposure to smoke and toxic products of combustion. A standard is being developed to ensure the performance of existing gear and to provide a method for retiring gear that has reached the end of its useful life. The problem becomes acute for firefighters and their protective clothing exposed repeatedly to contaminants during training exercises. Again, it is a complex multidisciplinary problem.

Finally, there is the concept of having a device called an Emergency Fire Fighter and Occupant Locator to locate people having transponders in a burning building. After careful evaluation, the concept appears solvable for residential occupancies but more challenging for larger commercial buildings, whose exterior walls are more opaque to electromagnetic waves.

Fire Hazard in Buildings

Recent data from New York State show a notable reduction in the loss of life following New York's adoption in 2005 of the new cigarette ignition propensity standard (i.e., "fire-safe cigarettes"). Apparently there has been a reduction in the unwanted ignition of fires by cigarettes in New York State. Smoking has long been the single largest cause of deaths from fires in the United States. However, the adoption of fire-safe cigarettes now causes a problem. The widely used ignition-resistance tests for mattresses and upholstered furniture (16 CFR 1633 [took effect in 2007] and pending 16 CFR 1634, respectively) have used a particular "pre-standard" cigarette, which is no longer manufactured. NIST is completing the development of a standard reference material, a uniform cigarette with the same ignition propensity as that of the former test cigarette.

Smoke inhalation kills more people than the number who die of burn injuries, and smoke obscuration is a principal factor in the escape time from a fire. There is need for a standard laboratory test method for estimating the toxic potency of smoke from burning buildings and furnishing. NIST has available considerable well-documented data for smoke and toxic products produced in full-scale residential fires. A project is underway to subject specimens from complex products (chairs, electrical cables, bookcases, etc.) to several different laboratory-scale test methods to determine the extent to which accurate toxic-potency data for smoke can be obtained, compared with data from room burns of the full objects.

Egress modeling is receiving considerable attention. A thorough technical foundation for egress modeling has three elements: building details, human behavior, and the movement of people. Research on these elements should lead to models as well as codes and standards.

Modeling of Fires

The well-known Fire Dynamics Simulator has provided the foundation for much of NIST's fire research over the past decade. Its development by NIST took 30 years of patient research. Fire protection engineers now use it worldwide. The engineer typically specifies the geometry and heat-release rate of the fire, and the code then predicts the subsequent movement of the smoke and hot products of combustion. It provides excellent visualization, is easy to use, and is surprisingly fast on a typical personal computer. There have been several recent improvements in the numerics in the code of interest to CFD specialists. These include employing the dynamic Smagorinsky closure, optimizing scalar transport, and implementing the Werner-Wengle wall-stress model.

FDS is limited in its ability to predict the fire spread or growth rates of hazardous-scale fires. This limitation prevents the use of FDS to predict whether a small fire will grow and transition into a big fire. It is a serious limitation. The difficulty arises from the fact that thermal radiation dominates the heat transfer in hazardous-scale fires, and FDS lacks a validated treatment for thermal radiation. As a result, engineers using FDS must specify the fire heat-release rate rather than letting the model calculate the heat-release rate. To move forward the division needs to reach out to other organizations for the expertise in measuring and modeling thermal radiation in fires. Other institutions, including the commercial insurance company FM Global and the Sandia National Laboratories (SNL), are currently moving the state of the art forward. Both FM Global and SNL have decades of experience in both measuring and modeling the heat transfer taking place in large fires.

Large Fire Laboratory

NIST has recently upgraded its Large Fire Laboratory (LFL), used by the division. Soon to be attached to the LFL will be the new National Structural Fire Resistance Laboratory. The expanded facilities will have a major impact on the entire BFRL program—both technical and managerial. There is a need for added staff. It will also require considerable managerial resources and a business plan for the operation of the facility over the next several years.

Measurements taking place inside large fires can be technically demanding. Instruments must be extraordinarily rugged to survive large-fire environments. The division was pleased to report its reduction in the uncertainty in the measurement of the rate of heat release from fires in the LFL. This reduced uncertainty increases the quality of the facility and its potential for national use. The BRFL should consider having a biannual workshop among the three leading U.S. large-fire research laboratories (NIST, FM Global, and SNL) dedicated to advancing measurement techniques specific to large fires.

Fire Grants Program

The Fire Grants Program, even though shrunk by a factor of eight in inflation-adjusted terms since the 1980s, has proven to be a vital resource in stimulating research in areas critical to the BFRL's needs and in developing future fire researchers in universities. The grants program, together with workshops and Cooperative Research and Development Agreements, are vital tools for focusing the rest of the nation in important research in fire science and engineering.

ADEQUACY OF INFRASTRUCTURE

The panel did not learn anything suggesting that the facilities in this priority area need improvement. The division is appropriately using ARRA funding for the new buildings. The staff has also devoted much time and effort to improving the general awareness of safety. For this they are to be commended. Even though the technical work reviewed is of high quality, there are significant areas not being addressed—specifically, measurements and modeling of flame heat transfer including thermal radiation.

Important technical staff members have been lost through promotion and retirement. Staff with leadership potential need to be added in these areas.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

The dissemination of the results of this work to the research and customer communities is excellent.

CONCLUSIONS

The panel's overall conclusions are as follows:

- The innovative BFRL Fire Research Division ably serves the national needs and is clearly superior to other research centers worldwide for excellence in fire research serving the national needs. Other fire research centers target different areas of specialization.
- The modeling of the physics and chemistry of fire is the fundamental strength of the division. Maintaining this strength will require adding staff with leadership potential and expertise in the modeling of flame heat transfer within fires.
- The division does an excellent job of interacting with customers, but it does not always take advantage of leading work taking place around the world (China, FM Global, and the Sandia National Laboratories).

RECOMMENDATIONS

The recommendations of the panel based on its assessment of the Strategic Priority Area of Measurement Science for Innovative Fire Protection are as follows:

- The BFRL should add staff with leadership potential and expertise in the modeling of flame heat transfer within fires.

- For the Large Fire Laboratory, additional staff are needed. Considerable managerial resources and a business plan for the operation of the facility over the next several years are also needed. The BRFL should consider holding a biennial workshop among the three leading U.S. large-fire research laboratories (NIST, FM Global, and the Sandia National Laboratories) dedicated to advancing measurement techniques specific to large fires.

7

Overarching Issues

Several areas cut across the five Strategic Priority Areas, impacting all aspects of BFRL's work, as discussed in this chapter.

OFFICE OF APPLIED ECONOMICS' SUPPORT OF AND INTEGRATION WITH LABORATORY INITIATIVES

Staff from the Office of Applied Economics at the BFRL have traditionally worked on projects led by other groups in the laboratory, both to help identify and to rank proposed projects and to facilitate the likelihood of implementing successful outcomes by accounting for human interaction and response to evolving technologies. The promulgation of measures and standards for the use and application of emerging science is only as successful as they are understood and used effectively. Historically, when BFRL activities were organized according to disciplinary unit, this crosscutting responsibility of OAE staff led to an awkward review and reporting process. Now, with the implementation of laboratory-wide strategic goals that are supported by multidisciplinary teams, most units within the BFRL function in this interdisciplinary mode.

A unique feature of the staff in the OAE is that most staff members have multidisciplinary backgrounds and/or experience. Many hold advanced degrees in economics, but with academic or industrial experience in engineering or the physical or natural sciences. Identifying potential staff candidates with these combinations of expertise is difficult because few institutions or universities are organized to facilitate cross-disciplinary activity. However, since the review 2 years ago, the OAE has been successful in filling four vacant positions with well-qualified individuals through extensive informational and recruiting activities. Since the primary assets for OAE's activities are the number and caliber of its staff, supported by adequate computational tools and informational access, this group has sustained a high degree of technical merit, given its recent hires and the ongoing training of existing staff.

Currently, the OAE budget seems adequate to achieve the stated goals, but with additional resources there might be much more that the OAE could do to further BFRL's objectives.

At the highest level, since the ultimate objective of many activities at the BFRL is to establish measures of performance and standards for the evaluation of alternatives that facilitate the economical introduction of evolving technologies, it would be useful to establish criteria for when, why, and how such standards are to be promulgated. Competing considerations include how a new measure and/or standard might speed the commercialization and widespread adoption of a new technology, material, or system versus how the premature adoption of a standard might inhibit further technological innovation. A second consideration is the likelihood that, in the absence of an industry standard, an individual firm might define that standard implicitly with its own unique product in order to monopolize the industry. Thus while the prospect of gaining market power may provide a powerful incentive to innovate, once a single firm is in control, particularly when it has a unique grip on an essential link to other aspects of the industry, additional incremental innovations may be stifled. These are threshold issues that set the context for performing a cost-benefit evaluation of the desirability of developing a new standard.

Since the focus at the BFRL has been on establishing and implementing performance-based (rather than prescriptive) standards, the OAE staff has been particularly valuable in devising methodologies for evaluating the merits of trade-off technologies and/or techniques. Examples abound in methods for selecting least-cost, safe, and environmentally benign building methods and materials as applied to the zero-net-energy-building goal. The staff not only identifies methods for estimating the value of each measure of a desirable outcome, they do so in a conformable manner so that the evaluation of trade-offs is facilitated. The standards prepared by the OAE staff typically are of a decision-making procedure or process that is intended to help potential users make their own evaluations, and state-of-the-art methodologies are typically employed as long as they can be set up in a user-friendly manner.

An added step that should be implemented in the future, now that a number of these evaluation standards have been in place for a number of years, is to compare actual performance and outcomes with those estimated using these methodological evaluation standards. A systematic ex post validation process might reveal differences between the predicted and actual performance of systems and components resulting from both technological deterioration and unanticipated human intervention and performance. Those disparities might then be anticipated and incorporated into the establishment of subsequent standards. One illustration might be the use of “real-options” decision-making processes to augment life-cycle-costing methodologies.

Another area warranting additional attention is in devising measures of construction productivity. The key is the proper identification and measurement of what is wanted as society moves into an age of sustainability. Life-cycle cost per unit area may simply be inadequate unless all other attributes that are valued by users and society can be measured in terms of dollars. As an example: are different measures required for constructing new space as compared to rehabilitating existing space, and is the trade-off between the two evaluated in a way that accounts for the environmental consequences?

If society is to enhance its anticipation of unintended consequences that might arise from the implementation of a particular measure, procedure, or standard, it helps if individuals with diverse training and experience are deployed to work on the goal. Therefore, in order to sustain the desired talent pool of multidisciplinary individuals at the BFRL, it is essential to continue to overcome disciplinary-based institutional barriers to hiring new staff.

CODES AND STANDARDS

In this section the role of the Building and Fire Research Laboratory in the development of codes and standards is described, supplementing coverage in the chapters on the individual priority areas.

1. *Assessment Criterion:* The technical merit of the current laboratory programs relative to current state-of-the-art programs worldwide.

- *Relative Technical Caliber:* The work of the BFRL reviewed during the panel's visit is of the highest technical caliber. It compares very favorably with work being done by others around the world. The search by the BFRL for a codes and standards manager is to be commended. The management of codes and standards activities will coordinate the efforts of the programs in the BFRL. It will also further the implementation in building codes of the measurement science improvements for fire and life safety of the type that evolved from BFRL's involvement in the analysis of the World Trade Center disaster. The WTC effort gained much positive recognition for the BFRL, and having a manager for codes and standards in place will allow the BFRL to continue its leadership role in the development of measurement science that leads to improved codes and standards.
- *Relevance:* The BFRL has the role of identifying needs for new measurement science to help in the later development of standards. Thus the work of the BFRL is by its nature ahead of the adopted codes and standards in the construction industry. This is the proper role for the BFRL to play. By aspiring to create new measurement standards, the BFRL creates "proto-standards," which lead in turn to widely used codes and standards. BFRL staff is well informed of work taking place in other national laboratories, at universities, in private industry, and in other nations. The staff has long-standing and active relationships with other research facilities and organizations around the world.
- *Balance:* Although the BFRL does much of its work in groundbreaking research into new fields, such as sustainable materials and fire research, it also provides input into the development of codes and standards for immediate use. The active participation of the BFRL in the development of new building code requirements based on the experiences gained in the WTC failure analysis have resulted in revisions that are now in place in the International Building Code. The BFRL also maintains active participation with standards development organizations such as the ASTM, the ISO, and the National Fire Protection Association, where laboratory staff serves on committees that develop new standards for use in the construction industry and also leads the measurement science efforts to identify needs for potential upcoming standards. The BFRL balances the short-term development of new standards for use in prescriptive design with the longer-term goal of providing a good basis for the future development of performance-based codes and standards.

2. *Assessment Criterion:* The adequacy of the laboratory budget, facilities, equipment, and human resources, as they affect the quality of the laboratory's technical programs.
   - *Available Tools:* The National Structural Fire Resistance Laboratory that has been designed and on which construction will start in the fall of 2010 will fill an important gap in the fire test facilities at the BFRL. Also coming to the NIST site is a new test house for use in studying methods for achieving net-zero-energy buildings. This facility will allow the BFRL

to measure the performance of various energy conservation technologies and techniques and that of local energy generation technologies. The Net-Zero Energy Residential Test Facility will allow the reconfiguration of many of its component parts to facilitate installation of new technologies and test protocols as they are developed.

- *Critical Mass:* As noted above, the hiring of a new manager of codes and standards will fill an important gap in the organization and staffing of the laboratory. The various groups working at the BFRL have been making contributions to the codes and standards developments discussed above, but this new overall manager will coordinate the efforts of the various groups. The BFRL has adequate funding for the efforts that it has underway and that are planned for the immediate future. It is hoped that the recent level of funding for the laboratory can be maintained or even increased.
- *Agility:* The BFRL has done an excellent job in responding to the increasing demand for measurement science associated with several fields of research directly related to codes and standards development. One of these is sustainable design. The demand for "green" technologies and materials is growing rapidly. There is a great need for assessment techniques and measurements to benchmark the use of various materials and technologies. The BFRL is among the leaders in identifying measurement science needs for these initiatives.

  The BFRL has also responded to the need for a reduction in the use of materials and processes with global-warming potential. The BFRL has been pioneering new efforts to move toward the design, construction, and maintenance of buildings that have a net-zero-energy-use budget. The BFRL is meeting the needs curve for net-zero buildings by helping to create measurement science techniques to close the technology gap that currently prevents the widespread construction of such buildings.

  Further, the BFRL has been doing outstanding work in the field of fire science for fires in the wildland-urban interface. Through partnerships with various fire protection organizations such as NFPA, the National Association of State Fire Marshals, and other laboratories, the BFRL has created test equipment to duplicate burning brands that often spread wildfires in urbanized areas.

3. *Assessment Criterion:* The degree to which laboratory programs in measurement science, standards, and services achieve their stated objectives and desired impact.
   - *Technical Planning:* The implementation of Stage-Gate project planning and review techniques puts in place an ongoing improvement process for project and laboratory management. The stated goal of producing performance-based codes and standards is admirable and proper for the BFRL. This goal is ahead of the capabilities of the construction industry to implement widely at this time, but it is nonetheless the right thing for the BFRL to be doing—leading by example.

- *Dissemination:* The construction industry is very fragmented, with many small component parts. The BFRL does a good job of informing this diverse audience. The participation of the laboratory in the codes and standards development processes exposes other participants in those processes to the work of the BFRL.
- *Impact:* BFRL's participation has historically been very good in standards development. Starting with the World Trade Center review, the BFRL is now moving into the building code development process as well. There is a need for new measurement science at both component and systems levels in construction. Since buildings are typically one-of-a-kind and built on-site, designers need information about the performance of subsystem components as well as ways of determining the performance of complex systems after they are assembled. The BFRL has the means and programs in place to contribute to addressing these needs. The BFRL has a mission to foster the development of new measurement science for new materials and techniques. The BFRL can also improve assessment methodologies for existing materials, as they are doing with research into such widely used materials as Portland cement.
- *Responsiveness:* The BFRL demonstrated great abilities to respond to a new need when it rose to the challenge of the WTC failure analysis. This brought the BFRL into the public eye in a very beneficial way and brought the laboratory into the code development process. The creation of the new post of manager of codes and standards will position the BFRL to have an ongoing impact in both the codes and standards arenas.

COMMENTS ON MANAGEMENT

Management at the BFRL has several levels. The primary level is that for projects, the intermediate level is management of the various divisions, and the top management level is for the laboratory as a whole. A number of the key personnel in management positions at all levels are likely to retire within the next 3 to 5 years. To the extent that certain programs are strongly dependent on the capabilities and leadership of a single individual, it is imperative to develop a plan to identify new managers, either from within the existing laboratory staff or through active outside recruitment. BFRL management should consider developing a formal succession planning program for technical staff in key management areas. Also, leadership training and staff development programs currently in place to develop new technical expertise and technical managers should be continued.

The implementation of Stage-Gate project planning and review techniques put in place an ongoing improvement process for project and laboratory management. The process is still in a state of rollout, and several areas should be considered as next steps. The review team did not see inclusion of clear milestones with specific time frames. The use of the Stage-Gate process to move the programs toward transition would benefit from receiving more precision by project leaders. The impact of results has been good in many cases, but without independent review, some major projects may not achieve their potential impact. Cross-programmatic reviews by nonproject personnel and the development of laboratory-wide review material and templates should be considered.

The Stage-Gate process has also led to increased consistency and cohesion across the BFRL. It has also assisted in the targeting of resources toward a focus on high-impact areas. The staff should continue to manage and prioritize projects using this tool. The staff should also refine the metrics of the tool based on experience with project outcomes and do postmortem analyses of projects to learn from the use of the process.

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Overall Conclusions

The work of the Building and Fire Research Laboratory is of the highest technical quality. It compares very favorably with work being done in similar research institutions around the world, with some exceptions. For example, in the High-Performance Buildings Program it is difficult to attain international leadership through "R&D push" alone, while at the same time meeting the needs of an industry whose innovative capacity is being pulled in a different direction by energy pricing and regulatory policies over which NIST has no control. For that reason, the panel strongly endorses recent efforts to adopt a Stage-Gate process and to lay the foundation for, or help the construction industry prepare for possible implementation of, whole-building performance standards. Both of these efforts will position the BFRL to realign its R&D priorities promptly if emphasis shifts to "demand pull" policies of the types being implemented in Europe and Asia: for example, pricing carbon emissions or taxing energy, or whole-building performance standards aimed at forcing industry to develop technologies that may not be cost-effective at prevailing energy prices.

The BFRL has an excellent record of publishing in peer-reviewed journals and of collaboration with universities nationally and internationally. The outcome of the BFRL research will advance progress toward achieving a renewal of the nation's physical infrastructure; better-quality, faster, safer, and less-costly construction; global competitiveness; and the protection of life and property.

The BFRL has responded effectively to the 2008 assessment panel recommendation that it adopt project management tools such as those used in industry. The implementation of Stage-Gate project planning and review techniques provides an ongoing improvement process for project and laboratory management. The stated goal of producing performance-based codes and standards is admirable and proper for the laboratory. For example, in the Strategic Priority Area on Measurement Science for Disaster-Resilient Structures and Communities, the research staff has, in a relatively short period of time, undertaken a broad range of projects, from the so-called ATC Roadmap, intended to bridge the gap between scientific earthquake analysis and engineering practice, to the assessment of first-generation seismic design methods and the development of efficient nonlinear seismic measurement science tools. With the implementation of laboratory-wide strategic goals that all are supported by multidisciplinary teams, most units within the BFRL now function in this interdisciplinary mode.

Good use of ARRA funding has been made for both upgrading BFRL facilities and investing in the National Structural Fire Resistance Laboratory and the Net-Zero Energy Residential Test Facility. The demands on staff time and resources to commission the NSFRL raise concerns regarding the need to develop a model for the sustained operation of this significant capital investment, involving coordination of in-house and extramural activities, and to develop a protocol for the selection of extramural projects and collaborative activities. Of equal concern is the impact that the planning and maintenance of the mandated Disaster and Failure Events Studies and Data Archiving initiative will have on the professional staff and its ability to continue, in view of the episodic nature of the failure investigations, to discharge ongoing programmatic responsibilities at the BFRL effectively.

The BFRL staff and management have addressed a pressing need to improve safety through upgrading facilities and improving safety management systems.

In the area of staffing, the BFRL is currently able to meet existing needs, but as more senior researchers retire, replacing them may be difficult. Not replacing key staff may lead to deficiencies in core competencies. On the plus side, there are leadership training and staff development programs in place to develop new technical expertise and technical managers. The outreach program to students at universities should be continued so as to recruit young talent and to provide postdoctoral fellowships to handle an increased workload.

The work of the BFRL's professional staff has achieved significant recognition in the building codes and standards community and has been successful in moving research products into standards. The BFRL has done an excellent job in responding to the increasing demand for measurement science associated with several fields of research directly related to codes and standards development. An added step that might be implemented, now that a number of these evaluation standards have been in place for a number of years, is to compare actual performance and outcomes with those estimated using these methodological standards. The creation of the new post of manager of codes and standards will position the BFRL to have an ongoing impact in both the codes and standards arenas. Efforts should continue to focus on implementing performance-based standards and integrating life-cycle concepts into building design and construction practices.

NIST is well positioned to provide technological leadership and the consequent ability to influence a competitive positioning of the United States in the building and fire-safety industries. As described in this report, the BFRL has a broad spectrum of opportunities and potential to expand its scope of inquiry and analysis. These include adding staff with leadership potential in the modeling of flame heat transfer in order to maintain the BFRL traditional leadership in modeling fire; defining an appropriate role for the BFRL at a time when nuclear power is seeing a rebirth; integrating the concepts of life-cycle analysis and sustainability into building performance assessment; and anticipating the kinds of measurement science needed to support the transition to performance-based standards and the Smart Grid as well as the multidimensional nature of building performance (energy, air quality, comfort, and electronic noise).