**AN ASSESSMENT OF SELECTED PROGRAMS AT THE NATIONAL INSTITUTE OF**

**STANDARDS AND TECHNOLOGY ENGINEERING LABORATORY**

**FISCAL YEAR 2020**

Panel on Review of the Engineering Laboratory at the National Institute of Standards and Technology

Committee on NIST Technical Programs Laboratory Assessments Board

Division on Engineering and Physical Sciences

A Consensus Study Report of







### THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

This study was supported by Contract No. SB134117CQ0017 with the National Institute of Standards and Technology. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any agency or organization that provided support for the project.

International Standard Book Number-13: 978-0-309-25755-8 International Standard Book Number-10: 0-309-25755-7 Digital Object Identifier: : https://doi.org/10.17226/26051

Copies of this report are available from Laboratory Assessments Board

National Academies of Sciences, Engineering, and Medicine

500 Fifth Street, NW #928

Washington, DC 20001

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; [http://www.nap.edu.](http://www.nap.edu/)

Copyright 2021 by the National Academy of Sciences. All rights reserved. Printed in the United States of America

Suggested Citation: National Academies of Sciences, Engineering, and Medicine. 2021. *An Assessment of Selected Programs at the National Institute of Standards and Technology Engineering Laboratory: Fiscal Year 2020*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26051.

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. John

L. Anderson is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at

### [www.national-academies.org.](http://www.national-academies.org/)

**Reports** document the evidence-based consensus of an authoring committee of experts. Reports typically include findings, conclusions, and recommendations based on information gathered by the committee and committee deliberations. Reports are peer reviewed and are approved by the National Academies of Sciences, Engineering, and Medicine.

**Proceedings** chronicle the presentations and discussions at a workshop, symposium, or other convening event. The statements and opinions contained in proceedings are those of the participants and have not been endorsed by other participants, the planning committee, or the National Academies of Sciences, Engineering, and Medicine.

For information about other products and activities of the Academies, please visit nationalacademies.org/whatwedo.

### PANEL ON REVIEW OF THE ENGINEERING LABORATORY AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

E. SARAH SLAUGHTER, NAE,1 Built Environment Coalition, *Chair*

MARK G. ADAMIAK, NAE, Adamiak Consulting, LLC WILLIAM BAHNFLETH, Pennsylvania State University WILLIAM F. BAKER, NAE, Skidmore, Owings and Merrill, LLP CRAIG L. BEYLER, Hughes Associates and Jensen Hughes THOMAS A. BIRKLAND, North Carolina State University MARK E. EBERHART, Colorado School of Mines

GERALD G. FULLER, NAE, Stanford University

RONALD O. HAMBURGER, NAE, Simpson, Gumpertz, and Heger, Inc. JULIA W. P. HSU, University of Texas, Dallas

JAMES E. HUBBARD, JR., NAE, Texas A&M University HOLLY L. JANOWICZ, J.R. Harris and Company

SRINIVAS KATIPAMULA, Pacific Northwest National Laboratory PHILIP T. KREIN, NAE, University of Illinois, Urbana-Champaign JOHN J. LEWANDOWSKI, Case Western Reserve University MAUREEN Y. LICHTVELD, NAM,2 University of Pittsburgh RICHARD G. LITTLE, Rensselaer Polytechnic Institute

BIRGITTE MESSERSCHMIDT COLLINS, National Fire Protection Association THOMAS D. O’ROURKE, NAE, Cornell University

RANDALL W. POSTON, NAE, Pivot Engineers and Purdue University POL D. SPANOS, NAE, Rice University

CHARLES K. WESTBROOK, NAE, Lawrence Livermore National Laboratory THERESA A. WESTON, The Holt Weston Consultancy, LLC

STEVEN R. WINKEL, The Preview Group, Inc.

***Staff***

MARTIN OFFUTT, Senior Program Officer AZEB GETACHEW, Senior Program Assistant EVA LABRE, Administrative Coordinator JAMES MCGEE, Director

1 Member, National Academy of Engineering.

2 Member, National Academy of Medicine.

### COMMITTEE ON NIST TECHNICAL PROGRAMS

ELSA REICHMANIS, NAE,1 Lehigh University, *Chair*

MICHAEL I. BASKES, NAE, Mississippi State University

LEWIS BRANSCOMB, NAS2/NAE/NAM,3 University of California, San Diego MARTIN E. GLICKSMAN, NAE, Florida Institute of Technology

JENNIE S. HWANG, NAE, H-Technologies Group CHRISTOPHER W. MACOSKO, NAE, University of Minnesota

C. KUMAR PATEL, NAS/NAM, Pranalytica, Inc. BHAKTA B. RATH, NAE, Naval Research Laboratory ALICE WHITE, Boston University

***Staff***

MARTIN OFFUTT, Senior Program Officer AZEB GETACHEW, Senior Program Assistant EVA LABRE, Administrative Coordinator JAMES MCGEE, Director

1 Member, National Academy of Engineering.

2 Member, National Academy of Sciences.

3 Member, National Academy of Medicine.

### LABORATORY ASSESSMENTS BOARD

JENNIE S. HWANG, NAE, H-Technologies Group, *Chair*

WESLEY L. HARRIS, NAE, Massachusetts Institute of Technology

W. CARL LINEBERGER, NAS,1 University of Colorado, Boulder

C. KUMAR N. PATE, NAS/NAM, Pranalytica, Inc. DR. ELSA REICHMANIS. NAE, Lehigh University

***Staff***

AZEB GETACHEW, Senior Program Assistant EVA LABRE, Administrative Coordinator JAMES MCGEE, Director

ARUL MOZHI, Senior Program Officer MARTIN OFFUT, Senior Program Officer

1 Member, National Academy of Sciences.

vii

## Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, 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 thank the following individuals for their review of this report:

Joseph P. Colaco, NAE,1 Florida International University, Charles Culp, Texas A&M University,

Reginald DesRoches, NAE, Rice University, Anthony E. Fiorato, NAE, Consultant,

Vivian Loftness, Carnegie Mellon University, Fred Mowrer, University of Maryland,

John E. Vidale, NAS,2 University of Southern California, and Sharon L. Wood, NAE, University of Texas at Austin.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by David W. Johnson, Jr., NAE. He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

1 Member, National Academy of Engineering.

2 Member, National Academy of Sciences.

ix

# Contents

[SUMMARY 1](#_TOC_250001)

1. THE CHARGE TO THE PANEL AND THE ASSESSMENT PROCESS 9
2. COMMUNITY RESILIENCE PROGRAM 11
3. STRUCTURAL PERFORMANCE UNDER MULTI-HAZARDS (SPUMH) PROGRAM 19
4. EARTHQUAKE RISK REDUCTION IN BUILDINGS AND INFRASTRUCTURE

PROGRAM 28

1. ENGINEERED MATERIALS FOR RESILIENT INFRASTRUCTURE PROGRAM 36
2. FIRE RESEARCH PROGRAMS 47
3. NET-ZERO ENERGY, HIGH-PERFORMANCE BUILDINGS PROGRAM 58
4. EMBEDDED INTELLIGENCE IN BUILDINGS PROGRAM 65
5. CROSSCUTTING CONCLUSIONS AND RECOMMENDATIONS 72

[ACRONYMS 77](#_TOC_250000)

xi

## Summary

At the request of the Director of the National Institute of Standards and Technology (NIST), in 2019 the National Academies of Sciences, Engineering, and Medicine formed the Panel on Review of the Engineering Laboratory at the National Institute of Standards and Technology and established the following statement of task for the panel:

The Panel on Review of the Engineering Laboratory at the National Institute of Standards and Technology will assess the scientific and technical work performed by the National Institute of Standards and Technology (NIST) Engineering Laboratory. The panel will review technical reports and technical program descriptions prepared by NIST staff, and will visit the facilities of the NIST laboratory. The visit will include technical presentations by NIST staff, demonstrations of NIST projects, tours of NIST facilities, and discussions with NIST staff. The panel will deliberate findings in a closed session panel meeting and will prepare a report summarizing its assessment findings.

The Director of NIST requested that in 2020 the panel assess the following activities conducted at the Engineering Laboratory (EL), which conducts activities in other areas as well:

* Community Resilience Program (CRP),
* Structural Performance Under Multi-hazards (SPUMH) Program,
* Earthquake Risk Reduction in Buildings and Infrastructure (ERR) Program,
* Engineered Materials for Resilient Infrastructure Program,
* Fire Research Programs,
* Net-Zero Energy, High-Performance Buildings Program, and
* Embedded Intelligence in Buildings (EIB) Program.

The Director of NIST also suggested that the panel consider during its assessment the following

factors:

* 1. The technical merit of the current laboratory program relative to current state-of-the-art programs worldwide;
	2. The portfolio of scientific expertise as it supports the ability of the organization to achieve its stated objectives;
	3. The adequacy of the laboratory budget, facilities, equipment, and human resources, as they affect the quality of the laboratory’s technical programs; and
	4. The effectiveness by which the laboratory disseminates its program outputs.

To accomplish the assessment, the National Academies assembled a panel of 24 volunteers whose expertise matched that of the work performed by the EL staff.1

On September 29 through October 1, 2020, the panel assembled virtually (the COVID-19

1 See the NIST Engineering Laboratory website at http[s://www.nist.go](http://www.nist.gov/el)v/el for information on Engineering Laboratory organization and programs.

pandemic prohibited an in-person meeting) and interacted with NIST staff for a 3-day assessment, during which it received welcoming remarks from the Director of NIST and the EL director, heard overview presentations by EL management and presentations by researchers at the EL, and virtually toured portions of the EL facility, and the panel chair attended an interactive session with the Director of NIST, the NIST associate director for Laboratory Programs, and the EL Laboratory Director. The panel also met in a closed session to deliberate on its findings and to define the contents of this assessment report. This report summarizes the panel’s findings, conclusions, and recommendations.

The choice of projects to be reviewed was made by the EL. The panel applied a largely qualitative approach to the assessment. Given the nonexhaustive nature of the review, the omission in this report of any particular EL project should not be interpreted as a negative reflection on the omitted project.

### GENERAL CONCLUSIONS

The NIST programs reviewed (CRP; SPUMH Program; ERR Program, Engineered Materials for Resilient Infrastructure Program; Fire Research Programs, Net-Zero Energy, High-Performance Buildings Program; and EIB Program) are each collaboratively performed by staff from across EL Divisional Groups. These programs have contributed major advancements in measurement science, standards, and technology over the past decade, which have strongly advanced U.S. competitiveness and innovations.

Current national conditions, including the international COVID-19 pandemic, major wildfires throughout the western United States, a record number of hurricanes in the Atlantic Basin, and numerous other recent high-hazard events have heightened awareness of an urgent need for NIST’s work in these specific areas. For example, the Net Zero Energy, High Performance Buildings Program quickly incorporated the CONTAMX engine in the FaTIMA tool to assist in evaluating risk due to COVID-19 transmission in buildings. The Fire Risk Reduction in Communities Program rapidly developed and disseminated its current fire assessment and prediction models and is actively working with the California Department of Forestry and Fire Protection (CAL FIRE) and other on-the-ground wildland urban interface (WUI) firefighters. Additionally, NIST is the only organization in the United States that has the authority to independently investigate structural failures of built facilities. These contributions and others are of increasingly high value to the United States, both in ensuring health and safety of communities as well as enabling production and commerce.

Several common themes arise across these programs. As the complexity of current extreme conditions increase, explicit collaboration and coordination across these seven NIST programs and the NIST community as a whole, as well as with external organizations, will be critical to achieve significant advancements in the future. Multi-disciplinary and multi-organizational teams can effectively pursue long-term, highly interdependent research roadmaps aligned with NIST’s mission to enhance economic security and improve the quality of life.

While the demands of the nation on these divisions increase, and as NIST’s research agenda expands in response, NIST staff reported that the personnel, equipment, and facilities have not substantially increased over time and that these programs are stretched thin in expertise and resources to meet growing needs. NIST staff also reported that critical equipment and campus infrastructure are now constraining necessary facility and equipment upgrades. Internationally recognized experts within these seven programs possess unique capabilities, but as needs evolve and as staff retire, NIST’s preeminence in these fields may be jeopardized without strategic human resource planning, including recruiting, mentoring, and retaining diverse engineering and technical personnel.

Additionally, emerging technologies (e.g., artificial intelligence, machine learning, and increases in computational capabilities) are likely to impact these programs, and it is important to maintain continuous assessment of the applicability of such technologies to EL programs.

While these seven programs contribute to new standards and codes, new measurement methods and standards, and new computer models and equipment, the effective dissemination and implementation of these important advancements is hindered by a lack of coordinated outreach. Accelerating the co-

development and diffusion of results through employing advanced communications and marketing approaches, particularly targeting end users, could save lives, protect the economy, and improve the quality of life in the United States. Measuring the outcomes of the work by these seven programs, focusing on demonstrated benefits to safety, quality of life, and economic security, could further ensure NIST’s future contributions in these fields through apprising the U.S. public and industry of this critical and important resource.

The necessary outreach and remote collaboration brought on by the pandemic response provides an opportunity to increase the effectiveness of NIST in the eyes of the public by making it possible for more stakeholders to participate in and observe the activities at NIST.

### ACCOMPLISHMENTS, CHALLENGES, AND OPPORTUNITIES

**Technical Merit of the Programs**

The technical merit of the seven programs reviewed by this panel is high, and NIST remains one of the highest-credibility sources for science-based tools for measurements, data, models, protocols, and reference standards nationally and internationally. For example, the Engineered Materials for Resilience Infrastructure Program has developed standard reference materials (SRMs) for concrete that are recognized and utilized worldwide by cement manufacturers and research laboratories. The regulations based on fire performance tests for mattresses developed by the Fire Research Division has reduced the number of deaths caused by flaming ignition of mattresses by close to 80 percent since its implementation.

These programs often use a combination of laboratory tests informed by in-field studies. For example, the CRP is actively learning from investigations performed in the aftermath of the 2017 Hurricane Maria, and the SPUMH Program based its 16 recommendations on the NIST Joplin tornado investigation. The Wildfire-Urban Interface Parcel program in the FRD uses targeted laboratory and field experiments, post-wildfire-urban interface (WUI) fire data collection and analysis, and a range of models, including vegetation and structure fire models, to understand WUI exposures.

Many of the programs collaborate with external organizations to enhance their effectiveness. For example, the CRP supports the Center of Excellence for Risk-Based Community Resilience Planning (CoE), an academic consortium of 14 universities headquartered at Colorado State University. The NIST ERR Program is the lead agency for the National Earthquake Hazards Reduction Program (NEHRP) with the Federal Emergency Management Agency (FEMA), the National Science Foundation, and the U.S. Geological Survey, and often partners with those agencies as well as industry associations to develop and advance related standards and codes.

Increased collaboration within NIST as well as nationally and internationally can further advance the technical merit and contributions of these programs. For example ERR’s partner agency in the NEHRP, FEMA, has moved forward with development of next-generation performance-based design procedures that characterize building performance directly in terms of the probable economic, human, and environmental impacts of building damage, while inherently considering the uncertainties associated with such characterization, and ERR is in a unique position, as lead agency, to advance this methodology.

Many of the pre-eminent earthquake engineers are at universities; some level of involvement with them would seem beneficial.

### Portfolio of Expertise

The programs have competent and qualified scientific and engineering expertise for their missions and program objectives. Members of the programs have been distinguished with awards and distinctions from industry, including the staff member in ERR who was named a Housner Fellow by the

Earthquake Engineering Research Institute (the Housner Fellows Program recognizes young to mid- career professionals with promising capacity for leading efforts to reduce earthquake risk); and the staff member in the CRP who was awarded the American Society of Civil Engineers Earnest E. Howard Award (the Howard Award is made annually to a member of the ASCE who has made a definite contribution to the advancement of structural engineering). The SPUMH group members have received 12 external awards, including a Gears of Government award for development and enhancement of the national wind design maps; Precast/Prestressed Concrete Institute’s (PCI’s) George Nasser award for work in developing robust precast concrete connections (this award is for a paper published by PCI by authors 40 years of age or younger); the American Concrete Institute’s (ACI’s) Arthur J. Boase award for work in assessing the effects of alkali-silica reaction (the award recognizes personal contributions to the concrete industry); and the National Storm Shelter Association’s Kiesling award, which recognizes individuals for outstanding service and contribution to the storm shelter industry through effective initiative and leadership.

Emerging research areas, however, may increase the need to add new or different areas of expertise. For example, some programs may need strengthening in experience in performance of large and complex physical tests. In addition, the programs will need to continually assess the portfolio of expertise with respect to critical program areas as personnel retire or move on to other organizations. NIST EL may access some of these specific areas of expertise through enhanced collaboration with other organizations, and may consider adding in-house staff to ensure core or strategic expertise.

### Adequacy of Resources

Many of these programs operate state-of-the-art laboratory facilities that provide unique capabilities to accomplish NIST’s missions and objectives. The National Fire Research Laboratory (NFRL) is strongly complemented by the development of the Burn Observation Bubble (BOB), which is a simple and creative implementation of commercially available gear to provide immersive visualization of severe fire environments that are otherwise unavailable. The unique Net Zero Energy Residential Test Facility (NZERTF) offers tremendous opportunities for a multitude of high-performance building studies, including equipment testing, energy efficiency, intelligent controls, monitoring, and indoor air quality (IAQ).

Recently updated and upgraded testing laboratories, such as the Performance-based Engineering Research for Multi-hazards (PERFORM) structural laboratory enhance the ability to perform testing in- house. Additional facilities (and related infrastructure) may need investment to enable the programs to achieve their key objectives. It remains important, however, that these programs maintain active and ongoing relationships with other major national and international laboratories and researchers to ensure access to special expertise or facilities.

In several areas, EL staff reported current and pending shortages in staff expertise. This represents an opportunity for EL to strategically plan its research and staff succession needs, considering research areas both likely to expand and diminish in importance as well as ways to leverage expertise through collaborations. Given financial constraints, it may not be possible to increase staffing levels within the EL. If growth is not possible, and new expertise is needed, then strategic planning will be needed to determine which programs should have a net reduction in staff. If a large number of staff are near retirement age, this is a good time for NIST to do a strategic plan to determine what the critical research areas should be for the future. It may not be necessary to replace all the expertise that will be lost with the retirements, especially if there will be need to increase the staff in new areas. Additionally, it is important to consider the role of collaborations with other organizations.

The programs have challenges related to their relatively small staff sizes, particularly in light of emerging diverse demands. In particular, the programs that are responsible for administering large-scale field investigations, such as the WUI Data Collection in the FRD and the NEHRP by the ERR, are dually responsible for both core research as well as forensic analyses. However, forensic investigations provide a

particular challenge in planning because the staff skills and level of effort are largely unpredictable. Direct funding of field investigations could put the investigation and research into better balance and would foster complementarity between the efforts.

### Effectiveness of Dissemination of Outputs

Products such as software tools and models are available to the public and effectively supported by the NIST team. BACnet, in the EIB program, is a dissemination highlight, with wide adoption in industry and substantial impact. CONTAM, in the NZE program, is one of the most widely used multizone modeling tools for the study of air and contaminant flows in buildings. In addition, NIST has developed four software programs (BEES, BIRDS, BIRDS NEST, and E3) for use in valuation of economic performance (life-cycle cost) and environmental performance (life-cycle assessment).

Broader adoption of NIST outputs could have a significant impact on achieving NIST’s mission and objectives—and help save lives. For example, given the massive installed base of existing buildings, the dissemination of critical outcomes, best practices for building systems—for guidance about preventative maintenance and for other information—is critical to the success of these programs and for the greatest impact.

There is no group or organization in the United States other than NIST that has the authority to independently investigate structural failures. The lessons learned from such investigations would represent important feedback to researchers and designers. It is not clear that the Structures Group is taking full advantage of its position.

### CROSSCUTTING CONCLUSIONS AND RECOMMENDATIONS

The report’s chapters present detailed conclusions and recommendations for each program reviewed. This section presents conclusions and recommendations that apply to two or more of the programs reviewed—first, in general, and second, by the factors considered by this panel (i.e., technical merit of the programs; portfolio of expertise; adequacy of budget, facilities, equipment, and human resources; and effectiveness of dissemination of program outputs).

### Technical Merit of the Programs

NIST EL has a long and distinguished record of technological leadership, innovation, and experience in providing analysis and solutions to large and small problems. EL research quality is exemplified by the programs’ science-based tools and outputs. The EL programs show an evolution over the past few years, which indicates a positive attitude toward adaptation to evolving needs. However, in response to these evolving needs, outside collaborations should be sought if expertise does not exist within NIST. In addition, insularity may at times be a risk.

### RECOMMENDATION: The Engineering Laboratory should establish formal procedures to ensure interaction with practicing professionals and researchers at other institutions, including federal agencies and universities, to ensure that the program does not become overly insular.

The NIST EL programs demonstrate global leadership in measurement science and its application. While successful outcomes from the individual projects advance the mission and vision of the EL, strategic thinking and planning to support long-term efforts is critical and essential.

### RECOMMENDATION: The Engineering Laboratory should articulate and plan more activities around a long-term strategic research plan, developed with input from independent outside advisory panels.

There are frequently good communications with technical peers and standards groups. At the same time, EL staff did not present a clear consensus understanding of the EL’s policy on the importance of publications of varying types (e.g., peer-reviewed, technical notes, training documents, and conference proceedings) relative to other critical activities. Since NIST is not an academic institution and needs to balance publications, standards support, reference materials, and research, its productivity cannot be measured by publications alone. However, where publications are encouraged, it should be made clear to the researchers whether they are measured by the number of publications or the number of citations from their publications.

### RECOMMENDATION: The Engineering Laboratory should communicate to staff clear goals for the rate of annual publications of various types.

**Portfolio of Expertise**

The high quality of the EL portfolio of expertise is evident in its impact on national and international codes and standards and its strong industry reputation. As programs evolve and new programs are introduced, additional areas of expertise will be needed to enable significant EL contributions and thought leadership. NIST EL contributions address a full range of issues directed to improved human productivity, safety, and quality of life, and the EL portfolio of expertise could be enriched to explicitly incorporate those competencies. For example, the areas of human behavior and health in residential and community settings do not appear to receive the same attention as other technical aspects of programs.

### RECOMMENDATION: The Engineering Laboratory should assess gaps in its expertise and add new competencies as needed, such as social scientists and medical scientists to the technical staff.

**Adequacy of Resources**

In some areas, the resources of programs seem to be stretched very thin. The prospect of future retirements suggests a challenge for ensuring the longevity of programs.

### RECOMMENDATION: The Engineering Laboratory should ensure longevity of programs through succession planning to ensure areas of expertise are not lost within NIST.

EL resources also have challenges related to the laboratory’s relatively limited size and the expanding diverse demands on its program areas. Because of the imbalance between potential demands and available resources, it is difficult for the EL to have a profound effect on the industry.

### RECOMMENDATION: The budget, human resources, facilities, and equipment resources required for both continuity and growth of the Engineering Laboratory programs should be reviewed, and adequate resources should be provided to ensure they continue to develop.

A diverse staff often yields insights and perspectives that enhance the quality of research.

### RECOMMENDATION: The Engineering Laboratory should assure an appropriate level of diversity of qualified researchers and managers as older members retire and new talent is brought on board.

The EL has long been the industry leader in metrication and standardization materials, equipment, systems, and processes. To maintain this leadership position, the research and testing facilities need to be maintained and upgraded to match the innovation occurring in the industry.

### RECOMMENDATION: The Engineering Laboratory should seek adequate funding of facilities maintenance to ensure that NIST can continue its industry leadership position in measurement and standardization.

**Effectiveness of Dissemination of Outputs**

Greater awareness of the programs’ products outside of NIST and its immediate stakeholders would significantly benefit the recognition of the value of the products and the awareness of the important role NIST can play nationally and globally. Working more directly with stakeholders and end users would provide valuable feedback to NIST’s efforts, which can be used iteratively to improve NIST EL outputs and products.

The lack of a clear Internet communications strategy for NIST programs is a serious one that needs to be addressed. This includes information about the programs, their roles, the impact they have had and intend to have, and opportunities for industry and academia to engage the programs. There is also a need for a strategy for using social media.

In light of the value of reaching out to external communities of researchers, designers, and localities, it is important that the EL continually assess the opportunities for external collaboration. Such assessment would mitigate against duplication of effort, identify and enlist individuals and organizations possessing expertise and/or facilities not resident at NIST, and assist in strategic planning to address in- house staffing concerns.

### RECOMMENDATION: The Engineering Laboratory should develop and actively promote a Stakeholder Engagement and Dissemination Strategic Plan that makes use of a broad range of traditional and emergent media to report and interpret results and solicit user input.

**RECOMMENDATION: The Engineering Laboratory should consider establishing a primary point of contact for outreach and dissemination to its diverse stakeholders, including companies, professional organizations, communities, regional and state agencies, and universities and community colleges.**

### RECOMMENDATION: The Engineering Laboratory should consider an enterprise evaluation system that would promote a holistic approach toward product development, implementation, and user feedback and would promote community engagement early and throughout the process of design through dissemination.

**RECOMMENDATION: The Engineering Laboratory should consider developing programs and tools that are user-driven, not developer-driven.**

### RECOMMENDATION: The Engineering Laboratory should develop stronger relationships with diverse portions of industry, such as design firms, utilities, manufacturing firms, facility owners, local governments, and other agencies to help ensure

**that its products are responding to the needs and cultures of different types of organizations.**

### RECOMMENDATION: The Engineering Laboratory should distribute its products directly to actual and potential users, and the outcomes of these dissemination efforts should be evaluated.

**RECOMMENDATION: The Engineering Laboratory should increase its development of partnerships with international organizations.**

Dissemination of critical outcomes and best practices for building systems—for guidance about preventative maintenance and for other information—is critical to the success of the program and for greater impact. Given the massive installed base of residential buildings, homeowners and other occupants can play a critical role in intelligent building operation.

This is best done in coordination with other federal agencies (e.g., the Department of Energy and the Environmental Protection Agency are active in this area also). Without coordination, the end result would duplicate work done in different ways.

**RECOMMENDATION: The Engineering Laboratory should work toward broader interface with homeowners and other end users to collect and review requirements, disseminate information from its programs, influence improved user interfaces, and help end users get the best results in building operations.**

## 1

**The Charge to the Panel and the Assessment Process**

At the request of the National Institute of Standards and Technology (NIST), the National Academies of Sciences, Engineering, and Medicine has, since 1959, annually assembled panels of experts from academia, industry, medicine, and other scientific and engineering communities to assess the quality and effectiveness of the NIST measurements and standards laboratories, of which there are now six,1 as well as the adequacy of the laboratories’ resources. 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 scientific and technological advances, and to improve and refine existing measurement methods and services.

At the request of the Acting Director of NIST, in 2017 the National Academies formed the Panel on Review of the Engineering Laboratory at the National Institute of Standards and Technology and established the following statement of task for the panel:

The Panel on Review of the Engineering Laboratory at the National Institute of Standards and Technology will assess the scientific and technical work performed by the National Institute of Standards and Technology (NIST) Engineering Laboratory. The panel will review technical reports and technical program descriptions prepared by NIST staff, and will visit the facilities of the NIST laboratory. The visit will include technical presentations by NIST staff, demonstrations of NIST projects, tours of NIST facilities, and discussions with NIST staff. The panel will deliberate findings in a closed session panel meeting and will prepare a report summarizing its assessment findings.

The Director of NIST requested that in 2020 the panel confine its assessment to the following activities conducted at the Engineering Laboratory (EL), which conducts activities in other areas as well:

* Community Resilience Program,
* Structural Performance Under Multi-hazards (SPUMH) Program,
* Earthquake Risk Reduction in Buildings and Infrastructure Program,
* Engineered Materials for Resilient Infrastructure Program,
* Fire Research Programs,
* Net-Zero Energy, High-Performance Buildings Program, and
* Embedded Intelligence in Buildings Program.

1 The six National Institute of Standards and Technology (NIST) laboratories are the Engineering Laboratory, the Physical Measurement Laboratory, the Information Technology Laboratory, the Material Measurement Laboratory, the Communication Technology Laboratory, and the NIST Center for Neutron Research.

The Director of NIST also suggested that the panel consider during its assessment the following

factors:

1. The technical merit of the current laboratory program relative to current state-of-the-art programs worldwide;
2. The portfolio of scientific expertise as it supports the ability of the organization to achieve its stated objectives;
3. The adequacy of the laboratory budget, facilities, equipment, and human resources, as they affect the quality of the laboratory’s technical programs; and
4. The effectiveness by which the laboratory disseminates its program outputs.

To accomplish the assessment, the National Academies assembled a panel of 24 volunteers whose expertise matched that of the work performed by the EL staff.2

On September 29 through October 1, 2020, the panel assembled virtually (the COVID-19 pandemic prohibited an in-person meeting) and interacted with NIST staff for a 3-day assessment, during which it received welcoming remarks from the Director of NIST and the EL director, heard overview presentations by EL management and presentations by researchers at the EL, and virtually toured portions of the EL facility. The panel chair attended an interactive session with the Director of NIST, the NIST Associate Director for Laboratory Programs, and the Director of the Engineering Laboratory. The panel also met in a closed session to deliberate on its findings and to define the contents of this assessment report.

The panel’s approach to the assessment relied on the experience, technical knowledge, and expertise of its members. The panel did not attempt to report an exhaustive assessment of every project reviewed. Rather, the panel’s goal was to identify and report accomplishments and opportunities for further improvement with respect to the following: the technical merit of programs at the EL; the portfolio of scientific expertise within the laboratory; the adequacy of the laboratory’s facilities, equipment, and human resources; and the effectiveness of the laboratory’s dissemination of its outputs. The panel illustrated its conclusions with salient examples of programs and projects that are intended collectively to portray an overall impression of the laboratory, while preserving useful suggestions specific to projects and programs.

To accomplish its mission, the panel reviewed the material provided by the EL prior to, during, and after the review meeting. The choice of projects to be reviewed was made by the EL. The panel applied a largely qualitative approach to the assessment. Given the nonexhaustive nature of the review, the omission in this report of any particular EL project should not be interpreted as a negative reflection on the omitted project.

2 See the NIST Engineering Laboratory website at http[s://www.nist.go](http://www.nist.gov/el)v/el for information on Engineering Laboratory organization and programs.

## 2

**Community Resilience Program**

This review of the Community Resilience Program (CRP) within NIST is based on presentations and other information given to the panel by NIST staff, videos describing elements of the NIST programs, discussions with NIST researchers and management, reference literature, and websites of NIST and other organizations.

The CRP is organizationally located within the Materials and Structural Systems Division (MSSD) at NIST’s Engineering Laboratory (EL). The division develops and promotes the use of science- based tools—measurements, data, models, protocols, and reference standards—to enhance the global competitiveness of U.S. industry through innovations in building materials and construction technology and to enhance the safety, security, and sustainability of the nation’s building and physical infrastructure. The division’s programs are organized to address means of reducing the risk of natural and manmade disasters and enhancing the resilience of buildings, infrastructure, and communities. The MSSD operates four primary programs: Structural Performance Under Multi-hazards, Earthquake Risk Reduction in Buildings and Infrastructure, Engineered Materials for Resilient Infrastructure, and Community Resilience.

The MSSD currently conducts its business in concert with the Disaster Resilience Research Grants Program that solicits and funds competitive research proposals at several academic institutions. The division is actively engaged in assessing the impact of Hurricane Maria on Puerto Rico. The MSSD ascertains the disaster resilience of buildings, infrastructure, and communities in cooperation with the Fire Research Division, most notably with programs on fire risk reduction for communities and buildings.

### TECHNICAL MERIT OF THE PROGRAM

**Accomplishments**

Resilience can be defined as the ability of a community to withstand and recover rapidly from disruptions and to adapt to changing conditions.1 Resilience planning has increased substantially in the past decade in response to increased natural disasters, such as hurricanes, earthquakes, wildfires, tornados, and floods. The CRP was established in 2015 by an interdisciplinary team of engineers and social scientists. The CRP’s product portfolio includes science-based tools to assess resilience and support informed decision-making for communities through guidance documents, computer programs, and disaster and failure studies, with the ultimate goal of reducing the impact of natural hazards and improving recovery. A major product with respect to community engagement is disaster resilience

1 Executive Office of the President, 2011, *Presidential Policy Directive/PPD-8, National Preparedness*. The White House, Washington, DC.

planning guidance, such as the *Community Resilience Planning Guide to Buildings and Infrastructure Systems*, Vol. 1 and 2. 2

The CRP collaborates with the Center for Risk-Based Community Resilience Planning (a Center of Excellence [CoE]), an academic consortium of 14 universities headquartered at Colorado State University. The first 5 years (2015-2020) of the CoE involved the creation of knowledge through the development of a computational modeling environment, referred to as IN-CORE. It also involved the development of data ontology, architecture, and management tools as well as field studies and method validation. In the next 5 years (2020-2025), the CoE will move from knowledge creation to implementation, with an emphasis on making IN-CORE useful and usable to communities. The use of IN- CORE has been illustrated in studies of community resilience to earthquakes, tsunamis, and tornados, as well as hurricanes along the Gulf Coast.

The CRP team is actively learning from investigations performed in the aftermath of the 2017 Hurricane Maria. The hurricane study provides primary data for modeling recovery, integrating infrastructure, business, schools, and hospitals. The Hurricane Maria investigation is used for developing recovery indicators and drawing lessons for community resilience.

### Challenges and Opportunities

The development of computational open-source software will speed the retrieval of data relevant to community planning for resilience. The CRP’s work on resilience indicators will also help communities process the large amounts of data available for physical infrastructure and contribute to decision-making with respect to preparation and recovery from disasters. Relevant information on measuring community resilience is also available from a National Academies of Sciences, Engineering, and Medicine’s publication that articulates six interdependent community capitals.3 The value of the indicators at the community level can be enhanced by collaborating with vulnerable communities living in disaster-prone geographic regions, including the U.S. Gulf Coast (hurricanes and floods) and the West Coast (wildfires, drought), to assure the feasibility of implementing those indicators in a tailored fashion, building on a target community’s assets and needs. For example, CRP has developed a Tracking Community Resilience Database that allows for information to be retrieved at the county level. Such information is valuable and will facilitate the acquisition of information on community infrastructure across the United States. The data, however, are collected at the county level only, making it difficult to support decision-making for smaller units of analyses. Not only do counties differ in size (e.g., Los Angeles versus Tompkins County), but large counties will require greater granularity in policy and planning decisions for the plurality of communities living in such large geographical subdivisions.

The MSDD leads both the CRP and the Program on Earthquake Risk Reduction in Buildings and Infrastructure. The Hurricane Maria investigations are taking place while earthquake investigations are being conducted in Puerto Rico by organizations like the Geotechnical Extreme Events

Reconnaissance (GEER).4 Opportunities exist to coordinate and share data, enabling an integrated impact assessment of both the hurricane and earthquakes on infrastructure and society in Puerto Rico.

2 National Institute of Standards and Technology (NIST), 2016, *Community Resilience Planning Guide for Buildings and Infrastructure Systems*, NIST Special Publication 1190 (Volumes 1 and 2), Gaithersburg, MD.

3 National Academies of Sciences, Engineering, and Medicine, 2019, *Building and Measuring Community Resilience: Actions for Communities and the Gulf Research Program,* Washington, DC: The National Academies Press, https://doi.org/10.17226/25383.

4 Geotechnical Extreme Events Reconnaissance (GEER), 2020, “Geotechnical Reconnaissance of the January 7, 2020 M6.4 Southwest Puerto Rico Earthquake and Associated Seismic Sequence,” [http://www.geerassociation.org.](http://www.geerassociation.org/)

### PORTFOLIO OF EXPERTISE

**Accomplishments**

Scientific expertise in the CRP is vested in an Applied Economics Office, Community Resilience Group, and Disaster and Failure Group. The CRP at NIST works with a multidisciplinary team consisting of engineers (structural, civil, and environmental), social scientists (sociology, psychology, GIS, and environmental), and economists (microeconomics and environmental). As mentioned previously, the CRP supports the CoE, a multidisciplinary team that has benefitted from the participation of more than 100 investigators, including faculty, graduate students, and postdoctoral fellows.

The CRP has competent and qualified scientific and engineering expertise in the areas of its mission and program objectives. The organization’s expertise supports the technical programs and ability to achieve its stated objectives. The lead managers of the CRP at NIST are recognized nationally, and the academic leaders of CoE at Colorado State University have an outstanding national and international reputation. There are many reputable researchers among the universities supported by the CoE.

### Challenges and Opportunities

To maximize the portfolio of CRP products applicable to the most vulnerable communities, there is an opportunity to expand the CRP team beyond the social science expertise. Other human health scientists—especially public health, environmental health, community planners, and disaster management scientists—can play an important role in facilitating the translation of data into reliance action at the community level. Such team members can be attracted intramurally, including scholars, as well as through collaborative efforts with academic institutions.

The lead CRP managers at NIST have been distinguished through the reception of a multitude of awards and distinctions. These awards generally can be divided into internal and external distinctions.

Internal distinctions involve EL Morale Builder, Mentor, and Safety Awards. These internal awards represent formal recognition by the NIST EL of significant contributions to the operation of NIST. The external distinctions include awards such as the ASCE Earnest C. Howard Award, which represents important contributions external to NIST. The EL’s reputation depends on both internal and external excellence but is especially tied to contributions outside NIST. For this reason, it is advantageous to emphasize the external and distinctions, including globally, for CRP scientists as well as emerging scholars and to place special emphasis on professional society peer recognition.

### ADEQUACY OF RESOURCES

**Accomplishments**

The facilities, equipment, and human resources of the CRP are distributed among the Applied Economics Office, Community Resilience Group, and Disaster and Failure Group, as discussed above. These resources support achieving the objectives of community engagement, science-based tools, and disaster and failure studies. To the extent that the CRP makes use of testing and experimental work carried out by other programs such as earthquake and wind engineering and fire research, it will be impacted by the aging of the research infrastructure used by these groups. The CoE computational modeling environment IN-CORE provides additional computational support.

The facilities, equipment, and human resources provide competent and qualified support for the CRP technical programs and CRP’s ability to achieve its stated objectives. The success of these resources is closely linked to the dissemination of outputs, which is discussed in more detail below.

### Challenges and Opportunities

Success of the CRP’s products is ultimately determined by the degree of uptake by targeted users—communities and organizations on the front lines of disasters involved in strengthening resilience. It is essential that computer software, models, and tools developed by CRP be user-based and driven by the needs and capabilities of actual communities.5,6

The CRP is particularly well supported from an engineering and codes and standards perspective.

However, increased community resilience will require the direct participation of community planners, emergency managers, public administrators, public health and health-care professionals, and utility and business leaders. It is not clear whether and how the CRP effectively targets this diverse mix of stakeholders. The input of practicing professionals, in addition to researchers and academicians, is critical to achieving effective outcomes and ensuring the success of the program.

Many of the CRP staff are in the early stages of their careers. However, their efforts are supported by a cadre of highly respected researchers and academicians at NIST and the CoE. Overall mentoring programs exist, but many of the activities carried out by the CRP are relatively new to the NIST culture, so the traditionally deep pool of potential in-house mentors is not readily available. It is unclear whether and how the challenge of an aging workforce is addressed by the selection of emerging scholars. There seems to be a collegial culture at NIST headquarters and between CoE researchers and NIST staff that could assure a rich cadre of mentors. There are few human health, social, and geospatial scholars in the CRP; the degree to which they are integrated into the CRP was not made clear.

### EFFECTIVENESS OF DISSEMINATION OF OUTPUTS

**Accomplishments**

The CRP disseminates its outputs through various mechanisms, including blog posts, interviews, and presentations at NIST; contributions to standards promulgated by ASTM International, the American Society of Civil Engineers, and other bodies; publications; and surveys (principally through the Natural Hazard Engineering Resilience Institute [NEHRI] DesignSafe surveys). Publications include book chapters, conference papers, journal papers, and NIST publications. The number of NIST publications is approximately equal to the number of book chapters, conference papers, and journal papers. The CRP conducted approximately three workshops per year from 2014–2017, including national workshops at Coral Gables, Florida, and Minneapolis, Minnesota. Two international workshops were held, in Dulles, Virginia, and Ispra, Italy, in 2016 and 2017, respectively. The CRP has disseminated planning guides, economic assessments, public alerts, system models, assessment methods, repositories, and tools, such as the NEHRI DesignSafe Household and Building Damage Surveys. The CRP works with several local jurisdictions, such as Boulder, Colorado; Bozeman, Montana; and Charleston, North Carolina. It engages professional organizations and other federal agencies.

The CRP supports the CoE, which in turn provides IN-CORE, the open-source computational environment for resilience analysis and assessments available to researchers. The CoE works with testbeds at Seaside, Oregon; Galveston, Texas; Memphis, Tennessee; and Mobile, Alabama; hindcasts at Joplin, Missouri; and multidisciplinary longitudinal field studies of community recovery at Lumberton, North Carolina. The Lumberton longitudinal study involves riverine flooding from Hurricane Matthew

5 R. Little, T. Manzanares, and W. Wallace, 2015, Factors influencing the selection of decision support systems for emergency management: An empirical analysis of current use and user preferences, *Journal of Contingencies and Crisis Management* 23(4): 266-274.

6 R. Little, R. Loggins, and W. Wallace, 2015, Building the right tool for the job: Value of stakeholder involvement when developing decision-support technologies for emergency management, *Natural Hazards Review* 16(4): 05015001, doi: 10.1061/(ASCE)NH.1527-6996.0000182.

and includes interaction with water and electric utility companies. The CRP has had beneficial direct interaction with a small number local communities (i.e., Nashua, New Hampshire; Cedar Rapids, Iowa; Howard County, Maryland; Fort Collins, Colorado; and the Delaware Department of Transportation).

### Challenges and Opportunities

The Community Resilience Systems ARC (Alternatives for Resilient Communities) Model with the Centerville data set shows great promise as a decision-support and training tool to develop and evaluate community responses to various hazard scenarios, but it is not readily deployable for stand-alone use by practitioners. Simpler tools, directly usable by the practitioner community, may be needed as well. The EDGe$ economic decision guide is a valuable tool developed by the Applied Economics Office to evaluate the costs and benefits of alternative resilience strategies. This tool will become more important as coastal and riverine communities need to address the impacts of sea-level rise and increased flood risk on their resilience options. The Applied Economics Office recently published NIST Special Publication 1258, *Complex Event Resilience of Small- and Medium-Sized Enterprises: Natural Disaster Planning During the COVID-19 Pandemic*.7 This is a timely focus on the impacts of a pandemic on community resilience. The CRP could be a valuable source of content to support the development of courses and training modules for professional certification and postsecondary (associates, bachelors, and masters) educational programs in community resilience and disaster preparedness and response.

If an institution is to become an agent of change, it is important to change agencies. These agencies include federal institutions, such as NIST, but also lifeline agencies, including water supply, electrical power, transportation, telecommunications, gas and liquid fuel, and wastewater operators, which provide for the front-line defense and recovery from natural disasters.8 Stronger relationships between the CRP and these utilities could help ensure that its products are responding to the needs and cultures of these types of organizations.

The CRP is engaged in investigations in Puerto Rico in the aftermath of Hurricane Maria. The devastation associated with this hurricane provides an excellent opportunity to learn how the damage to the electric power system influenced local businesses, communities, and the Puerto Rican economy. The study of Hurricane Maria as well as longitudinal studies like the one in Lumberton, North Carolina, provide the ability to partner with utilities, especially electric power utilities, which are so important for emergency response and recovery from disasters.9

The CRP is focused on resilient infrastructure and therefore could benefit from international work on hazards and infrastructure. International centers are an excellent source of collaboration. The United Kingdom Collaboratorium for Research in Infrastructure and Cities (UKCRIC)10 was established with an approximate $180 million capital investment from the UK government that includes funding for 12 infrastructure laboratories, six urban observatories, and the Data and Analytics Facility for National Infrastructure. Its goal is to enable the collaborative multidisciplinary research necessary to underpin the renewal, sustainment, and improvement of infrastructure and cities in the United Kingdom and elsewhere. UKCRIC is a natural collaborator for CRP and offers the opportunity to develop an international partnership that leverages the investments made in both organizations.

7 NIST, 2020, *Complex Event Resilience of Small- and Medium-Sized Enterprises: Natural Disaster Planning During the COVID-19 Pandemic*, NIST Special Publication 1258, Applied Economics Office, Gaithersburg, MD. 8 NIST, 2016, *Critical Assessment of Lifeline System Performance: Understanding Societal Needs in Disaster*

*Recovery*, NIST GCR 16-917-39, prepared by the Applied Technology Council, Gaithersburg, MD.

9 T.D. O’Rourke, A.J. Lembo, and L.K. Nozick, 2003, “Lessons Learned from the World Trade Center Disaster about Critical Utility Systems,” pp. 269-292 in *Beyond September 11th: An Account of Post Disaster Research*, Natural Hazards Research and Applications Information Center, Boulder, CO, April.

10 See the United Kingdom Collaboratorium for Research in Infrastructure & Cities home page at http[s://www.uk](http://www.ukcric.com/)c[ric.co](http://www.ukcric.com/)m.

There are several ongoing activities that could be part of a comprehensive dissemination strategy (e.g., the “Taking Measure” blog), but the CRP appears to underemphasize these activities relative to the technical achievements that are reported. Much of the output of the CRP is in the form of NIST reports of various types that are quite good but can be somewhat difficult to locate on the NIST website unless one knows specifically what to look for. The output of the CRP overwhelmingly takes a “what to do” focus, but the program is mostly silent on the “how to do it.”

Dissemination of CRP products (output) provides the greatest opportunities for advancement. For example, integrating a benchmark-driven evaluation component can inform the utility of the products for frontline users (outcomes), which in turn can improve the quality and utility of the product. Similarly, an assessment of the impact of CRP products can provide important program direction for new product development.

### CONCLUSIONS AND RECOMMENDATIONS

**Technical Merit of the Programs**

The CRP’s research quality as exemplified by the program’s science-based tools to assess resilience and support informed decision-making are of excellent and of well-recognized quality. The intramural products are augmented by those developed by the CoE.

The CRP has tremendous potential for impacting people directly. The quality of the CRP would be enhanced by better connection with the human health infrastructure and with those who address the impact of disasters on vulnerable health systems and vulnerable populations (e.g., working with local utility companies and land-use planners).

The CRP can enhance its tools and products by modeling the impact of multiple disasters (e.g., hurricanes and earthquakes) encountered by communities simultaneously or within a short period of time. This could be facilitated by CRP and the Earthquake Risk Reduction Program collaborating more deliberately and formally.

### RECOMMENDATION: The Community Resilience Program should enhance its valuable and meritorious work by heightening its focus on factors that directly impact people, including close coordination with related activities being performed by local, national, and global stakeholders in the public, private, and not-for-profit sectors, especially public health entities.

**Portfolio of Expertise**

Scientific expertise in the CRP is evident in the competent and qualified engineering team in the areas of the organization’s mission and program objectives. The lead CRP managers at NIST have been distinguished through a multitude of awards and distinctions that involve internal and external recognition.

Most of the CRP’s research portfolio is focused on the physical aspects of infrastructure such as buildings, pipes, wires, and roads and the engineering-based institutional aspects such as codes and standards. There appears to be far less emphasis on how these elements intersect with the human aspect of infrastructure, namely the people and agencies that deliver the services.

The CRP portfolio is excellent with respect to the team’s expertise in the physical and institutional infrastructure domains. However, gaps in human infrastructure expertise may limit the utility of its products and tools. From a human capital/infrastructure perspective, the effectiveness of the scholars program would be enhanced by strategically connecting with and accepting new scholars in the

disciplines where retirements are anticipated and in disciplines where there are gaps in expertise that hamper the impact of the program’s tools and products.

### RECOMMENDATION: In addition to social scientists, the Engineering Laboratory should consider strengthening its Community Resilience Program workforce in the human health sciences both intramurally and extramurally—for example, through partnerships with schools of public health.

**Adequacy of Facilities, Equipment, and Human Resources**

The facilities, equipment, and human resources of the CRP support the objectives of community engagement, science-based tools, and disaster and failure studies. These resources, including those at the CoE, provide competent and qualified support for CRP’s technical programs and its ability to achieve its stated objectives. Retirement of senior staff is a current challenge. Some investments exist to build a pipeline of scholars.

The facilities, equipment, and human resources of the CRP are competent at present. However, the EL, including the CRP, faces a significant workforce reduction through retirement of senior staff. The pipeline of scholars represents an important strategy to rebuild the EL workforce in general and the CRP specifically.

### Effectiveness of Dissemination of Outputs

The target audience for much of the program carried out at the CoE appears to be other researchers and tool developers. It is not clear how this work directly benefits the practitioners in community planning, emergency management, and other disciplines that will need to implement change. Although implied, the CRP does not specifically call out the need to address resilience measures through the lens of particularly vulnerable populations such as the poor, elderly, and medically compromised, who suffer disproportionally during hazard events. In the same vein, the impacts of extreme events on health- care delivery are not specifically highlighted. It is important for the CRP to articulate to its stakeholders the pros and cons of the tools it develops and clearly articulate the limitations.

Outreach efforts by the CRP do not appear to reach those that may directly benefit from its tools and products. A focus on resilience measures targeting vulnerable populations is limited.

### RECOMMENDATION: The Community Resilience Program (CRP) should develop and actively promote a stakeholder engagement and dissemination strategic plan that makes use of a broad range of traditional and emergent media to report and interpret results and solicit user input. The CRP should consider establishing an information flow whereby activities of testing, analysis, failure studies, and computer modeling yield program outputs that include tools and techniques, education and training, design and building codes, and conferences and publications.

**RECOMMENDATION: The Community Resilience Program (CRP) should consider establishing a primary point of contact for outreach and dissemination to professional organizations, communities, regional and state agencies, and universities and community colleges. This effort should also include developing stronger relationships with several utilities to help ensure that products of the CRP are responding to the needs and cultures of such organizations. In addition, the Engineering Laboratory should analyze the current components of the Disaster Resilience Grants Program with an eye toward identifying how**

### the program could include support for state and local demonstration projects that utilize CRP products.

The CRP would be improved by a sharper focus on user needs. The development of computational open-source software will accelerate the retrieval of data relevant to community planning for resilience. It will also challenge CRP to develop programs and tools that address the practical needs of communities of all sizes and to demonstrate clearly that these needs are being met. The effective investment of the CRP resources is measured by the degree to which the resulting products are used by communities and organizations to strengthen their resilience. A major challenge and opportunity for the CRP is to develop programs and tools that are user-driven, not developer-driven. The Community Resilience Program, by its title, creates expectations that the end users are communities—especially vulnerable populations living in disaster-prone areas. Since the mission of NIST is also to improve quality of life, the current products are of high quality, but the products do not seem to reach end users directly.

### RECOMMENDATION: Programs and tools developed by the Community Resilience Program should be user-driven, not developer-driven; address a demonstrated community need; and be guided by a multi-disciplinary user advisory group. This should include a benchmark-driven enterprise evaluation system that promotes a holistic approach to product development, implementation, and user feedback and promotes community engagement early and throughout the process of design through dissemination.

Greater awareness of CRP’s products outside of NIST and its immediate stakeholders would significantly benefit the recognition of the value of the products and the awareness of the important role the CRP can play nationally and globally. Working more directly with stakeholders and end users would provide valuable feedback that can be used iteratively to improve CRP’s products.

Expanding dissemination of the community resilience products beyond the current channels (federal agencies and engineering academic partners) to state and local agencies, especially health departments, local decision makers, and community organizations, could greatly increase the impact of the CRP at minimal cost and effort.

## 3

**Structural Performance Under Multi-Hazards (SPUMH) Program**

The Structural Performance Under Multi-hazards (SPUMH) Program has an overall objective of addressing the gap between basic research and building codes, standards, and practice through measurement science research. It has a multi-phased mission to (1) predict structural performance up to failure under extreme loading conditions; (2) assess and evaluate in situ structural capacity using novel, smart sensing metrology and the ability of existing structures to withstand extreme loads; (3) design new buildings and retrofit existing buildings using cost-effective, performance-based methods; and (4) derive lessons learned from disasters and failures involving structures. The SPUMH Program accomplishes this with a staff of 13 with expertise in structural engineering, wind engineering, mechanical engineering, sociology, and geoscience, with assistance from five associates. Base funding is $4.15 million per year. Recent projects within the program include improvement in the nation’s wind design standards, development of design provisions for tornado-resistant design, research into the effects of alkali-silica reaction (ASR) in existing concrete structures, and development of performance-based fire protective design for structures.

All but two of the 13 staff hold Ph.D.’s, and these two are currently undergraduate students in civil engineering. Post-doctoral experience ranges from 1 year to more than 50 years. The program staff’s median experience level is 27 years, and the average is 25 years. Of the program’s 13 researchers, 2 are females. Collectively, the program staff has published more than 35 invited and/or refereed papers on their areas of research. Staff members have received 12 external awards, including a Gears of Government award for development and enhancement of the national wind design maps, *PCI Journal*’s George D. Nasser Award for work in developing robust precast concrete connections, the American Concrete Institute’s Arthur J. Boase award for work in assessing the effects of ASR, and the National Storm Shelter Association’s Keisling award.

The SPUMH Program consists of the following three research thrusts: (1) develop validated tools that predict structural performance to failure under extreme loading conditions; (2) develop validated tools to assess and evaluate the capabilities of existing structures to withstand extreme loads; and (3) develop performance-based guidelines for cost-effective design of new buildings and, where warranted, rehabilitation of existing buildings. The research thrusts have motivated a wide range of projects, including the investigation of the Joplin Missouri Tornado and Hurricane Maria; improvement in the nation’s wind design standards and practices; development of design provisions for tornado resistance; development of computational wind engineering procedures for using computational fluid dynamics; research into the effects of ASR in existing concrete structures; development of a life-cycle condition assessment platform; and continued work on developing robust, collapse-resistant structures, following on the World Trade Center investigations performed in the past. Collaboration with the EL fire science researchers would yield information on the effects of fire on structural performance.

The Structures Group’s research includes analytical and experimental studies performed with both intramural and extramural resources. Applied research associates support the group’s work in developing wind and tornado hazard maps. Together with the Earthquake Engineering Group, the Structures Group has recently commissioned the Performance-based Engineering Research for Multi- hazards (PERFORM) Laboratory. The PERFORM Structural Testbed will enable large-scale testing to

assess structural performance under extreme winds, disproportionate collapse, earthquakes, and material degradation.

### TECHNICAL MERIT OF THE PROGRAM

**Wind Hazards**

### Accomplishments

NIST has long led the nation’s research into wind hazards and design of structures for wind resistance. In recent years, NIST has performed a series of wind hazard studies that have resulted in updated wind hazard maps adopted by the building codes and nation’s standards. The staff’s national wind hazard study conducted in 2014-2015 resulted in adoption by the American Society of Civil Engineers (ASCE) standard ASCE-7-16 of a new set of wind design maps with substantially reduced design wind loads throughout much of the western United States, enabling development of buildings and structures at lower cost while maintaining desired protection again wind losses. More recent work will enable adoption by the ASCE 7-22 standard of long-return period maps, useful in performance-based wind design, as well as new maps for Puerto Rico and the U.S. Virgin Islands that represent substantially improved fidelity over prior maps.

The program staff’s study of the wind boundary layer’s variation with storm size has led to a proposal to modify the ASCE 7-22 study to include more accurate representation of wind-speed variation with elevation above ground. When adopted, this will result in the design of buildings for improved wind resistance reliability.

Recent research has focused on the development of computational wind engineering (CWE) procedures for using computational fluid dynamics (CFD) and the development of data-assisted design (DAD) tools. The staff has collaborated with Iowa State University and the engineering firm Walter P. Moore to import these procedures into ETABs, a popular structural-analysis software platform.

### Challenges and Opportunities

With the adoption of a pre-standard for performance-based design of structures for wind resistance, the structural engineering profession is increasingly in need of tools to facilitate designs of this type. The staff’s efforts in CWE and DAD design holds promise to provide these needed tools. NIST has the opportunity to provide the technical guidance that the industry needs to avoid misapplications of this emerging technology that could lead to unfortunate results. The incorporation of DAD into ETABs has the potential to revolutionize wind design procedures. However, ETABs is just one of several proprietary software products used by industry. The selective teaming with one software vendor can be limiting to the broad adoption of this capability.

While CFD has promise as an important tool to permit building-specific assessment of wind effects, there is current widespread skepticism in the design community as to its validity. Unless addressed, this may inhibit the adoption of this technique in design practice.

### Implementation of Joplin Tornado Recommendations: Moving Beyond Tornado Hazard Maps

NIST completed its investigation of the 2011 Joplin tornado and issued a final report in 20141. The report detailed 47 findings and 16 recommendations for improving the characterization of tornado hazards; the design, construction, and maintenance of buildings and shelters in tornado-prone regions; and emergency communications that alert and warn of imminent threat from tornadoes. The project’s objective is to implement all 16 recommendations from the NIST Joplin tornado investigation, at the earliest possible date, based on code and standard development cycles.

### Accomplishments

Tornado hazards are not currently considered in the design of buildings, except for safety-related structures in nuclear power plants, storm shelters, and safe rooms. The inclusion of design criteria for tornados in building codes and design practice will be a significant accomplishment. The project has made progress on several of the recommendations provided during the first phase of the Joplin Implementation Project (completed in fiscal year 2019). Research and development for the tornado maps methodology, along with associated design provisions, has been completed, and submittals have been made to the ASCE-7 Wind Load Subcommittee and Main Committee for adoption into the 2022 edition of the standard.

### Challenges and Opportunities

On the basis of feedback received from the ASCE 7 standards committee, the tornado hazard maps and design provisions were developed to target the same level of structural reliability provided by the building code for wind resistance. Because the probability that a building will actually be subjected to a tornado is very small, the protection is against only moderate tornado events (EF-I or II), even for important structures with large footprints. While the new requirements introduced by NIST into the standards will reduce tornado-induced losses, they will not prevent disasters of the scale of the Joplin event. Further work will be needed to enhance and improve the tornado design provisions so that they will have more substantive effect and benefit.

### Alkali-Silica Reaction Research

The Alkali-Silica Reaction research program is funded by the U.S. Nuclear Regulatory Commission. The study’s objective is to develop the technical basis for evaluating effects of ASR on structural performance. This includes various experimental evaluations aimed at quantifying the effects of ASR on the following parameters: concrete mechanical properties; bond, anchorage, and flexural capacities; and seismic performance of concrete structural members.

1 The report is available at http[s://www.nist.gov/publications/final-re](http://www.nist.gov/publications/final-report-national-institute-standards-and-)po[rt-national-institut](http://www.nist.gov/publications/final-report-national-institute-standards-and-)e[-standards-and-](http://www.nist.gov/publications/final-report-national-institute-standards-and-) technology-nist-technical-investigation

### Accomplishments

This is an ongoing research area. Work accomplished to date includes completion of NIST technical notes—on assessing concrete mechanical properties2 and bond/anchorage of reinforcement in ASR affected concrete.3 Physical testing is under way to assess seismic performance of concrete structural members. This includes the development of a methodology for assessing the degradation of seismic resistance of concrete walls affected by ASR.

### Challenges and Opportunities

This is a topical and important research area that can greatly influence the evaluation of many types of structures, including commercial, industrial, and transportation structures. Although the effects of ASR have been known for a number of years, the discovery of ASR in commercial and state infrastructure has resulted in recent heightened media attention to this issue in some regions of the country. This presents an opportunity for NIST to expand the scope of investigation and recommendations on ASR beyond the nuclear industry to address these recent discoveries.

### Robust Structural Systems for Multi-Hazard Mitigation

The Robust Structural Systems for Multi-Hazard Mitigation program’s objective is to develop performance-based design methodologies for structural systems to achieve robustness against multiple hazards. The program has focused on robustness against disproportionate collapse, following the work performed on the World Trade Center investigations, and has been recently extended to focus on performance-based design for extreme winds. The project approach is categorized into the following three components: evaluation of structural robustness based on experimental validation; enhancement of structural robustness through the development of improved structural connections; and technology transfer through the development of guidelines, standard provisions, and acceptance criteria.

### Accomplishments

This is a developing research area that builds on the disproportionate-collapse work performed in the early 2000s related to the World Trade Center and Pentagon investigations. Research focused on robustness evaluation of concrete structures has resulted in several journal publications. NIST has coordinated with the Precast/Prestressed Concrete Institute (PCI) to develop improved precast beam- column connection concepts for future full-scale testing. NIST has also collaborated with the American Institute of Steel Construction (AISC) to develop improved steel gravity-frame connections that have been evaluated and designed based on computational modeling and component testing and will be demonstrated using full-scale testing. The program has made considerable contributions to future standards and guidelines, including the ASCE/SEI Disproportionate Collapse Mitigation Standard, ASCE/SEI Alternative Load Path Analysis Guidelines for Buildings and Other Structure, and the SSRC Guide to Stability Design Criteria for Metal Structures (7th edition).

2 National Institute of Standards and Technology (NIST), 2021, “Structural Performance of Nuclear Power Plant Concrete Structures Affected by Alkali-Silica Reaction (ASR) Task 1: Assessing In-Situ Mechanical Properties of ASR-Affected Concrete,” NIST TN 2121, Gaithersburg, MD.

3 NIST, 2021, “Structural Performance of Nuclear Power Plant Concrete Structures Affected by Alkali-Silica Reaction (ASR) Task 2: Assessing Bond and Anchorage of Reinforcing Bars in ASR-Affected Concrete,” NIST TN 2127, Gaithersburg, MD.

### Challenges and Opportunities

This research program provides the opportunity for NIST to directly impact the design profession by providing structural connection and system solutions that enhance structural robustness and limit disproportionate collapse. This requires NIST to evaluate design solutions that not only meet various performance objectives, but also provide an economic and efficient design solution compared with current construction practices. Collaboration with other agencies (e.g., AISCand PCI) and design firms will be instrumental in accomplishing this goal.

A program goal that has not been accomplished is to encourage adoption by the building codes, or design criteria that would require minimum standards of robustness for all structures. NIST put substantial effort into accomplishing this goal in the period 2003-2006; however, the building industries and the building code development organizations were resistant to inclusion of such requirements. NIST has been working with the ASCE to develop a standard for design for structural robustness. This standard is now nearing completion. However, it is not clear whether the building codes will require use of this standard when it is available. Unless the building codes require use of these criteria, the effectiveness of this program will be limited.

### PORTFOLIO OF SCIENTIFIC EXPERTISE

**Accomplishments**

The Materials and Structural Systems Division’s (MSSD’s) Structures Group has two primary areas of expertise: wind engineering and structural engineering.

The wind engineering personnel have deep expertise and experience in the engineering application of the science of wind. They have demonstrated through their successes that they have key roles in the development of the nation’s codes and standards related to wind and are highly regarded by the industry.

The structural engineering personnel address a broad range of topics that are generally associated with structural collapse issues. They have developed deep experience in studying structural failures, such as those associated with the destruction of the World Trade Center. They have demonstrated that they can address problems as diverse as ASR effects on the safety of nuclear facilities and the role of connections in preventing the collapse of steel or precast structures.

### Challenges and Opportunities

Much of the program staff’s expertise lies in individuals who are approaching or beyond typical retirement age. As these individuals inevitably do retire, the program will lose substantive expertise.

The wind engineering personnel comprise approximately half of the Structures Group and have been extremely important and effective in the development and refinement of national wind standards. This success is highly associated with the effectiveness of individuals in the Wind Engineering Group. As with any small group, the loss of key individuals through retirement or other circumstances can have major effects. The Wind Engineering Group does have mid-career individuals who will have the responsibility of maintaining the group’s influence over the long term. They need to continue to develop and refine a long-term succession/talent plan.

The Structures Group also has challenges related to its small size and diverse demands. Because of the imbalance between potential demands and human resources, it is difficult to have a profound effect on the industry. A group multiple times the current size would still have limitations. This group has a unique and very important role through the statutory Disaster and Failure Studies Program. Historically,

understanding structural failures have led to advancements in the industry.4 There is no group or organization in the United States other than NIST that has the authority to independently investigate structural failures. It is not clear that the Structures Group is taking full advantage of its position.

### ADEQUACY OF RESOURCES

**Accomplishments**

The MSSD Structures Group has a significantly updated and upgraded structural testing laboratory (PERFORM) that has recently been commissioned. It has a strong floor, modular strong walls, hydraulic actuators, hydraulic distribution system, and other components. It is roughly equivalent to the testing facilities at some U.S. research universities. There are larger structural testing facilities at a few

U.S. universities and at overseas government laboratories and universities. The MSSD has high-quality equipment and can perform dynamic testing in addition to static testing. The facility has done testing related to the ASR study as well as some testing of precast concrete connections.

The Structures Group also has substantial computational resources that allow it to do computational demanding work in simulations for CWE and CFD as well as large and complex finite element modeling of structures and structural components.

### Challenges and Opportunities

The ability to do in-house testing is important, and the testing should be done at the highest industry standards. There may be some testing that would be better done by other structural testing laboratories that have different or better facilities or special expertise. The presence of the PERFORM testbed should not influence the decision as to where to do testing if another laboratory is better equipped or has special expertise. It is also important that MSSD maintain active and ongoing relationships with other major U.S. structural testing laboratories and researchers.

### EFFECTIVENESS OF DISSEMINATION OF OUTPUTS

**Accomplishments**

The Structures Group disseminates its research results through the following four primary means: publication of National Construction Safety Team Reports (NCSTARs) and technical notes; publication of papers and articles in journals and conference proceedings; best practices documents and guidelines, as well as pre-standards in partnership with industry; and working directly with standards development organizations and the model building code development organizations to introduce technical requirements into industry practices.

The group contributed to publication of a large series of NCSTARs associated with studies of the cause of collapse of the New York World Trade Center Buildings during the period 2002-2005. In March 2014, the group published a comprehensive report on the effects of the May 22, 2011, Joplin, Missouri, tornado. An investigation into the effects of Hurricane Maria on Puerto Rico in 2017, which involves several members of the Structures Group, is under way. The reports that have been published are comprehensive and identify the cause of structural failure and potential improvements in design and construction practice to avoid such failures in the future. In essence, these reports lay out a roadmap for improvement of the nation’s standards.

4 H. Petroski, 1994, *Design Paradigms*, Cambridge University Press, Cambridge.

The reports associated with the 2001 attacks on the Pentagon and World Trade Center resulted in recommendations for incorporating structural robustness into building design. NIST made several attempts during the period 2003-2006 to insert structural robustness provisions into the International Building Code; however, the building community did not agree that this was necessary. Instead, a building industry coalition developed alternative, less impactful provisions that were adopted into the building code.

NIST has also worked with the ASCE to develop a best practice guide for design for structural robustness; a standard is being developed through the consensus committee process. It is not clear whether the building codes will require implementation of the standard.

The 2014 Joplin Missouri report recommended development of design and construction requirements to provide protection for buildings against tornados. NIST successfully worked with the International Code Council to develop a standard for design and construction of storm shelters5 that was adopted by the International Building Code. In addition, NIST has developed a set of probabilistic tornado hazard maps for the contiguous United States and introduced requirements for tornado-resistant design for inclusion into the ASCE 7-22 standard that will require design of important structures for resistance of moderate (EF-I and II) tornadoes. The earliest possible adoption of these criteria would be in the 2024 International Building Code.

For many years, the ASCE 7 standards committee has relied heavily on the NIST Structures Group for support in developing and maintaining the wind-resistant design criteria contained in the standard and adopted by the building codes. Both the 2016 and 2022 editions of these standards include major revisions based on the NIST work.

### Challenges and Opportunities

The building industry is most open to major changes in practice following a substantive disaster, such as an earthquake, hurricane, wildlands-urban interface fire, or terror attack, when the public perceives that the performance of the built environment was sadly lacking and demands change. NIST has been effective at investigating deficiencies in the standards and practices associated with such disasters; however, the development of improved practice recommendations takes substantive time, typically measured in years. By the time recommendations that were motivated by the 2001 terror attacks and the Joplin tornado were ready for adoption, the public demand for change had waned, and the industry’s desire to offer construction at a low cost impeded the adoption of the recommendations. However, once requirements are adopted by the building codes and standards, NIST has had good success in making incremental improvements. Efforts to improve the nation’s building practice may be more effective if an iterative approach is used. This includes the rapid introduction of new requirements into the building codes and standards following an event, while the window of opportunity created by a disaster is still open, and refinements made in later years as research points to appropriate science-based criteria.

### CONCLUSIONS AND RECOMMENDATIONS

**Technical Merit of the Program**

The statutory Disaster and Failures Studies Program puts the Structures Group in the unique position of being able to help the nation learn from structural failures. There are numerous structural collapses each year; some are related to major seismic, wind, or other environmental events, and some are isolated events.

5 International Code Council, 2014, “Standard and Commentary: ICC/NSSA Standard for the Design and Construction of Storm Shelters,” ICC-500, Washington DC.

### RECOMMENDATION: The Structures Group should maintain and refine a robust process for identifying and examining the collapses that can potentially lead to important knowledge for the design and maintenance of existing and future structures.

Systems engineering analysis is appropriately applied not only to such factors as loads and materials, but also to the element of human functions and tasks within the design process. Reliability studies properly include consideration of human reliability.

### RECOMMENDATION: In addition to traditional studies of the reliability of loads and materials, the Structures Group should study the issues of human error in design of structures that occur because of these complexities and develop recommendations identified to increase the reliability of design.

The code requirements for design of new structures are extremely complex and require deep knowledge of multiple codes and standards as well as the computer software needed to calculate the forces and design the members and connections.

Presently, the structural design profession faces a significant challenge because of a lack of database compatibility between various commercial structural engineering software programs. This leads to inefficiencies in U.S. design practices. NIST is in a unique position to offer standardized solutions to structural database interoperability.

### RECOMMENDATION: In order to permit broad impact of the linking of wind engineering and design tools with the Database Assisted Design program, the NIST program should consider, beyond the current collaboration with a single software supplier, collaborative development of open-source software.

**RECOMMENDATION: The Structures Group should consider adopting an interoperability initiative potentially using the Database Assisted Design program associated with the design of structures for wind as a prototype.**

### RECOMMENDATION: The Structures Group should evaluate the potential impact that the proposed tornado maps have on projected economic loss and deaths due to tornados, and whether the reliability implied in the hazard maps is considered acceptable.

**RECOMMENDATION: The Structures Group should expand the scope of investigation and recommendations on alkali-silica reaction beyond the nuclear industry.**

### RECOMMENDATION: The Structures Group should expand the program titled “Robust Structural Systems for Multi-Hazard Mitigation” to include seismic applications in addition to extreme wind and disproportionate collapse. The group should also increase collaboration with other agencies and design firms to develop robust design solutions that are economic and efficient.

**RECOMMENDATION: Testing in the Performance-based Engineering Research for Multi-hazards (PERFORM) facility should be periodically peer reviewed by outside researchers to ensure that the Materials and Structural Systems Division is using state-of- the-art protocols and procedures for their testing, data collection, and data analysis.**

### Adequacy of Resources

A diverse staff often yields insights and perspectives that enhance the quality of research.

### RECOMMENDATION: The Structures Group should ensure an appropriate level of diversity of qualified researchers as older members retire and new talent is brought on board.

**Effectiveness of Dissemination of Outputs**

Interaction with organizations responsible for building codes development and implementation, benchmarking, design, and related research yields a two-way advantage—it provides knowledge to NIST researchers, and it enhances NIST’s reputation and influence.

### RECOMMENDATION: The Structures Group should develop industry benchmarks and guidelines for the application of computational wind engineering and computational fluid dynamics as applied to the design of buildings. In addition, the Structures Group should provide education and outreach to the design community to assist in the adoption of these techniques.

**RECOMMENDATION: The Structures Group should continuously outsource some of its physical structural testing to maintain a close connection to other major structural testing laboratories in the United States.**

A function of the Structures Group is to enhance the global competitiveness of U.S. industry through innovations in building materials and construction technology. Construction technology is very topical and drives many decisions related to the design and construction of structures.

**RECOMMENDATION: The Structures Group should expand their focus on construction technology, including research that is aimed to increase construction productivity, economy, and innovation.**

## 4

**Earthquake Risk Reduction in Buildings and Infrastructure Program**

The Earthquake Risk Reduction in Buildings and Infrastructure Program has the following dual mission: (1) to develop and deploy advances in measurement science related to earthquake engineering, including performance-based tools, guidelines, and standards for designing buildings to resist earthquake effects and improve building safety, thus enhancing disaster resilience of buildings, infrastructure, and communities; and (2) to perform the statutory lead agency duties for the National Earthquake Hazards Reduction Program (NEHRP). The Earthquake Risk Reduction program accomplishes this with a staff of seven engineers, one social scientist, and one program manager/analyst. A portion of the time of two engineer’s and all of the program manager/analyst’s time is dedicated to the NEHRP lead agency responsibility. The budget for the Earthquake Engineering Group is $4.15 million per year, with an additional $1 million per year dedicated to the NERHP lead agency role. The program is also jointly budgeted with the National Science Foundation (NSF) to administer $3.1 million in disaster research grants.

All engineers and the social scientist hold Ph.D.’s. Postdoctoral experience ranges from 3 years to more than 30 years. The group’s median experience level is 8.5 years, and the average is 12.5 years. One engineer and the social scientist are female. Collectively, the group has published more than 30 invited and/or refereed papers on their areas of research. One staff member was awarded the Housner Grant by the Earthquake Engineering Research Institute. This award recognizes promising and motivated early- to mid-career professionals with the confidence, skills, and sense of responsibility needed to exercise leadership by developing fellows’ capacity for advocacy and leading efforts to reduce earthquake risk.

Since the mid-1990s, a major thrust of the NEHRP agencies (NIST, the Federal Emergency Management Agency [FEMA], NSF, and the U.S. Geological Survey [USGS]) has been the development and advancement of performance-based seismic design and implementation of this methodology in the improvement of the nation’s building codes and standards, and thereby, the nation’s earthquake resilience. NIST sought public input and guidance on the most important and appropriate research thrusts to support this goal, as published in the ATC-57 report.1 Earthquake research thrusts are drawn from the tasks identified in that report and include improving performance-based seismic evaluation and design procedures and identifying economical and effective earthquake-resistant systems. A final thrust area is as the lead NEHRP agency.

The Earthquake Engineering Group’s research includes analytical and experimental studies performed with both intramural and extramural resources. When initially tasked with the NEHRP lead agency role, the Earthquake Engineering Group relied heavily on external resources through a contract with the NEHRP Consultants Joint Venture and individual universities. Increasingly, the group has been shifting to a mode of self-reliance in which most research is performed using internal resources and capabilities. Together with the Structures and Materials group, the Earthquake Engineering Group has recently commissioned the Performance-based Engineering Research for Multi-hazards (PERFORM) Structural Testbed.

1 Applied Technology Council, 2003, *The Missing Piece: Improving Seismic Design and Construction Practices*, Redwood City, CA.

### TECHNICAL MERIT OF THE PROGRAM

**Improving Performance-Based Seismic Design Procedures**

The earthquake engineering community developed a first-generation performance-based seismic evaluation and design (PBD) methodology in the mid-1990s, under the ATC-332 project. The American Society of Civil Engineers (ASCE) standardized this methodology in its ASCE 41 publication.3 ASCE 41-17 has been adopted by the nation’s building codes and has become the primary means by which civil and structural engineers assess probable building performance in earthquakes and by which engineers design seismic retrofits of buildings to improve their performance. This standard is also used as the basis of seismic design for some new buildings with enhanced performance objectives. As identified in the ATC-57 report, the reliability of this methodology has not been ascertained or verified, calling into question whether the substantial investment currently made in hardening the nation’s building stock for earthquake resistance is either necessary or adequate. Some years ago, NIST undertook an evaluation of selected buildings designed to the then-current building code using the ASCE 41 procedures. Using the ASCE 41 procedures, NIST determined that these code-conforming buildings could not meet the life- safety protection goals of the code. This indicated either that the building code was not adequate to provide building designs capable of meeting its stated goals or that the ASCE 41 procedures were excessively conservative in assessing building performance. Given that the FEMA P-695 study4 characterized and verified the reliability of the code provisions, the inadequacy of the ASCE 41 procedures was apparent.

An important thrust of the Earthquake Engineering Group’s programs since that time has been to improve the PBD procedures. Research tasks undertaken in support of this goal include verification of the collapse reliability of steel frame buildings; collapse performance modeling of non-ductile concrete columns; quantification of material, loading, and modeling uncertainties; and development of improved assessment criteria for performance-based seismic design.

### Accomplishments

Identification of the excessive conservatism inherent in the ASCE 41 performance assessment methodology is a significant and important accomplishment. Supported research has identified potential reductions in this conservatism through use of improved loading protocols in experimental investigations to predict element performance characteristics. Substantial NIST-supported work in this area was published under the ATC-1145 series of documents. Earthquake Engineering Group staff have been instrumental in moving recommendations from these studies into pending updates of the ASCE 41 and related standards developed by materials industry associations.

2 Applied Technology Council, 1997, *NEHRP Guidelines for Seismic Evaluation of Existing Buildings*, Report No. FEMA 273, Federal Emergency Management Agency, Washington, DC.

3 American Society of Civil Engineers, 2017, *Seismic Evaluation and Rehabilitation of Buildings*, ASCE 41-7, Reston, VA.

4 Federal Emergency Management Agency, 2009, *FEMA P695 Recommended Methodology for Quantification of Building System Performance and Response Parameters*, Project ATC-63, Applied Technology Council, Redwood City, CA.

5 Applied Technology Council, 2017, *Recommended Modeling Parameters and Acceptance Criteria for Nonlinear Analysis in Support of Seismic Evaluation, Retrofit and Design*, NIST Report No GCR-17-917-45, National Institute of Standards and Technology, Gaithersburg, MD.

Massive effort is needed to improve the nation’s seismic performance assessment procedures.

The procedures embodied in the ASCE 41 standard are based on more than 40 years of research conducted at universities throughout the United States, Europe, and Asia during the last half of the 20th century. The Earthquake Engineering Group’s studies identify that this research was excessively conservative in characterization of structural performance. Extensive analytical and experimental work is needed to update these studies using more appropriate procedures. To date, NIST has been able to perform such studies on steel moment-resisting frame and nonductile concrete structures. These are only two of more than 20 structural systems represented in the nation’s building inventory. Substantial additional work is needed to fully improve and enhance the PBD procedures embodied in ASCE 41 in their entirety. Successful accomplishment of this work will allow better assessment of the nation’s existing earthquake risk, identification of those buildings that are highest priority for mitigation, and more economical use of available resources to improve the nation’s earthquake resiliency.

While NIST has focused on improvement of present-generation procedures, its partnering NEHRP agency, FEMA, has moved forward with development of next-generation PBD procedures6 that characterize building performance directly in terms of the probable economic, human, and environmental impacts of building damage, while inherently considering the uncertainties associated with such characterization. The Earthquake Engineering Group’s advanced capabilities in structural reliability analysis and characterization of uncertainties, as well as their broad connection with the earthquake community as lead NEHRP agency, places the group in a unique position to advance the development and effectiveness of this methodology.

### Identifying Effective Earthquake-Resistant Systems

Engineers traditionally provided earthquake protection through design of robust systems with substantial strength and stiffness. These robust structural systems are expensive to build or retrofit into existing structures, embody substantial carbon, and deliver substantial seismic forces and displacements to supported nonstructural components, systems, and contents. Development of more elegant structural systems, for both new structures and retrofit of existing structures, will make provision of seismic protection more affordable, more practical to attain, and more sustainable. Research tasks undertaken in support of this goal include the following: developing cost effective relationships between building characteristics and seismic retrofit costs and benefits; earthquake risk reduction in buildings and infrastructure; seismic performance of steel buildings in the central and eastern United States; reliability of fiber-reinforced composite systems in resilient infrastructure; advancing the seismic implementation of high-strength reinforcing bars in concrete walls; seismic assessment of pre-Northridge earthquake weak panel zones and welded column splices; and improving earthquake re-occupancy and functional recovery.

### Accomplishments

This is a developing research area. Work accomplished to date includes development of research plans for specific studies and initiation of a process to solicit proposals for a new extramural Indefinite Delivery Indefinite Quantity (IDIQ) contractor that will assist with the work in many of these tasks.

6 Applied Technology Council, 2012, *FEMA P58: Next-Generation Building Seismic Performance Assessment Methodology*, Report No. FEMA P-58, Federal Emergency Management Agency, Washington DC.

This is an important research area. Successful development of cost effective and practical systems to provide robust design solutions and resilient structures is necessary to make earthquake resilience an attainable goal. Much work needs to be done to move forward with the research tasks in this area. Japan has extensive experience in designing sophisticated earthquake resistant buildings where they design in- force absorption for the earthquake-induced motion. Collaboration with their laboratories or agencies is likely to be informative.

### Lead NEHRP Agency

Intense earthquakes are an infrequent but high-consequence phenomenon. Traditionally, U.S. and international building codes have sought to accept damage in these rare events but avoid massive life loss by permitting design of structures that are anticipated to withstand substantial, but not complete, damage in such events. The massive damage suffered by New Orleans from Hurricane Katrina and Christchurch, New Zealand, following the 2010-2011 earthquakes there, and the long recovery times that have ensued in both cities, have challenged this life safety paradigm and suggested that it is not sufficient. Society now demands the development of resilient communities that can remain viable following such major events.

However, it is not clear how best to go about revising community development practices to accomplish this goal. As part of its reauthorization of the National Earthquake Hazard Recovery Program, Congress charged NIST with development of a report to Congress on how to develop a framework for building practices to achieve community resiliency. In addition to this task, NIST serves as the coordinating NEHRP agency partnering with FEMA, NSF, and USGS in assuring that building practices for federal buildings are sufficiently resilient and that the nation’s building codes and standards are appropriate to achieving this goal.

### Accomplishments

NIST successfully produced a final report to Congress on *Research Needs to Support Establishment of an Immediate Occupancy Performance Objective Following Natural Hazard Evenys*.7 NIST also completed a draft report to Congress on *Recommended Options for Improving the Built Environment for Post-Earthquake Re-Occupancy and Functional Recovery Time*.8 In addition, NIST worked with the National Security Council and the Office of Scientific and Technology Policy (OSTP) to help draft Executive Order 13717 Establishing a Federal Earthquake Risk Management Standard in February 2016, and NIST drafted the implementation guidelines for federal agencies concerning EO13717 and has revised the *Standards of Seismic Safety for Existing Federally Owned and Leased Buildings (RP-10)*.9 NIST also acted as the secretariat for the Advisory Committee on Earthquake Hazard Reduction, an advisory committee to the President of the United States on earthquake policy issues.

7 NIST. Available at https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1224.pdf

8 NIST. Available at http[s://www.nist.go](http://www.nist.gov/publications/recommended-options-improving-built-environment-)v/pu[blications/recommended-options-improving-built-environment-](http://www.nist.gov/publications/recommended-options-improving-built-environment-) post-earthquake-reoccupancy-and

9 *NIST.* Available at [https://www](http://www.gsa.gov/cdnstatic/ICSSC_RP8_December_2011_508c.pdf).gsa[.gov/cdnstatic/ICSSC\_RP8\_December\_2011\_508c.pdf](http://www.gsa.gov/cdnstatic/ICSSC_RP8_December_2011_508c.pdf)

The responsibility to serve as lead NEHRP agency is not itself a research activity. While serving in this capacity provides resources to the Engineering Laboratory that it might otherwise not realize, the secretariat duties can detract from the other thrust areas by drawing both personnel and resources.

### PORTFOLIO OF SCIENTIFIC EXPERTISE

**Accomplishments**

The Earthquake Engineering Group includes one senior, two mid-career, and several early-career researchers. All hold doctoral degrees and three hold professional engineering licensure. One has 10 years of engineering practice. As evidenced by their publications, the group has a wealth of analytical research expertise and knowledge of structural reliability principals. The group lead, who held senior positions with the Network for Earthquake Engineering Simulation (NEES) Consortium and NSF, has some laboratory research experience. One of the research engineers also has some laboratory research experience.

### Challenges and Opportunities

The PERFORM testbed provides the Earthquake Engineering Group with an important tool to conduct intermural laboratory experimentation into structural behavior. It appears however, that the group is lacking in experience in performance of large and complex physical tests. This may limit the group’s ability to take advantage of this important capability.

### ADEQUACY OF RESOURCES

**Accomplishments**

Together with the Structure’s Group, the Earthquake Engineering Group has successfully commissioned the PERFORM Structural Testbed. PERFORM provides the capability to dynamically, and quasi-statically test large structural assemblies under complex loading conditions with peak structural loading of 220,000 pounds. Comparable capability at U.S. universities include a 1 million pound machine at the University of California, Berkeley, a 2.4 million pound machine at the University of Washington, a 2 million pound machine at Lehigh University’s Advanced Technology for Large Structural Systems (ATLSS) Center, and similar large testbeds at Purdue University, the University of Michigan, Ann Arbor, the University of California, San Diego, and the University of Illinois, Urbana-Champaign, among others. The PERFORM testbed does have enhanced flexibility to accommodate unusual structural geometries and systems.

### Challenges and Opportunities

The capacity to perform large-scale structural tests in-house provides the Earthquake Engineering Group with the ability to perform independent study of the earthquake resistance of a wide variety of structural components and systems. The challenge to the group will be to demonstrate an ability to perform such tests competitively with the many comparable research laboratories at major U.S. universities.

### EFFECTIVENESS OF DISSEMINATION OF OUTPUTS

**Accomplishments**

The Earthquake Engineering Group disseminates its work through a variety of resources, including publication of TechBrief and technical reports, publication of journal and conference papers, seminars for professional organizations, and direct support and participation in the standards development process. During the period 2008-2017, NIST developed, through its extramural IDIQ consultant, a series of 13 TechBriefs on design of structural systems for seismic resistance. The TechBriefs, prepared by leading authorities on each structural system, are readily available for download from the NIST and NEHRP consultants websites and are widely referenced by practicing engineers in the course of design work.

During this same period of time, NIST produced through the same extramural consultant a series of eight technical reports covering such topics as the following: program plans for assessing collapse risk assessment of concrete buildings; evaluation of the FEMA P695 Methodology for assessing seismic performance factors, applicability of multi-degrees-of-freedom analysis in design, selecting and scaling earthquake ground motions for use in design and analysis, a research plan for exploring the seismic capacity of deep wide flange steel columns, a comparison of U.S. and Chilean building codes, soil- structure interaction for building structures, and use of high-strength reinforcement in steel columns. The reports on soil-structure interaction and use of high-strength reinforcing steel in concrete structures have directly supported recent updates to the ACI 318 and ASCE 7 standards. Research conducted on deep, wide-flange steel columns have contributed directly to updates of the American Institute of Steel Construction (AISC) standards and also the ASCE 41 standard for seismic rehabilitation and evaluation.

Several Earthquake Engineering Group researchers are active participants in industry committees that develop the nation’s design and construction standards. These include the AISC Committee on Specifications and the ASCE committees on Seismic Rehabilitation and Minimum Design Loads and Associated Criteria for Buildings and Other Structures. A member of the Earthquake Engineering Group led an effort at the AISC Specifications Committee to develop a new standard, AISC 342, which will provide nonlinear seismic analysis of structures useful both for evaluation and retrofit of existing buildings and design of new buildings.

### Challenges and Opportunities

Growing societal interest in resilient communities presents the need for creation of new design, analysis, and construction standards to meet this challenge. The Earthquake Engineering Group is ideally suited to direct as well as self-perform the needed research to enable development of these standards.

Much of the substantial work performed by the group over the past 10 years has been accomplished through the extramural contract with the NEHRP Consultants Joint Venture. This consultant established uniquely qualified teams, comprising domestic and international experts from practice and academia, to execute specific assignments. Expiration of the IDIQ contract under which this work was performed compromises the group’s capability to perform similar high-quality studies. To the extent that the Earthquake Engineering Group elects to self-perform these research tasks, it will need to increase its internal staffing levels. To the extent such studies are self-performed, it will be important to have formal mechanisms for obtaining external review and input so that the work does not become excessively insular.

### CONCLUSIONS AND RECOMMENDATIONS

**Technical Merit of the Program**

The Earthquake Engineering Group’s studies have found that that procedures embodied in the ASCE 41 were excessively conservative in the characterization of structural performance.

### RECOMMENDATION: The Earthquake Engineering Group should broaden its work with steel frame and concrete wall structures to encompass the many other common buildings systems.

**RECOMMENDATION: The Earthquake Engineering Group should work to establish next-generation loading protocols and/or adaptive hysteretic modeling approaches that will enable reduction in the inherent conservative bias in present performance-based design procedures.**

### Portfolio of Expertise

The Earthquake Engineering Group includes one senior, two mid-career, and several early-career researchers. The PERFORM testbed provides the Earthquake Engineering Group with an important tool to conduct intermural laboratory experimentation into structural behavior. It appears, however, that the group is lacking in experience in performance of large and complex physical tests. This may limit the group’s ability to take advantage of this important capability.

### RECOMMENDATION: The Earthquake Engineering Group should seek to broaden its capability with mid- or senior-level researchers with extensive structural laboratory expertise in order to take full advantage of the Performance-based Engineering Research for Multi-hazards (PERFORM) testbed now available.

**RECOMMENDATION: The Earthquake Engineering Group should establish an external peer review process composed of leading researchers and practicing engineers to provide input on the specific research tasks undertaken and the details of significant research programs.**

### RECOMMENDATION: The Earthquake Engineering Group should establish formal procedures to assure interaction with practicing professionals and researchers at other institutions to assure that the program does not become overly insular.

**Effectiveness of Dissemination of Outputs**

An important thrust of the group’s programs has been to improve the performance-based seismic evaluation of design (PBD) procedures.

### RECOMMENDATION: As lead National Earthquake Hazards Reduction Program agency, the Earthquake Engineering Group should partner with the Federal Emergency Management Agency and NIST to improve and implement the FEMA P-58 methodology in industry design guidelines and standards.

**RECOMMENDATION: The Earthquake Engineering Group should partner with private industry to develop new cost-effective, damage-resistant, and damage-tolerant structural systems.**

## 5

**Engineered Materials for Resilient Infrastructure Program**

The resilience of the nation’s structures and infrastructure to aging and disaster ultimately rests on the quality of the materials used in its fabrication. The Infrastructure Materials Group contains 17 federal employees (13 permanent staff, 4 term staff) and 2 associates and has appropriately chosen to focus its attention on concrete and polymers. The average years of service of the staff in this program is 12 years. Polymers are essential because they protect the envelope of buildings against water intrusion (sealants, window claddings, thin films to block ultraviolet [UV] light and to resist windows from blowing out in hurricanes and tornadoes). With polymers, the focus has been on UV degradation, and this is certainly important. Concrete analyses and experimentation/modelling across size and length scales have been a traditional strength of NIST, with recent works continuing in the development of standard reference materials and analyses of degradation mechanisms/problems (alkali-silica reaction [ASR], Pyrrhotite) as well as potential repair strategies for aging infrastructure.

### TECHNICAL MERIT OF THE PROGRAM

**SPHERE Operations**

The Simulated Photodegradation via High Energy Radiant Exposure (SPHERE) program in the Engineering Laboratory (EL) is comprised of 11 people and is directed at stakeholders in the polymers, coatings, sealants, and construction industry to aid in the selection and design of appropriate materials across a range of sectors, including new construction. The SPHERE program and its unique equipment enables assessment of accelerated weathering and service life prediction by providing a fundamental understanding of the deterioration and aging mechanisms of materials. The staffing appears to be appropriate for the ongoing mission of the program and combines a number of junior and more senior investigators.

The SPHERE provides an accelerated aging environment to gather data on how materials experience changes in their properties when exposed to outdoor weathering, such as water, UV, elevated temperatures, thermal cycling, and mechanical fatigue. These property changes result in lower performance of the materials than assumed when the materials were selected and initially installed. The SPHERE can expose these materials to UV, under controlled temperature, relative humidity and

strain. The 2m SPHERE has been operating for more than 15 years and is heralded as a benchmark for the SPHERE technology such that its well-documented environmental conditions data (temperature, UV, and relative humidity) will be used to validate any new SPHERE devices. NIST is developing the capability of a smaller (0.25 m) more economical 6-port SPHERE. The exit apertures in the 6-port SPHERE can be

connected to specimen chambers, with the specific type of chamber utilized being dependent on the material being tested.1

### Accomplishments

This program has made significant advances in its 2m SPHERE testbed for understanding aging of polymer materials. The initial demonstration that links field and laboratory exposures was successful and although the initial model was for pure epoxy without fillers and other additives for mitigating UV degradation, more recent work has investigated polyethylene (PE), polyethylene terephthalate (PET), and polyethylene terephthalate glycol (PETG) with ongoing comparisons to field exposures. Of significance is the development and design of a smaller 6-port SPHERE that can be deployed by end users, such as manufacturers of polymer products for the construction industry, as well as other market sectors (e.g., sealants, coatings, polymer fiber-reinforced plastic [FRP] composites). The aging mechanisms are being comprehensively studied with 2m SPHERE testing, and robust models are being developed that demonstrate good correlation with field testing. External support from the Nuclear Regulatory Commission (NRC) on the NIST Cables Project was conducted to confirm the NRC condition-based qualification methodology. The design of a smaller commercial prototype SPHERE has been completed. One of these units has been purchased by an industry partner from a third-party vendor.

### Challenges and Opportunities

There is some work to be accomplished to successfully deploy the smaller 6-port SPHERE for industrial applications. The initial models and experiments using the 2m SPHERE for pure epoxy without fillers and other additives for mitigating UV degradation, and the more recent work on PE, PET, and PETG has shown good correlation with field exposures. The next steps will be to include these factors to provide a more realistic test material to real-world polymer materials containing additives/UV absorbers and transition to a 6-port SPHERE Data/Validation Project, with comparisons to both field and 2m SPHERE data. The deployment of the smaller SPHERE may have a significant impact on industrial manufacturers who want to provide robust and long-lasting construction materials.

### Additive Manufacturing with Cement-Based Materials

Over the past 10 years, the construction industry has increased its use of additive manufacturing (AM) with cement-based materials, sometimes referred to as 3D printing of concrete (3DCP). Despite the fact that there has been relatively little increase in construction productivity due to 3DCP,2 the technology provides an opportunity for game-changing productivity improvements in certain types of concrete construction, such as shelters, housing, wind turbines, and repair to existing elements in tight spaces. The NIST program is focused on the understanding the behavior of 3D-printed elements to loading, with the goal of providing performance standards, and is currently comprised of nine people.

1 National Institute of Standards and Technology, 2021, “Accelerated Weathering Laboratory: Metrology and Technology Transfer,” https://[www.nist.gov/programs-projects/accelerated-weathering-laboratory-metrology-and-](http://www.nist.gov/programs-projects/accelerated-weathering-laboratory-metrology-and-) technology-transfer, updated January 7, 2021.

2 Concrete Products, 2019, “ACI Foundation’s Strategic Development Council Brings the Future Faster,” <http://concreteproducts.com/index.php/2019/04/23/>aci-foundation-s-strategic-development-council-brings-the- future-faster.

### Accomplishments

The program is early in its development. The team has defined early-stage goals aimed at understanding the unique interplay between the material properties of the concrete “ink” (rheology, setting time, and layer-upon-layer adhesion) and the process of directionally dispensing concrete through nozzles to form structural geometries. A laboratory with robotically controlled AM equipment has been developed with a number of different nozzles for experimental examination of their effects on concrete printing. This group has shared information with other NIST groups that are developing 3D printing for polymers and metals and for small-angle scattering experiments. Cement pastes have been printed on a benchtop scale, constructing a single filament stacked structure.

### Challenges and Opportunities

The early age of the program and the rapidly developing field of 3DCP represents both a challenge and an opportunity. It is important to develop a fundamental understanding of actual structural performance of elements that are 3D printed, which will depend on the types of robotic devices and technologies that are utilized for the manufacturing. This basic understanding will provide the industry with confidence that using 3DCP can in fact raise productivity and provide safe structural capacity to loading. The Infrastructure Materials Group at the EL has the advantage of bringing state-of-the art tools, such as small angle neutron scattering, to link material microstructure to bulk material properties, such as rheology and electrical conductivity. Of potential interest is the interfacial microstructure between subsequent layers of printed concrete and the resulting resistance to crack formation along those seams. The ability to collaborate with the NIST Performance-based Engineering Research for Multi-hazards (PERFORM) laboratory is likely to accelerate such efforts. The group could beneficially consider collaborating with ongoing international efforts and identifying U.S. universities performing research in this rapidly evolving area.

### Direct Assessment of Concrete-Making Materials for Standards and Specifications

This program, currently staffed by five people and related to direct assessment of concrete- making material for standards and specifications, is a continuation of the long NIST tradition of investigating the fundamental nature, character, and performance of one of the world’s most used construction materials. The current specifications for cement are based on mid-century normative ones that are now outdated due to changes in the mineralogical, chemical, and physical characteristics of modern cement manufacture. Also, the basis for evaluating concrete in the field for acceptance is based on a slump cone test as a qualitative measure of concrete flowability and not on a physical and direct measure of rheological character. A detailed study has been conducted to evaluate various types of rheometer geometries and their stress-strain rate response as a direct measure of viscosity and yield stress and to better understand the performance of fresh concrete. This was combined with the development of well-defined, model pastes that will allow practitioners to properly calibrate their rheometers to produce reliable data on concretes formulated in the field.

### Accomplishments

This work continues NIST’s fundamental investigations of cement-based materials. The hydration studies examining the reactions of cement and measuring and characterizing reaction rates are of high value and continue to be nationally and internationally recognized. The investigative methods using digital holographic microscopy, environmental powder reactions, and simulation are best in class.

This work has taken the fundamental understanding of cement hydration from macro- and meso-scale down to microscale. The research aimed at understanding and standards development of a device to measure the pertinent rheological character of fresh concrete has provided good advancement and understanding of its flow-processing behavior. The development of standard reference materials (SRMs) for concrete reference materials for Portland cement clinkers is recognized and utilized worldwide by cement manufacturers and research laboratories. In particular, the Portland Cement Fineness (114/46) has sold roughly 800 units annually, while the Portland Cement Clinkers (2686/2687/2688) has sold about 120 units annually. The Concrete Rheology SRMs are new products introduced in 2019: Concrete Paste (2492) has sold 4 units; Mortar (2493) has sold 1 unit; and Concrete (2497) has not sold any units yet.

The combination of this materials development with computer simulations of particles suspended at high volume fraction and subject to particle-particle interactions have provided robust understanding of concrete microstructure and dynamic response. Four sold-out workshops on cement materials characterization have occurred over the past 6 years, encompassing more than 240 attendees from industry, academia, and government. These workshops produced a group of experts that have participated in round robin and proficiency testing using standardized test methods developed at NIST, such as ASTM C1365.

### Challenges and Opportunities

There are significant opportunities to standardize the use of rheometry as a field test method for quality control. The slump test, which is in widespread use in the concrete industry, is a subjective and qualitative measure of flowability. The Engineered Materials Program recognized an important opportunity and has produced impressive work on the development and use of different rheometer geometries for reliable flow-curve measurement, the formulation of SRMs for proper calibration of instruments, and the use of large-scale simulations of particle suspensions to appreciate structure-property relationships. This team has also established and published a database of kinetic reactions of cements and their rates. There are ample opportunities to continue to educate and qualify the industry on the various characterization methods, especially the ASTM standard method for X-ray diffraction. Continuance of the program of concrete reference materials development is important.

### Assessing Pyrrhotite in Concrete

There has been significant attention in the media3 concerning massive concrete cracking in home foundations in Connecticut. This project was initiated from congressional funding of $1.5 million and is expected to continue for another 2 years. The mechanism that has been identified is the use of a schist aggregate that contains pyrrhotite that is subject to expansion and subsequent concrete cracking. This has led to the need to replace concrete in tens of thousands of home foundations in Connecticut. This is a new research area for NIST. The goal is to develop a rapid test that can be standardized to assess the susceptibility of concrete damage to pyrrhotite and to develop reference materials for calibration of a test standard. The success of this program can have significant implications on the concrete materials industry. This program is currently staffed with six people.

3 N. Post, 2016, “Connecticut Grapples with Failing Concrete Foundations,” *Engineering News Record*, June

21.

### Accomplishments

Since this is a new research project, progress to date has been limited. Still, the program goals are well positioned to lead to a test method to assess potential pyrrhotite damage of concrete and a reference material for assessing pyrrhotite in concrete. As this is a new program, the materials submitted by NIST for this review do not include information about the accomplishments of this research to date, other than providing a grant to the University of Connecticut Civil Engineering Department to work on developing a test method for pyrrhotite in concrete as well as developing a risk assessment model.

### Challenges and Opportunities

This research has great potential to minimize concrete damage due to deleterious aggregates that cause pyrrhotite. The challenge will be to develop a simple test that can be used by industry. This also represents the opportunity. This would mitigate the type of problems that occurred in Connecticut and other areas along the east coast.

### PORTFOLIO OF EXPERTISE

**SPHERE Operations**

### Accomplishments

The project team is staffed by very high-quality chemical and polymer engineers and material scientists with different levels of NIST service. There has been a strong continuity of the project team that has led to significant progress over the last 6 years. The expertise of the team members applied to develop the 6-port apparatus represents a good innovation that is likely to translate well to industry.

### Challenges and Opportunities

The team as configured is well set to continue with its important industry-relevant work related to aging and deterioration of polymer materials. There are good opportunities to integrate the 6-port SPHERE testbed directly into industrial use. Continued engagement and outreach to other potentially relevant industry partners will be beneficial.

### Additive Manufacturing with Cement-Based Materials

**Accomplishments**

The technical expertise of the program’s participants is strong and builds on the long history in cementitious material research, materials characterization, robotics, and structural performance testing.

### Challenges and Opportunities

This nascent program affords the project team the opportunity to emerge as leaders in the field.

However, toward this end it will be important that the team communicate with non-NIST personnel, including other national and international researchers as well as construction industry and standardization

organizations. Technology transfer through this program could be significant because the capabilities of the NIST 3DCP researchers are strong and unique.

Successful development of this technology will require a commitment of time by rheologists, microscopists, and theorists. This expertise does exist within the Engineered Materials Program, but the personnel are simultaneously engaged in other projects, and the scheduling of their time may become highly constrained. Additional staffing may be required to continue to elevate this area to a leading national effort.

### Assessing Pyrrhotite in Concrete

**Accomplishments**

The technical expertise in the concrete materials team at NIST is well qualified for the goals of the project.

### ADEQUACY OF RESOURCES

**SPHERE Operations**

### Accomplishments

The facilities continue to be some of the best in the world. The facilities do not appear to be an impediment to the continuation of the research program.

### Challenges and Opportunities

There would be a great interest by industry in the availability of a portable test method for determining life of polymer materials. The challenge will be to gain wide acceptance of the 6-port device and to get it standardized.

### Additive Manufacturing with Cement-Based Materials

**Accomplishments**

NIST has rapidly put together a team of experts and facilities, including an additive manufacturing testbed for 3DCP. The program will have a good blend of experts from various fields and will include structural testing of elements for bond characterization and shear in the PERFORM program.

### Challenges and Opportunities

One challenge will be for the team to be agile and facile in the rapidly changing 3DCP field.

However, it will remain important to conduct good and reliable experiments that demonstrate the performance of 3D-printed elements and provide basic knowledge of the processes and materials.

The scientific team that is assigned to this project brings together expertise in cementitious materials, rheology, microstructural characterization, and the strength of materials. The PERFORM laboratory affords this program state-of-the-art measurement methods in rheology, the strength of

materials, X-ray diffraction, UV and Raman spectroscopies, nano-indentors, atomic force microscopy (AFM), and scanning electron microscopy (SEM). The diversity of scientific backgrounds gives this team a great advantage. However, this same team is tasked with advancing an equally diverse set of research programs within the purview of the Engineered Materials for Resilient Infrastructure Program. Additional staffing may be required to continue to elevate this area to a leading national effort, while the level of support staff (technicians and postdoctoral fellows) that augment the program activities was not made clear.

With regard to infrastructure, Building 206, where the 3D Concrete Printing project resides, lacks some environmental controls (no air conditioning in the summer), modern information technology (IT) infrastructure, and it is largely without utilities due to the building’s origins as an aggregate storage facility. These issues should be addressed for the safe and efficient use of this high-profile area.

### Assessing Pyrrhotite in Concrete

**Accomplishments**

The facilities, equipment, and technical expertise are well positioned to handle the goals of the program.

### EFFECTIVENESS OF DISSEMINATION OF OUTPUTS

**SPHERE Operations**

### Accomplishments

The project team has prepared 85 technical publications since 2014 that span internal technical reports, 30 peer-reviewed scientific and symposia papers, along with 7 peer-reviewed book chapters and 3 books on service life prediction. Eight standards have been developed with the NIST SPHERE technology. In addition, there has been outreach to industrial partners in various consortia (e.g., photovoltaic, polymer surface interface, sealants) and workshops (e.g., Service Life Prediction of Polymeric Materials). As this continues, it will need to gain acceptance of the models and the SPHERE system as a means of assessing polymer materials across a wide spectrum of sectors.

### Challenges and Opportunities

There are great opportunities to engage with end users of the SPHERE system, including manufacturers of new construction materials, the polymers AM and structural polymers community, and design professionals who specify those materials. The challenge is the same as the opportunity, which is to get buy-in on the experimental methodology and the modeling that have been advanced in the SPHERE program by the end users. Successful engagement of end users will lead to development of standards and acceptance by the industry.

### Additive Manufacturing with Cement-Based Materials

**Accomplishments**

The 3DCP research group has produced a number of publications in a short period of time. These include a review of 3DCP for infrastructure construction, an article on the rheological control of 3DCP pastes, a paper describing a roadmap for extrusion of 3DCP pastes, a paper on formulating sustainable cementitious binders for 3DCP, and contributions describing two nonintrusive testing methods of extruded pastes—ultrasonic wave propagation and electrical conductivity. In addition, one of the members is chair of ACI 564: 3-D Printing with Cementitious Materials, which will continue to provide good visibility to this evolving program The MACE consortium was developed to determine the measurement science needs in this area. With regards to infrastructure, Building 206, where the 3D Concrete Printing project resides, lacks some environmental controls (no air conditioning in the summer), modern IT infrastructure, and it is largely without utilities due to the building’s origins as an aggregate storage facility. These issues should be addressed for the safe and efficient use of this high-profile area.

### Challenges and Opportunities

There are significant opportunities to advance the field and provide free flow of information and findings to other researchers, industry, and other stakeholders. The 3DCP effort at NIST brings together an outstanding cast of experts in the key areas of importance to this emerging construction technology (cementitious science, suspension rheology, simulation of non-Newtonian materials, strength of materials measurements, and microstructure determination). The major pieces of scientific and robotic-controlled 3DCP equipment have been established, and the team is positioned to develop printing strategies, materials, and standards that can be translated into practice. Linkage with ongoing efforts at other international locations and standards developing organizations is needed, in addition to linkage with other (polymer) AM efforts at NIST, where a Measurement Science Roadmap for Polymer-based AM (NIST.AMS.100-5) has also been prepared.

### Direct Assessment of Concrete-Making Materials for Standards and Specifications Accomplishments

The outreach of the team members in the form of technical reports (7 NIST internal), 31 peer- reviewed publications, at least 9 standards and test methods development, workshops (e.g., Cement Workability, Green Concrete, Cement Microscopy) with academia, government, and industry and consortia (e.g. COMEX, CREME) is notable. Three separate SRMs for concrete rheological measurements have been prepared along with international round-robin testing. Two separate ASTM standards on cement characterization were also revised with NIST input, while the work in cement characterization has also garnered a prestigious paper award.

### Challenges and Opportunities

The team has developed important insights into the characterization of cement over a wide range of length scales and has made important contributions to the rheological properties of fresh concrete. This has included the development of measurement tools, standardized materials, and theoretical modeling.

This will assist in the development of alternative concrete mixtures using less cement and for the use of alternative cements and pozzolanic materials for sustainability. There are opportunities to impact the

testing and quality of fresh concrete with further development and standardization of the helical rheology device.

This research group is composed of accomplished scientists and engineers. However, there has been a notable reduction in the size of the team but not in the scope of the important problems where materials impact infrastructure resilience. Cementitious materials are central to infrastructure, and these are flowable, non-Newtonian pastes while structures are being created. One concern is that this group does not currently have a dedicated rheologist following the departure of its expert in this area.

### Assessing Pyrrhotite in Concrete

**Accomplishments**

Accomplishments in the area of dissemination of outputs were not presented because this is a new program initiated in response to congressional funding. The legislation calls for NIST to partner with academic institutions to establish standards, guides, and specifications for acceptable levels of pyrrhotite in concrete aggregate. A grant was awarded to the University of Connecticut’s Department of Civil Engineering to work on developing test methods and risk assessment models.

### Challenges and Opportunities

There will be ample opportunities to disseminate the research and to develop a standard test method for ensuring aggregates are not susceptible to pyrrhotite expansion.

### CONCLUSIONS AND RECOMMENDATIONS

**Technical Merit of the Program**

### SPHERE Operations

This has been a strong research area, and expanded focus of its attention would maximize the development of the 6-port testing device for industry. The testing device could be standardized with the potential of eventual round-robin testing. Expanded focus on the polymer additives would assess more realistic industry products. Opportunities for collaboration with the AM polymers and structural polymers/composites communities would be beneficial in addition to FRP composites for infrastructure repair.

### RECOMMENDATION: Directed efforts for the use of the SPHERE (Simulated Photodegradation via High Energy Radiant Exposure) should be expanded to the areas of additively manufactured polymers and structural polymers to complement and extend the ongoing work on industrially relevant polymers with additives/ultraviolet absorbers. This should also be extended to paintable sealants as well as fiber-reinforced plastic composites for large infrastructure repair, in order to continue to impact the area of aging infrastructure.

**Additive Manufacturing with Cement-Based Materials**

This project, which will combine the fundamental science of cementitious paste flow and curing with structural and mechanical measurements over a wide range of length scales, promises to advance 3DCP and increase its utility and capability.

### RECOMMENDATION: In addition to study of the productivity that 3D printing of concrete (3DCP) may offer in new construction, efforts should be directed to the use of 3DCP for large infrastructure repair for aging systems. In that regard, the 3DCP program should take advantage of the NIST Performance-based Engineering Research for Multi- hazards (PERFORM) facility for evaluation of interface adhesion between 3DCP layers, reinforcing bar pull-out tests, structural performance of elements in shear and flexure, and evaluation of the repair of damaged structures.

**RECOMMENDATION: The 3D printing of concrete (3DCP) program personnel should continue to link with other NIST efforts on additive manufacturing as well as other ongoing national and international efforts in 3DCP.**

### Direct Assessment of Concrete-Making Materials for Standards and Specifications

There is great value in continuance of the research of a rheological test apparatus for viscosity measurement of fresh concrete, with the goal of developing a standard for industry, and great value also in the work on the development of concrete reference materials.

A better understanding of the atomic-scale mechanisms responsible for ASR and insights into methods to mitigate its effects justifies the exploration of atomistically based modeling tools that are proving generally useful across the disciplines of materials design. Although ASR and other aspects of cement chemistry are among the more complex phenomena of engineering science, tools for atomistic and quantum mechanical modelling have advanced to a point justifying the exploration of these as part of a more expansive effort to understand and model the properties of cementitious materials. In particular, as a starting point, these tools may be particularly useful in investigations of siloxanes to mitigate ASR effects.

### RECOMMENDATION: Additional standard reference materials for rheology should continue to be developed, with the addition of a dedicated experimental rheologist to the team, and shared with the community to increase the impact of the program, while modeling efforts should be integrated more globally across these programs to also impact evolving standards for both the generation and evaluation of new materials.

**RECOMMENDATION: The excellent work and implications associated with the alkali- silica reaction (ASR) studies should be expanded to include the subsequent impacts of ASR on corrosion degradation mechanisms in ASR-affected structures, while the program focus should expand to include both theoretical and experimental components directed toward the design of alternative materials to replace Portland cement, reduce carbon emissions, and enhance the sustainability of constructed infrastructure. Crossover of this work to other areas such as the Community Resilience Program should be considered.**

### Assessing Pyrrhotite in Concrete

Development of a standardized test will represent a major improvement in production of concrete and concrete durability.

### RECOMMENDATION: In addition to developing a test method for assessing the potential for expansion due to pyrrhotite, and thus exclude certain aggregates for use in concrete, the research group should explore chemical approaches in the form of admixtures and treatments that may control or mitigate the effects of pyrrhotite. In this effort, atomistic/quantum mechanical modelling should be considered as a way of identifying treatments that poison the breakdown of pyrrhotite to secondary minerals.

**Portfolio of Expertise Additive Manufacturing with Cement-Based Materials**

The assembled team and the instrumentation at its disposal is highly competent and appears to be unique. This group of scientists and engineers, however, consists of individuals with responsibilities in several other projects of equal interest and importance. These competing interests will need to be managed, and this may be difficult at the current staffing levels.

**RECOMMENDATION: The staffing required for both continuity and growth of this program should be reviewed, and adequate resources should be provided to ensure it continues to develop.**

## 6

**Fire Research Programs**

The Fire Research Division (FRD) develops, verifies, and utilizes measurements and predictive methods to quantify the behavior of fire and advances techniques to reduce the impact of fire on people, property, and the environment. The FRD strives to provide leadership for advancing the theory and practice of fire safety engineering, firefighting, fire investigation, fire testing, fire data management, and wildland burning.

The FRD consists of five staff groups—Fire Fighting Technology, Engineered Fire Safety, Flammability Reduction, Wildland-Urban Interface Fire, and the National Fire Research Laboratory (NFRL). The groups work in two main program areas: fire risk reduction in communities (with thrusts in fire service activities and wildland-urban interface [WUI]) and fire risk reduction in buildings (with thrusts in residential fire safety, structure-fire interactions, and advanced modeling).

### TECHNICAL MERIT OF THE PROGRAM

**Accomplishments**

Homes are still where the majority of fires and fire deaths occur. According to National Fire Protection Association (NFPA),1 the death rate per 1,000 reported home fires in 2014–2017 was more than twice as high in fires that began with the ignition of either upholstered furniture or mattresses and bedding as it was in 1980–1984. In the period 1980-1984, 44 in 1,000 deaths began with upholstered furniture fires; the number rose to 88 in 1,000 in the period 2013-2017. In the period 1980-1984, 15 in 1,000 deaths began with mattress or bedding fires; the number rose to 38 in 1,000 in the period 2013- 2017.

During the 5 years of 2014–2018, cooking was the leading cause of home fires and home fire injuries, while smoking was the leading cause of home fire deaths. This shows the need to solve the home fire problem. At NIST, this is being addressed with programs on upholstered furniture flammability and residential fire safety innovation, such as advanced home fire alarms, cooking fire hazard reduction, and reduced ignition–propensity cigarettes. The research focus on the WUI is also related to this effort, because there is increasing residential fire death and property loss in those areas in such fires.

The fire performance test for mattresses, developed by NIST, was successfully implemented in the Consumer Product Safety Commission (CPSC) regulation in 2007 for furniture flammability.

According to a recently published study by NIST,2 this regulation has reduced the number of deaths caused by flaming ignition of mattresses by close to 80 percent since its implementation in 2007.

1 M. Ahrens and R. Maheshwari, 2020, *Home Structure Fires*, National Fire Protection Association, November, http[s://www.n](http://www.nfpa.org/News-and-Research/Data-research-and-tools/Building-and-Life-Safety/Home-Structure-Fires)fp[a.o](http://www.nfpa.org/News-and-Research/Data-research-and-tools/Building-and-Life-Safety/Home-Structure-Fires)rg[/News-and-Research/Data-research-and-tools/Building-and-Life-Safety/Home-Structure-Fires.](http://www.nfpa.org/News-and-Research/Data-research-and-tools/Building-and-Life-Safety/Home-Structure-Fires)

2 S.W. Gilbert, D.T. Butry, R.D. Davis, and R.G. Gann, 2020, “Estimating the Impact of 16 CFR Part 1633 on Bed Fire Outcomes,” NIST Technical Note 2092, https://doi.org/10.6028/NIST.TN.2092.

Adding to the complexities of reducing home fire deaths is the increasing focus on the environmental impact of chemical flame retardants. Flame retardants had previously been the go-to solution for reducing the flammability of residential upholstered furniture (RUF) at NIST and elsewhere. However, this approach is no longer desirable and is even banned in many jurisdictions. To avoid the use of flame retardants, NIST has focused on developing barrier technologies to prevent the flaming ignition of RUF. This change in focus from fire retardants to barrier methods, made after consultation with stakeholders, shows NIST’s ability to refocus research based on stakeholders’ needs. The work has successfully developed two different barrier technologies, one patented in 2017 and the other with patent pending. NIST’s work is laying the foundation for implementing needed regulation of upholstered furniture.

Providing accurate fire performance metrics enables the reduction of the burning hazard of RUF. The testing program focuses first on fire performance in real scale and then on providing a bench-scale test method that replicates the performance in real scale. This takes great advantage of NIST experience with large-scale testing as well as making good use of existing test equipment, such as the cone calorimeter. Results confirm that the cube test as part of the cone calorimeter provides the parameters needed to predict fire performance in real scale.

In addition to flaming tests for RUF, NIST is also addressing the hazard of smoldering ignition of RUF from cigarettes. NIST SRM 1196/a cigarettes are required by ASTM 1352/1353, NFPA 260/261, CPSC 16 CFR 1632, BHGS TB 117-2013, and many European standards and regulations for assessing the flammability of soft furnishings. It was encouraging to hear that work toward a 10-year supply of this Standard Reference Material (SRM) will be done in fiscal year (FY) 2021–2022 Previous work on the mechanism of smoldering behavior in RUF has led to improvements in the bench-scale smoldering test, ensuring better alignment of the test method with smoldering behavior in real scale.

Nuisance alarms from smoke detectors are a common reason for these alarms to be taken out of service, thereby leaving people more vulnerable to fire. Solving the problem of nuisance alarms is a critical step in ensuring increased home fire safety. The work at NIST has led to smoke detector standards being modified based on NIST technical guidance. Current editions of ANSI/UL 217 and ANSI/UL 268 require new fire performance tests and a nuisance alarm resistance test for all smoke alarms and smoke detectors. New products are on the market now with a requirement that all alarms and detectors manufactured meet these new requirements by June 2021. This is another example of NIST’s basic research making its way into people’s lives.

Another critical issue to address in-home fire safety is the role of cooking fires. NIST’s work informed the technical basis for changes to the standard on household electrical ranges, UL858, to prevent cooktop ignition during unattended cooking. Additionally, recently published research from NIST emphasizes the significant hazards from unattended cooking, which is the leading cause of cooking fires.

The program is addressing the fact that fire targets of WUI fires, such as wood piles or decks, can then in turn become sources for fire spread into the built environment. The focus is on the complex relationships of fire spread of WUI fires from vegetation to site elements such as fences, or wood storage piles to exterior decks and then to structures. A structure on fire becomes the source of more ignitions downwind. Observations from forensic fire analysis and fire tests show great variations in fire performance of such seemingly simple systems like fences, depending on the direction of the wind in relation to the orientation of the fence.

The Emberometer is a unique measurement system under development at NIST that measures the ember flux in terms of size and numbers of embers. The Emberometer serves a real need to measure the generation and propagation of embers in laboratory tests and field fire conditions. The work is still in the early development stage and is another component of WUI data collection and modeling prediction that will require many years to realize its potential. It is intended to measure the actions of fire-generated particle showers (firebrands) that can be a mechanism of fire spread in WUI fires. As WUI modeling improves, test data and modeling data on such WUI fire components as embers and firebrands will be essential to improving the predictive capabilities of WUI fire models. Duplicating embers and measuring their properties adds to the understanding of the propagation of WUI fires by embers. This will, over time,

lead to better predictive modeling and will also lead to better building system designs to prevent or slow fire caused by embers.

The burn observation bubble (BOB) is a simple and creative implementation of commercially available gear to provide immersive visualization of severe fire environments that are otherwise unavailable due to the fire being observed destroying the observation equipment. The program makes innovative uses of blown glass bubbles to provide water-cooled glass enclosures for cameras to provide a fire-resistant environment for fire observation inside of a fire. The simplicity of the concept and its execution belies the great value of this invention. In addition to the BOB, the FRD is developing important data visualization methods that overlay technical data on the visual images obtained by the BOB system. This close integration of data and video provides a more comprehensive view of the fire than has been possible previously. The visualization methods are a teaching tool both for research and for public information.

The goal of the Emergency Response Robots program is to improve the safety and effectiveness of first responders by assessing and improving the capabilities of emergency response robots. This is of potentially great value in buildings as well as in the WUI environment of fast-moving fires in rough terrain where both fire risks and mobility make robots well suited for observation and firefighting tasks. The program has been recognized with many awards, most recently the Presidential Gears of Government Award (2020) for developing the first-ever comprehensive suite of emergency response robot test methods and data collection tools to evaluate and improve bomb-disposal robots and operators. These efforts led to enhanced testing and advanced robot capabilities that enable emergency responders to perform extremely hazardous missions from safer standoff distances for a wide range of emergency response scenarios. Firefighting robots have recently begun going into active service in local fire departments.

The research conducted in the NFRL facility in recent years has been of high quality and innovative. The commissioning of the new systems was meticulously undertaken in a manner that will serve the facility’s research over the coming years. The research on the fire response of composite steel- concrete floor systems has been highly productive and has fostered excellent international collaboration. The importance of fabrication details and connections yields major lessons and implications for structural design. The open archiving of data from these experiments will be a resource for modelers and other researchers for many years.

### Challenges and Opportunities

While NIST’s effort in the area of flammability has had an important impact, the combination of its efforts on mattresses and cigarettes has yet to address fully the risks inherent in bed fires. Much progress is needed in upholstered furniture fire performance.

The evaluation of the toxic effluents produced during a fire is a gap in the work on home fire safety research. Reducing RUF or other products’ fire hazard should not disregard the biggest killer in fire—smoke. While it can be argued that lowering the heat release will also lower the smoke production, the unintended consequence can be the production of more toxic effluents, affecting people close to the fire’s origin. This was addressed when the impact of flame retardants was assessed years ago. But with the focus solely on reducing flammability, the issue of toxic effluents during fire has seemingly dropped. NIST had been on the forefront of research into the toxic effluents from fires, so it is surprising that this field of research is no longer pursued. There is increasing interest globally in the role of toxic effluents during fire, as evidenced by a recent research on fire smoke and toxicity by the European Union’s study to evaluate the need to regulate within the Framework of Regulation (EU) 305/2011 on the toxicity of smoke produced by construction products in fires, and the United Kingdom’s Ministry of Housing, Communities and Local Government procurement pipeline requirements, such as CPD/004/121/050, “Research - Fire Safety: Smoke & Toxicity.”

Recent years have seen rapid growth in the number of people living in the WUI, and this move has led to new classes of fire incidents being addressed by NIST. The WUI data collection program is designed to extend the fire incident investigation, reporting, and analysis system into the WUI zones where there has been a large increase in fire incidents all over the United States in recent years. This data gathering is based on forensic analysis of actual events to determine the mechanisms for their start and spread. The program is based on case studies to identify vulnerabilities, drive research, and develop hazard mitigation solutions. The program is seeking to widen the base of its knowledge beyond single- building fire performance to the inter-relationships between structures and the other elements in the WUI zone, such as fences and adjacent vegetation. This is designed to provide an analytical base for the wider NIST drive to increase knowledge and predictive capabilities about WUI zone fires and how to mitigate them on a community-wide basis.

The WUI Parcel Vulnerability Program is a coordinated effort using targeted laboratory and field experiments, post-WUI fire data collection and analysis, and a range of models, including vegetation and structure fire models to understand WUI exposures. The program provides measurement science–based tools for the development of WUI fire-resistant test methods, standards, and codes. The goal of accurate modeling for WUI fires, especially at a parcel or community scale, is worthwhile and timely. The number of complexities involved in outdoor fires involving open boundary conditions and varying terrain, and vegetation mixes inherent in WUI fire modeling, go beyond the framework of modeling structure. Usable and accurate WUI fire models have not yet been fully developed, but the demonstrated need for WUI fire prediction and mitigation makes the goal well worth pursuing.

Ongoing development has demonstrated the ability to use the Fire Dynamics Simulator (FDS) to interpret experiments and predict future experiments and other fires in the laboratory and in natural environments. This modeling capability has a considerable development history, with origins dating to the 1970s and 1980s, with new features shown in a demonstration of a simulation of a large outdoor fire with a spatial domain of 1 square kilometer with a resolution of 1 meter. This prototype does not yet represent an especially powerful capability, but it indicates the ongoing direction of this modeling effort. There are questions pertaining to the level of commitment to this simulation component of the program, considering its stated funding allocation of $1.2 million for FY 2020 and an extended list of intended tasks. These codes are open source, so changes and improvements can be contributed from a wide variety of people from other institutions and companies, but these codes are supervised by NIST. More information concerning the level of commitment and expectations for productivity from their code development efforts would be very helpful in evaluating this part of the program. It is very likely that the use of complex models for analyses of natural fires can be expected to be enlightening and instructive, but they are still likely to be limited to qualitative information rather than detailed accurate pictures of real-life natural fires. Increased collaborations with other organizations, particularly those supported by the Department of Defense and the Department of Energy, which have significant programs in high- performance computing and extensive experience in massively parallel computing, would be very beneficial. An advantage for NIST would be the unclassified nature of its major codes, which would play into those programs that are focused on classified work and whose staff might welcome unclassified publication opportunities to broaden their own simulation experiences and contribute to their reputations.

### PORTFOLIO OF SCIENTIFIC EXPERTISE

**Accomplishments**

The Reduced Flammability Group includes scientists with an extensive portfolio of high-quality publications and promising upcoming researchers. The list of peer-reviewed publications, as well as awards, is impressive.

Staff working on WUI parcel vulnerability demonstrated cross-disciplinary relationships and a good match for the program’s goals and staffing. The program is staffed by fire science and fire modeling

experts, integrated with the other WUI teams engaged in data gathering, structure fire modeling, and resistance improvement. There are experimental collaborations with other parts of NIST and outreach to the Insurance Institute for Business and Home Safety (IBHS) laboratory and the Building Research Institute of Japan (BRI) open wind tunnel.

The researchers developing the Emberometer are leaders in this newly developed field. It appears that they are essentially inventing this aspect of WUI fire analysis in terms of going beyond fire observation. This is emerging technology, and the researchers have the technical expertise to develop the actual machinery for generating actual firebrands and measuring their action in fire tests and field tests.

The BOB researchers seem to be a good blend of technical and material experts ranging from a master glass blower to virtual reality specialists in the visualization of data. The data overlay comes from close collaboration with instrument data superimposed on the visual images captured using the BOB.

The Emergency Response Robot project staff has wide-ranging capabilities that are weighted to the disciplines driving robotic development—mechanical engineering and computer science. There is high-level academic expertise in those disciplines, but also emergency response experience to help develop relevant test methods and criteria. There is a high degree of collaboration with the Fire Research Laboratory and with WUI efforts for specific fire and materials testing of robots under actual fire conditions. The group also leverages external personnel from collaborating organizations both for outreach for information dissemination and for obtaining necessary expertise.

The NFRL scientific staff bring a wide range of in-depth expertise in large-scale testing. They bring a rigorous and innovative approach to the research. This innovation includes instrumentation, video documentation, and data presentation.

### Challenges and Opportunities

It is concerning that some areas addressed by the Reduced Flammability Group, such as smoke toxicity, seem to be phased out with the retirement of the staff who used to spearhead it. Other areas, such as cooking fire safety, could potentially suffer the same fate. Succession planning based not just on individual replacement but program longevity needs to be considered to ensure that areas of expertise are not lost within NIST. Relying on retirees coming back for limited hours as associates cannot by itself be effective.

An impediment to progress on the work with the Emberometer seems to be the ongoing need for refining the ember-generation capabilities of new iterations of the device to match the observed behaviors of such embers in actual fires. As with other aspects of WUI, the ability to model the data captured by the device is not as well developed as the observation and measurement techniques for assessing actual embers. This is in part due to the difficulty of measuring ember production in the dangerous environment of actual WUI fires. This is where innovations in observation like the BOB help cross-connect NIST programs. This is coupled to the need to validate and refine the performance of each iteration of these devices as more data is gathered about how they function in relation to how actual WUI fires work.

There appears to be limited interaction across divisions at NIST. This is concerning when work in one division can result in recommendations that are counterproductive to what other divisions are trying to achieve. A specific example is that the work on energy efficiency in the Energy and Environment Division only interacts with the FRD on indoor air quality but not in the area of product flammability.

Considering that the fire performance of buildings can be significantly impacted by technologies used to improve energy efficiency, knowledge exchange between the two divisions needs to be strongly encouraged. On the other hand, there are extensive interactions between the FRD and the Materials and Structural Systems Division with regard to fire-structural interactions.

Cooperation with the Office of Applied Economics makes it possible for the FRD to provide detailed studies of the impact of their work, such as NIST TN2092 on the impact of the mattress flammability standard. This cooperation needs to be continued.

There was little data regarding the composition or the technical expertise of the teams working on WUI data collection. However, the overall characteristics of this work dovetail with that of the overall WUI effort. Field data collection is done by 4-6 member teams drawn from the basic laboratory staff for this effort, with additional members drawn from NIST staff with relevant expertise. The teams also do data collection from other agencies and information sources for weather station and atmospheric condition data. The notion of drawing forensic staff from the laboratory raises the question of whether the forensic efforts are in competition with other laboratory programs for scarce staffing resources.

### ADEQUACY OF RESOURCES

**Accomplishments**

The capability to do real-scale as well as bench-scale testing is essential to achieve the FRD’s objectives within the fire programs. The facilities to do real-scale testing appear appropriate for the purpose, with the existence of numerous oxygen consumption calorimeters in sizes from 0.5 MW up to 20 MW. The list of bench-scale tests available to researchers is comprehensive.

The budget for the WUI Parcel Vulnerability Program is $1.255 million. The program is part of the well-integrated WUI effort for data collection, fire testing, and modeling improvement. Exterior fire modeling depends on interaction with other laboratories in Japan and the United States. The facilities at the NFRL are geared toward building fire testing. The outdoor fire models are also dependent on data gathered in WUI fires. There are strong ties to the groups working with the Emberometer and the BOB camera system and the fire modeling groups at NIST.

The BOB water-cooled globes allow the use of underwater cameras with pan and zoom features.

The assembly techniques of the prototype models of the camera were very simple and relatively inexpensive. The simple techniques have been made a deliberate piece of equipment development to make the equipment widely available.

The budget for the Emergency Response Robot Program is $770,000 from NIST and $1.325 million from the Department of Homeland Security. This program is still quite active, although the urban search-and-rescue robot program has ended. The Emergency Response Robot Program has an existing off-campus 8,200 sf test facility that will be migrated back to the main NIST campus and expanded to have 10,000 sf of interior space and 10,000 sf of exterior space on the surrounding site.

### Challenges and Opportunities

While the list of equipment did include Fourier Transform Infrared equipment for toxic gases, it appears this was only linked to a couple of the bench-scale tests. Specific test equipment to measure the toxic smoke production from products such as the Steady State Tube Furnace, the vitiated Cone Calorimeter, or the NBS smokebox was absent from the list of test equipment presented.

The research programs are comprehensive and ambitious, but with the significant workload of solving big problems, the staff appears to be stretched thin. There is limited expertise within the social science field as well as within the area of smoke toxicity.

The $1 million budget for WUI data collection appears scaled to relate to just the data collection efforts, not to any utilization of the data for best practices development or for modeling. The data collection efforts have evolved over time to have various detail levels and scales, from WUI 0 to WUI 2 data collection protocols. These efforts range from $10,000 per week for small teams at Level 0 and small fires to $1 million for 2-years efforts for Level 2 teams on large WUI fires. Reconstruction of Camp Fire is funded at about $750,000 per year and is now in its third year. Much of the discussion about data gathering also touched on testing and validation, which could be seen as other segments of the overall

WUI efforts for building fire modeling, prediction and protection, and community-level modeling, prediction, and protection. Those are outside of the stated budget.

The WUI fire program lacks a clear mission and objectives, making it difficult to assess the resources needed to support it. It would be worthwhile for the Engineering Laboratory (EL) to undertake a review of the WUI program’s mission, objectives, stakeholders, and resources, and potentially more extensive collaboration with other EL and NIST programs.

The Emberometer equipment is in its third iteration. The discussion of this equipment was presented as a virtual tour of the equipment during the full panel portion of the discussion. There was not a detailed review of the program for the fire research subpanel. As with many of the programs the subpanel reviewed, the budgets for projects at the individual level were not presented. The tour discussion had no data on the size or scope of the Emberometer project, either for staffing or budget. To be useful for measuring embers under controlled conditions, the device needs to be tied to a wind tunnel for actual testing other than when it is used for field deployment in actual fires. The only laboratory suitable for such testing is located in Japan. There is a smaller-scale test facility at the IBHS wind tunnel in the United States, but that is a closed system that is not well-suited to ember fire testing work. The lack of an open- system wind tunnel at NIST is an impediment to progress in laboratory studies of WUI fire phenomena.

As excellent as the NFRL facilities and equipment are, the facilities limit the productivity of the research. The throughput of fire-structural interaction research is strongly limited by sample cure times and the limited storage capacity. The addition of more sample curing space would economically enhance the productivity of the facility.

### EFFECTIVENESS OF DISSEMINATION OF OUTPUTS

**Accomplishments**

The residential fire safety work of NIST is effectively disseminated to the research, engineering, and standards communities through conference presentations, peer-reviewed articles, technical notes, and participation in national and international standards committees. Successes include the following: smoke detector standards are being modified based on NIST technical guidance; work by FRD provided the technical basis for changes to the standard on household electrical ranges, UL858, to prevent cooktop ignition during unattended cooking; development of two different barrier technologies for residential upholstered furniture, one already patented in 2017 the other with patent pending; NIST SRM 1196/a cigarettes are required by ASTM 1352/1353, NFPA 260/261, CPSC 16 CFR 1632, BHGS TB 117-2013, and many European standards/regulations for accessing flammability of soft furnishings; and a cube test for RUF is under development as a voluntary standard, ASTM-WK65005.

The WUI Data Collection program has good outreach to many diverse groups with extensive WUI field experience, such as the California Department of Forestry and Fire Protection (CAL FIRE), the Federal Emergency Management Agency, and the U.S. Forest Service. They also have strong ties to WUI fire-modeling efforts in other NIST programs and seem intent on tailoring their data collection efforts toward increased model capabilities and development of best practices in WUI zones based on observed WUI fire conditions. Several NIST WUI case studies are currently being used for firefighter training and fire protection engineers’ education.

The WUI Parcel Vulnerability Program has strong ties to many stakeholder groups—homeowners; federal, state, and local authorities having jurisdiction (e.g., CAL FIRE); codes and standards organizations (California Ch 7A, NFPA, ICC); first responders (incident commanders, firefighters, police such as Western Fire Chiefs); insurance companies, through the Insurance Institute for Home and Business Safety; trade organizations (AWC, construction, real estate); and the National Fire Protection Association Firewise program and education outreach.

The WUI Parcel Vulnerability Group participates in the Technology Maturation Accelerator Program (TMAP). The group’s entry in the TMAP competition was for a screen enclosure designed in

collaboration with a manufacturer, to be used for mitigation of fire spread by firebrands both to and from woodpiles. It finished in the top 10 of dozens of submittals for two review cycles. The TMAP program seems broadly applicable to all NIST activities.

The simplicity of the BOB assembly techniques makes this a system that can readily be implemented for use under both laboratory and field conditions. This is a great low-tech expansion of laboratory outreach. Some of the prototype assemblies were built from simple off-the-shelf elements for under $500. The partnerships that the fire laboratory has with field organizations like NFPA, firefighter organizations like CAL FIRE, and the U.S. Forest Service make the information widely available. The ties to data collection and modeling available through other data collection programs make possible the presentation of visual data on the newly available fire views. This is useful to researchers while being accessible to the general public. The power of feeling as though one is inside a fire with information about temperatures, combustion products, and fluid dynamics events presented as a single integrated image is made possible by this relatively simple but very powerful device.

One of the goals of the Emergency Response Robots program is to disseminate the outcomes to promote innovation, increase U.S. competitiveness, and improve the safety and effectiveness of emergency responders performing extremely hazardous tasks. This research group pioneered the use of robot competitions to validate and disseminate standards for robots in general and for the emergency response robots that are the focus of current efforts. The group participates in worldwide robot competitions to gather data on robot performance. This participation also raises the profile of NIST in both the robot technical development community and with the public. The leader of this effort is the chair of an ASTM committee developing ASTM International Standards Committee on Homeland Security Applications Response Robot (E54.09), which will ultimately be responsible for developing more than 60 detailed standards for robotic activities ranging across logistics, sensing, ground maneuvering, mobility, dexterity, situational awareness, and communications.

### Challenges and Opportunities

The international fire-structural interaction research community is aware of the program outputs from the fire-structure interactions work. Some results are moving to the structural codes and standards community. The fire protection engineering community, the fire service, the building community, and the general public are much less aware than they might be. When you have a gem, you need to show it off.

Combinations of numerical simulations and photography of phenomena such as flame acceleration in realistic geometries and other illustrations of unfamiliar WUI-specific fire hazards could be very effective ways to illustrate the immediate value of NIST research in these rapidly growing communities.

The Emberometer papers published for the development of the device are thorough and convincing as first steps toward measurement and prediction of ember and firebrand development and movement as part of WUI fires. NIST has noted that these efforts are first steps. The ties of the Fire Laboratory to the existing Japanese and U.S. wind tunnels require dissemination. Dissemination of mechanical construction details to allow widespread construction and use of the devices appears to be taking place. The increase in the level of information available on information platforms that operate like social media makes information dissemination simpler and more detailed. Real-time observations and data exchange can take place in remote locations. Social distancing requirements during the pandemic needs to continue.

There are no direct communications to end users of NIST research, such as the policymakers or even the public. Work on cooking fire safety is an example of a work area where the results could benefit public education. While cooperation with stakeholders such as the NFPA can serve as a funnel for NIST work into public education material, it appears to be a missed opportunity for NIST to be able to brand themselves to the end users of their research.

### CONCLUSIONS AND RECOMMENDATIONS

**Technical Merit of the Program**

NIST has a long and distinguished record of technological leadership, innovation, and experience in providing analysis and solutions to large and small problems dealing with fire safety in many practical and often challenging environments. Its past reports are cited by industry, government, academia, and others who need to obtain guidance and information on difficult problems.

The laboratory programs show an evolution over the past few years, which indicates a positive attitude toward adaptation to evolving needs. Research focus is changing to the increased need for such things as WUI fire knowledge, with the ultimate goal of WUI modeling at a parcel or even a community level. There is also a movement toward science-based structural fire protection to allow for better- informed design. There have also been changes in focus in reduced flammability of interior furnishings as there is a move towards fire barrier technology to replace chemical flame retardants. This changing research shows adaptiveness.

There is a need for enhanced long-term goal setting with tangible milestones. WUI, like other research areas, requires a balance of laboratory, field, and computational components. The balance needs to be reassessed and defined through a long-range plan.

There are good communications with technical peers, codes and standards groups, and the public fire service. At the same time, the level of peer-reviewed papers is less than one paper per technical staff member. It is important that technical staff publish in the peer-reviewed literature every year, and an average of more than one paper per year would be healthy.

### RECOMMENDATION: The Fire Research Division should create goals for the rate of annual publication of various types for the division, the sections, and technical staff.

**Adequacy of Resources**

There are facilities issues that limit the productivity and effectiveness of the laboratory operations. Increasing the materials storage and curing space for NFRL could enhance the throughput of structure-fire interactions research. The lack of a wind tunnel severely limits the ability of NIST to do the needed research on WUI fires.

### RECOMMENDATION: The Fire Research Division should add National Fire Research Laboratory facilities for curing structural samples and add a wind tunnel suitable for use in wildland-urban interface fire research.

The Other Agency (O.A.) and forensic investigations are important ways for NIST to understand real-world problems to guide basic research. As currently implemented, these activities drain resources from basic research. There is a need for more staff to maintain core research while doing forensic and

O.A. work. There needs to be a balance and continuity to the research. Forensic investigations provide a particular challenge in planning since the staff skills and level of effort are largely unpredictable. Direct funding of forensic investigations would put the investigation and research into better balance and would foster a complementary rather than competitive footing.

The resources at the FRD seem to be stretched very thin. The number of researchers and the size of budgets have been reduced while some areas of research are expanding, such as WUI research. There also do not seem to be enough resources devoted to maintaining the high-quality data processing systems originally initiated and now managed by NIST, such as the Fire Dynamics Simulator (FDS), to continue to evolve and improve those open-source programs. Technical and scientific staff should be increased such that the forensic, O.A., and basic research can reasonably progress in a timely manner. The advanced

modeling research group needs to be expanded commensurate with their expanded scope into WUI modeling and the overall challenge of their work. Advancements in science are clearly limited by the number of technical staff. To promote this goal, the focus should be on recruiting young researchers who will mature to replace the many near-retirement age staff.

### RECOMMENDATION: The Fire Research Division should consider balancing the funding level needed with the ambitious programs in progress specifically in relation to

* + **Establishing direct funding for forensic investigation as well as additional staff separate from the funding and staffing of core research activities.**

### Investing in the in-house data processing systems needed to maintain and further develop existing modeling tools.

* + **Ensuring longevity of programs through succession planning to ensure areas of expertise are not lost within NIST.**

The area of human behavior (e.g., occupant response and egress behaviors) in residential settings in fire is being addressed by NIST but does not appear to have the same attention as more technical programs (fewer publications). All NIST fire safety research programs, but especially the programs on home fire safety, could benefit from having additional input from the social sciences. This is also true for areas related to external threats such as in WUI fires. Many fatalities in those fires are related to people not knowing when and how to leave a fire area.

### RECOMMENDATION: The Fire Research Division should add social scientists to the technical staff for both building and wildland-urban interface fire research.

NIST-wide mentoring of young staff is a relatively recent development, having started in 2018.

The focus of that effort seems proper, on recruiting and growing young technical staff. There were several programs that, while discussed in specific research project discussions, appear to be laboratory-wide, such as “Women in STEM” and forums focused on underrepresented groups such as Asian and Pacific Islander research staff. It appeared from discussions that such groups are encouraged and supported by laboratory management.

### RECOMMENDATION: The Fire Research Division should continue to promote and support groups that encourage cross-division engagements and mentoring.

**Effectiveness of Dissemination of Outputs**

The FRD has formed good working relationships with many stakeholders from the government and the private sector. The Technology Maturation Accelerator Program (TMAP), as used in the WUI research, provides an example of a public–private partnership that represents an innovative way to further the impact of NIST in the eyes of the public as well as making use of the advanced technical skills possessed by NIST such as the fire laboratory and open-source fire modeling software.

At the same time, there appears to be limited interaction across divisions at NIST. This is concerning when work in one division can result in recommendations that are counterproductive to what other divisions are trying to achieve. A specific example is that the work on energy efficiency in the Energy and Environment Division only interacts with the FRD on indoor air quality but not in product flammability. Considering that the fire performance of buildings can be significantly impacted by technologies used to improve energy efficiency, knowledge exchange between the two divisions is encouraged. Another example is that passive solar design may increase the amount of glazing that could become an avenue for fire spread through radiant energy in WUI zones.

### RECOMMENDATION: The Fire Research Division should enhance its interactions with the Energy and Environment Division and the Community Resilience Program with the purpose of reviewing ongoing projects and their impact on work in the two divisions.

Overall, the NIST FRD is doing important work in more areas than many stakeholders know and certainly more than the general public appreciates. There is a need for NIST to present its results to stakeholders and the general public. There are no direct communications to end users, such as the policymakers or even the public. Work on cooking fire safety is an example of a work area where the results could benefit public education. The combination of fire visualization and data presentation could have significant value for producing public information documents for things like WUI fire safety measures. While cooperation with stakeholders such as NFPA can serve as a funnel for NIST work into public education material, it seems like a missed opportunity for NIST to brand themselves to the end users of their research. The collective websites of the FRD are not well used for communicating with stakeholders and the general public. There seems to be little focus on maintaining current websites, and there seems little attention to creating content that serves the technical community and the general public. The communications with these two diverse interest groups are comingled and confused. While the division has been innovative in the visual communication of data, there are unexplored opportunities online. Increasing the visibility and impact of the laboratory in the eyes of the public and political decision makers will be greatly enhanced by the communications tools now being used and refined to continue the work of the laboratory even from diverse remote locations. These Internet collaboration tools can also integrate well with the goal of developing and maintaining open access to laboratory research.

### RECOMMENDATION: The Fire Research Division should promote the work of the division through direct communications and better use of the public affairs office. This should include

* + **Updating and expanding the division’s websites to better communicate with the technical community and the general public.**

### Building on the public outreach and interactions created by the COVID-19-driven necessity for remote work to maintain and encourage continued outside agency and public participation with NIST. Even when in-person meetings are again possible, broadcasts of meetings on web services should be continued and should promote application of the lessons learned about collaboration in separate venues with goal of aiding efforts for fire research in widely scattered sites around the world.

**RECOMMENDATION: The Fire Research Division should use NIST staff to train field observers from outside organizations that are familiar with fire forensics, with the goal of solidifying the connections and information exchange with first responders and disaster service workers.**

## 7

**Net-Zero Energy, High-Performance Buildings Program**

The Net-Zero Energy, High-Performance Buildings Program is one of two programs that are being pursued within the Energy and Environment Division. The program objective is to develop and deploy advances in measurement science to move the nation toward net-zero energy, high-performance buildings while maintaining healthy indoor environments. The program has four technical thrusts—whole building metrics, building load reduction, equipment efficiency, and onsite energy generation.

The division consists of 11 projects led by 11 separate project leaders. There are 25 full-time permanent staff members (20 scientists and engineers and 5 technicians); 8 other employees (term employees, postdoctoral researcher, and students); and 6 NIST associates.

### TECHNICAL MERIT OF THE PROGRAM

**Accomplishments**

The program demonstrated significant accomplishments across all four technical thrusts.

The Whole Building Metrics thrust displayed technical accomplishments across the spectrum of building sustainability areas, including the development of metrics and evaluation tools for indoor air quality (IAQ) applicable to low-energy buildings. Of special note is the flexibility and speed exhibited in responding to the COVID-19 pandemic in several ways, including by incorporating the CONTAMX engine into the FaTIMA tool developed to assist in evaluating the impacts of aerosol exposure controls in response to COVID-19.

The unique Net Zero Energy Residential Test Facility (NZERTF) offers tremendous opportunities to test low-energy systems with the goal of demonstrating net-zero energy performance. Systems tested included space conditioning equipment, air distribution, domestic water, and demand-controlled ventilation. The NZERTF is expected to be used to support the Chemical Assessment of Surface and Air (CASA) project in fiscal year (FY) 2022, which is a collaborative, multi-institution field effort to quantify indoor air chemistry issues (connected to the Sloan Foundation Indoor Chemistry program).

Significant contributions in high-performance buildings include the following: the production of formaldehyde measurement and reference material production—formaldehyde is one of the most common and most concerning volatile organic compounds (VOCs) emitted by many building materials, and it is the only VOC that is regulated currently—and the study of emissions from cigarette butts, which is new science directed at assessing a potential health risk, conducted with sponsorship of the U.S. Food and Drug Administration (FDA) as well as internal NIST funds.

The initiation of a project to understand factors that contribute to water quality under the operational parameters of high-performance buildings is necessary to achieve the net-zero goal. In net- zero energy, high-performance buildings, the reduction in water usage leads to unintended, undesired consequences, such as pipe corrosion, deposition of corrosion byproducts, decreased waste conveyance, increased biofilm formation, and pathogen growth.

NIST continues to develop software programs (BEES, BIRDS, BIRDS NEST, and E3) for use in valuation of economic performance (life-cycle cost) and environmental performance (life-cycle assessment). BIRDS NEST (Building Industry Reporting and Design for Sustainability Neutral Environmental Software Tool) software will replace BIRDS (which measures the environmental performance of building products by using the life-cycle assessment approach specified in the ISO 14040) and is interoperable with the Department of Energy’s OpenStudio, the Athena Sustainable Materials Institute’s (ASMI’s) Impact Estimator for Buildings, and compatible with a variety of other software tools. It is used by building designers and architects familiar with building energy modeling E3 is an economic evaluation engine that will provide economic calculations to academics and software developers.

Under the Building Load Reduction thrust, the IAQ research group developed the important extensions of IAQ analysis tools (specifically CONTAM) to couple with energy simulation software (EnergyPlus and TRNSYS) to provide improved characterization and analysis of net-zero energy buildings. The NIST program on evaluation of insulation materials remains the world’s leading program for the measurement science of current, widely used insulation materials. Insulation is a key component in the energy efficiency of the building envelope, which is a long-lasting building system.

The Equipment Efficiency thrust’s accomplishments will enable the use of the low-global warming potential (GWP) refrigerants to be used safely in building applications. Development of heat transfer and system performance information will assist in the selection and implementation of the best replacements for high-GWP hydrofluorocarbon (HFC). The thrust has advanced testing and modeling of the fire behavior of low-GWP working fluids, which have higher flammability than the working fluids they are replacing. This work is among the best in the world and is globally integrated with collaborators. The thrust is also testing high-efficiency equipment (various kinds of heat pumps, including CO2, an emerging technology) in environmental chambers and the NZERTF. The data analysis and simulations identify climate-appropriate solutions and implement optimization in design software. Additionally, novel equipment (e.g., magnetic refrigeration) has been investigated.

The On-Site Energy Generation thrust’s accomplishments include the characterization of photovoltaic components and materials within them. The NIST research team has designed and built SI- traceable reference cells for terrestrial one-sun (AM1.5) condition. The United States was behind other nations (e.g., Germany and Singapore) in developing photovoltaic (PV) standards. This brings the United States to parity with other countries. There is a need for U.S. researchers to obtain reference cells to validate their PV performance. This is a very important function of this group of researchers. NIST Campus PV arrays and weather station data (https://doi.org/10.18434/M3S67G) are good resources.

Polymeric materials are used widely in PV modules. While the silicon light absorber can last for a long time, less is known about the long-term performance of these polymers in encapsulants and back sheets. This project helps develop and implement facilities and measurement techniques to study these supporting, but critical, materials in the PV modules.

### Challenges and Opportunities

The Assessment of Insulation Thermal Performance project is expanding into the measurement of innovative insulation materials. Because some of these new insulation materials have different mechanisms of thermal transport, current test methods may not provide a complete characterization of the material performance. For example, phase change materials need to have a procedure that accounts for the energy storage in the phase change.

There is no mention of a thermoelectric program to harvest waste heat, which might be an important aspect of low-energy buildings.

There are concerns about safety issues, in particular fire safety, associated with materials used in low-energy buildings. Cross-division collaborations would be productive in gathering data to better understand these issues.

The Engineering Laboratory’s (EL’s) capabilities for developing a flammability metric for low- GWP working fluids are unique and would offer benefits if the capabilities were deployed in other applications—for example, the use of low-GWP processing aids in industrial processes.

The NIST PV research group has started to investigate indoor PV standards and reference cells. Low-light studies and indoor white light harvesting will be important for wide deployment of Internet of Things (IoT) devices and sensors needed to monitor energy usage in low-energy buildings. Indoor PV measurement standards are urgently needed.

The PV performance project so far has worked only on traditional inorganic PV materials, (e.g., Si, GaAs, and Ge); second-generation and third-generation PVs (e.g., organic PVs and halide perovskite PVs) have now achieved very high efficiencies under AM1.5. They might be even more applicable for indoor PV applications.

Understanding the compounding effects of multiple stresses—for example, thermal and mechanical, on degradation mechanism of the polymers used in PV systems is important. Understanding how to use laboratory results to predict field service outcome is necessary for the next phase of the study.

The renewed awareness of indoor air quality created by the COVID-19 pandemic combined with the growing use of simulation in engineering practice is an opportunity for further development of the capabilities and integration with other tools of CONTAMW.

### PORTFOLIO OF SCIENTIFIC EXPERTISE

**Accomplishments**

The Net-Zero Energy, High-Performance Buildings team is one of the leading modeling tool development groups in IAQ, complemented by experimental/field investigation capabilities of the group.

A staff member has been recognized by a prestigious Presidential Early Career Award for Scientists and Engineers (PECASE) in 2019 and is the driver of the NIST PV program. Collaboration with researchers who specialize in the net-zero buildings to implement indoor light harvesting for IoT devices is beneficial for the next phase of the electrical performance of solar PV cells and arrays project.

Non-destructive optical and chemical characterizations are important for studies into the service life prediction of polymers used in PV systems. The laboratory expertise and field studies are both necessary to achieve the objective.

The combination of experimental and simulation capabilities has led to achievements necessary for the industry to fully utilize the low-GWP refrigerants.

The development of metrics and tools for sustainable buildings, such as BEES, BIRDS, BIRDS NEST, and E3, requires close collaboration between economists and engineers. NIST is an ideal environment for such an interdisciplinary project.

NIST is long recognized as the leader in insulation measurement and standards.

EL has very good expertise in laboratory, field measurements, and modeling in contaminant control and IAQ.

The water use in high-performance buildings project builds on NIST’s existing building water heating energy efficiency study on testing methods for water heaters.

### Challenges and Opportunities

NIST is no longer making organic PVs, and so there is no internal collaboration for the PV group in EL to explore newer technologies. The group needs to seek collaborations outside of NIST.

In the insulation thermal performance project, succession planning for retiring personnel is critical. It appears that principal investigator succession transition has been successful, but it is less clear what the plans are for succession planning for the technician resource.

The water use in high-performance buildings project requires expertise in fluid dynamics, heat transfer, biology, and modeling. The information provided did not show a multidisciplinary team.

### ADEQUACY OF RESOURCES

**Accomplishments**

The NZERTF is a unique facility that provides opportunities for a multitude of high-performance building studies, including equipment testing, energy efficiency, and IAQ. Although built several years ago, significant foresight into the design of the building has allowed the structure to maintain building loads that remain lower than current code-compliant building. The three ground-source heat pumps in the NZERTF are impressive and will allow quantitative comparison of different technologies. Additionally, side-by-side, small-duct high-velocity, and conventional heat pump systems will provide valuable comparison data.

The emission testing laboratory used for formaldehyde and cigarette butt studies has excellent capabilities.

A substantial multiyear overhaul of the unique guarded hot-box facilities was completed this year.

The HVAC&R research group has a combination of capabilities in material property characterization, application testing (mini-breadboard heat pump [MB-HP]) and modeling. Equipment modifications were made to accommodate new refrigerant flammability concerns.

The laboratory’s experimental apparatus and modeling capabilities for the investigation of flammability of low-GWP refrigerants are excellent and unique.

There are advanced measurement capabilities, including LED array sources, complete I-V-T (current versus voltage versus temperature) measurement stations, and wide-field hyperspectral imaging system, open up the ability to study different PV materials and devices.

The state-of-the-art accelerated laboratory weather chamber is critical for study of long-term polymer degradation.

### Challenges and Opportunities

Additional equipment is needed for measuring non-steady state material thermal transfer properties.

Several facilities are necessary for the successful completion of projects, including the environmental chambers, which are aging and need maintenance and possibly upgrade and enhancement.

A single researcher is listed for the water use in high-performance buildings project. For something this complex, it seems that a team is needed.

### EFFECTIVENESS OF DISSEMINATION OF OUTPUTS

**Accomplishments**

There are many instances of collaboration with universities and others outside of NIST to apply tools in their research. Some examples include the following: collaboration with the Boston University School of Public Health to study of interventions to reduce multifamily housing energy use and contaminant exposures using coupled simulations; collaboration with the New Jersey Institute of Technology on the analysis of comfort data from prior heat pump (HP) system tests; and participation in

the multi-institution Chemical Assessment of Surface and Air (CASA) project that will be widely disseminated under Sloan Foundation sponsorship.

The NIST PV research group publishes in appropriate journals (e.g., *IEEE Journal of Photovoltaics* and *Applied Physics Letters*). As part of the group’s outreach, members attend PV specialist conferences.

Applications of tools (e.g., CONTAM) are frequently published in journals and presented at conferences. In FY 2018, stakeholders from the building energy efficiency, water efficiency, and water quality communities were convened to formulate measurement science research needs for plumbing systems. The result was a roadmap published by NIST (https://doi.org/10.6028/NIST.TN.2088). Staff participate in the International Thermal Conductivity Conference and publish in relevant journals such as *Metrologia*, *Journal of ASTM International*, and *ASHRAE Journal*. Staff regularly present at the International Society of Indoor Air Quality and Climate Indoor Air conference, the largest and most important conference for indoor air quality science.

Staff members are active participants in the development of several ASTM standards on standardized test methods for improving materials testing, laboratory weathering, and service life prediction of PV polymers and components. Additionally, they actively contribute to several ASTM standards on chemical emissions from building materials, including formaldehyde; they provide continuing leadership insulation standard reference materials that are widely used by industry (1450e Fibrous Glass Board, 1452 Fibrous Glass Blanket, 1453 Expanded Polystyrene and 1459 Fumed Silica Board); and contribute to thick calibration transfer specimens for manufacturers of residential insulation (linked to ASTM Committee C16 on Thermal Insulation).

Staff have been significant participants in interactions with refrigerant stakeholders and standards development. Within ASHRAE, staff are active on: T.C. 3.1—Refrigerants and Secondary Coolants, Research Subcommittee; SSPC 34, Flammability Subcommittee; the Project Management Subcommittee for ASHRAE-RP1806; the Project Management Subcommittee for new HF formation project; and presenting at ASHRAE meetings. For the Air-Conditioning, Heating, and Refrigeration Institute (AHRI), staff hold membership on the AHRI Flammable Refrigerants Subcommittee and are helping to identify and guide new research on refrigerant flammability. For the International Organization for Standardization (ISO), staff hold membership in TC86, SC 8/WG8: Burning Velocity Test Methods, providing on-going detailed input to new ISO standard test methods on LBV (laminar burning velocity). Staff are technical points of contact for two NIST Standard Reference HVAC& R Databases: (1) CYCLE\_D, for evaluating refrigerant cycle performance based on thermodynamic properties [(https://www.nist.gov/srd/nist-standard-reference-database-49),](http://www.nist.gov/srd/nist-standard-reference-database-49%29) and (2) REFLEAK, for estimating the composition shift of zeotropic refrigerant blends resulting from the leak/recharge processes [(https://www.nist.gov/srd/nist-standard-reference-database-73).](http://www.nist.gov/srd/nist-standard-reference-database-73%29)

Staff make their NIST-developed simulation tools publicly available. The development of software is driven by industry needs, and these tools are widely used in academia. CYCLE\_D-HX has been completed, and validated with extensive testing, and placed on the NIST EL website in FY 2018 for free download [(https://www.nist.gov/services-resources/software/](http://www.nist.gov/services-resources/software/cycled-hx-nist-vapor-compression-)c[ycled-hx-nist-vapor-compression-](http://www.nist.gov/services-resources/software/cycled-hx-nist-vapor-compression-) cycle-modelaccounting-refrigerant). BEES, BIRDS NEST, and E3 are associated with the metrics program and sustainability and economic analysis of projects. CONTAM is one of the most widely used multizone modeling tools for the study of air and contaminant flows in buildings. It has been coupled with multiple complementary tools for energy simulation and also with CFD software. The CONTAMX computational engine has been used in special purpose tools including LoopDA for natural ventilation analysis and FaTIMA for exposure analysis.

### Challenges and Opportunities

Since NIST is not an academic institution and needs to balance publications, standards, reference materials, and research, the productivity cannot be measured by publications alone. However, it should be

clear to the researchers whether they are measured by the number of publications or the number of citations from their publications. The Net-Zero Energy, High-Performance Buildings program’s only publication from 2018, associated with the Measurement Science for Service Life Prediction of Polymers Uses PV Systems project, seems to be below expectation.

Little work is being done with standards development on the electrical performance of solar PV cells and arrays, and it seems this is potentially a fruitful area for standards.

### CONCLUSIONS AND RECOMMENDATIONS

Many of the accomplishments of the Net-Zero Energy, High-Performance Buildings program involve the measurement, characterization, and modeling of indoor air quality in high-performance buildings. Indoor air quality concerns related to COVID-19 and smoke from wildfires lately have increased the urgency of research in this area. Creating a separate technical thrust in IAQ may allow NIST’s EL-unique capabilities to be used to address a greater number of applications.

### RECOMMENDATION: The Net-Zero Energy, High-Performance Buildings program should organize a specific technical thrust in indoor air quality (IAQ) in order to increase the program’s ability to provide a focused and effective response to urgent IAQ issues.

The NZERTF is a unique facility that provides benefits both to NIST and to external researchers and collaborators. There is potential to expand the use of the facility to further develop the program’s interactions with external collaborators.

### RECOMMENDATION: The Engineering Laboratory should proactively seek opportunities to fully utilize the capabilities of Net Zero Energy Residential Test Facility to expand collaborations between the program researchers and other researchers.

The EL’s unique position in the development of IAQ analysis tools (especially CONTAM) and the coupling of CONTAM with energy simulation software has provided improved analysis capabilities of net-zero energy building performance. These capabilities can be extended with an improved CONTAM user interface and continued projects that analyze the interaction between indoor environment and energy efficiency.

### RECOMMENDATION: The Engineering Laboratory should improve the CONTAM user interface and seek opportunities to demonstrate the interaction between indoor air quality and energy efficiency analyses.

The EL has long been the industry leader in the metrication and standardization of insulation and HVAC&R equipment. To maintain this leadership position, the testing facilities need to be maintained and upgraded to match the innovation occurring in industry.

### RECOMMENDATION: The Engineering Laboratory should seek adequate funding of facilities maintenance to ensure that NIST can continue its industry leadership position in measurement and standardization of energy-efficient materials and systems.

The work of the EL to understand the performance, especially the flammability, of low-GWP working fluids is critical for the successful transition to low-GWP fluids. As the transition to low-GWP fluids is occurring across industrial sectors, this research can be expanded to support industrial processing.

### RECOMMENDATION: The work to develop a flammability metric for low- global warming potential working fluids should be expanded to include additional industrial applications.

The creation of calibrated standard reference solar cells by the EL researchers established an SI- traceable reference instrument and brought the United States on par with other countries. However, it is prudent to look ahead, rather than playing catch-up. In the past decade, there have been many breakthroughs in third-generation photovoltaic cells, in particular organic and perovskite solar cells.

Additionally, standards need to be established for new applications beyond one-sun conditions (e.g., indoor IoT applications). If expertise does not exist within NIST, outside collaborations should be sought.

### RECOMMENDATION: The NIST Photovoltaics research group should establish standards for solar cells based on materials beyond traditional inorganic semiconductor solar cells and for testing conditions beyond terrestrial one-sun illumination. If expertise does not exist within NIST, outside collaborations should be pursued.

Dissemination of EL results takes on several different forms—for example, publication in referred journals or NIST technical notes, software, standards, and reference materials. Depending on the nature of the work, groups naturally have different portfolios. The dissemination activities are not uniformly high across all projects. It would also be helpful for the staff to know the precise metric for evaluation. In terms of publication of refereed papers, the EL needs internal clarification as to whether the number of papers or the number of citations of the papers that is important. Additionally, the number of standards adopted has not been tracked.

**RECOMMENDATION: The Engineering Laboratory should articulate clear evaluation criteria for output and use these criteria to determine whether to encourage or to sunset a project. Since NIST is unique in setting standards, adoption of standards by industrial groups should be tracked.**

## 8

**Embedded Intelligence in Buildings Program**

The Embedded Intelligence in Buildings (EIB) Program seeks to develop and deploy advances in measurement science that will improve building operations to achieve lower operating costs, higher energy efficiency, and occupant comfort, safety, and security through the use of intelligent building systems.1 The project topics related to this mission include building operational improvements to achieve energy efficiency while enhancing occupant comfort and safety, developing intelligent agent approaches for control of complex building systems, improving building commissioning and functional performance tests, integrating with intelligent electricity grids, building management system interoperability, and fault detection and diagnostics for building systems.

The EIB Program resides within the Energy and Environment Division (EED) of the NIST Engineering Laboratory (EL). Some EIB Program staff members work in the Smart Grid Office and are not part of the EED. The EED supports about 51 technical staff members. The EIB Program operates with an annual budget of $3.4 million, of which approximately 10 percent is supported from the NIST Smart Grid Office and the remainder from the EED. Staffing has not had a net change in the past 5 years, as new hires are offset by retirements and departures.

Intelligent controls for heating, ventilation, and air conditioning (HVAC) are an area of rapid growth within the broader HVAC market, expected to reach a global value of about $33 billion by 2026.2 The potential economic impact of advances in embedded building intelligence is enormous, since HVAC accounts for about 50 percent of residential energy use3 and 44 percent of commercial building energy use.4 The issues have national importance, since survey information has reported that more than 90 percent of residential HVAC systems are operating with at least one fault and that even more fail basic diagnostics because of flow restrictions or incomplete installations.5

On a global scale, the 2018 Intergovernmental Panel on Climate Change report noted that in 2010 buildings accounted for 32 percent of total global energy use, 19 percent of greenhouse gas (GHG) emissions, and up to one-third of fluorinated gases.6 Energy use and emissions from the building sector

1 Embedded Intelligence in Buildings Program description is available at <http://www.nist.gov/programs-> projects/embedded-intelligence-buildings-program.

2 *GlobeNewsWire*, 2020, “HVAC Controls Market to Expand with 12.2% CAGR through 2026,” <http://www.globenewswire.com/news-release/2020/06/16/2048592/0/en/HVAC-controls-market-to-expand-with-12-> 2-CAGR-through-2026.html.

3 U.S. Energy Information Administration (EIA), 2015, “Energy Use in Homes,” http[s://www.ei](http://www.eia.gov/energyexplained/use-of-energy/homes.php)a.go[v/energyexplained/use-of-energy/homes.php.](http://www.eia.gov/energyexplained/use-of-energy/homes.php)

4 EIA, 2012, “Commercial Buildings Energy Consumption Survey (CBECS),” 2012 data, Table E1, [http://www.eia.gov/consumption/commercial/data/2012/c&e/cfm/e1.php.](http://www.eia.gov/consumption/commercial/data/2012/c%26e/cfm/e1.php)

5 J.P. Proctor, 2004, “Residential and Small Commercial Central Air Conditioning; Rated Efficiency Isn’t Automatic,” ASHRAE Winter Meeting.

6 O. Lucon, D. Ürge-Vorsatz, A. Zain Ahmed, H. Akbari, P. Bertoldi, L.F. Cabeza, N. Eyre, et al., 2014, “Buildings,” Chapter 9 in *Climate Change 2014: Mitigation of Climate Change*, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, and New York, NY, [http://www.ipcc.ch/site/assets/uploads/2018/02/ipcc\_wg3\_ar5\_chapter9.pdf.](http://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter9.pdf)

could double or triple by 2050 unless trends are changed. Section 433 of the Energy Independence and Security Act (HR 6, December 2007) requires that all new federal buildings and major renovations meet the energy performance standards of the “2030 Challenge” beginning in 2010. The 2030 Challenge proposes that all new buildings, developments, and major renovations shall be carbon-neutral by 2030.7 This move toward net-zero energy (NZE) and high-performance buildings and communities is an important motivator of the NIST program.

Given the huge stock of existing buildings, many cities are establishing “Tune-Up” mandates8 to require periodic retro-commissioning of commercial buildings larger than about 5,000 m². As the NIST team pointed out, in most cases energy reduction links to improved occupant comfort, as systems are adjusted to perform to their design targets. Although sophisticated building automation systems are used in large commercial buildings in the United States to manage HVAC systems, the NIST team reported that most buildings are not properly commissioned, operated, or maintained. External studies suggest that over 30 percent of annual primary energy consumed in today’s U.S. commercial buildings could be saved with fully functional advanced controls.9 Existing buildings and emerging high-performance buildings require accurate sensing, effective use of existing controls, deployment of advanced controls, and enhancement with embedded intelligence. Associated technologies include embedded automated fault detection and diagnostics (AFDD) for building systems, automated continuous commissioning of building systems, fault-tolerant controls, and effective user interfaces are essential for strong national-scale impact.

Building integration of renewable energy is another major trend. Intelligent buildings with integrated renewable resources (photovoltaic solar panels, for example) offer an opportunity to link the control of loads, small-scale storage, and renewable resources into combined “grid friendly” end use. The challenge for architects and building systems designers is how to develop system-level concepts for more effective energy management. Interconnection of renewable energy is based primarily on power electronic inverters, with fast dynamic control but no inherent inertia. Several studies have shown that inverter droop controls can mitigate undesired dynamic impacts on the grid, provided there is some energy headroom or storage.10,11 Electric vehicles offer possible storage resources when integrated into a building system with vehicle-to-grid (V2G) interfaces.

A building itself has the potential to act as large-scale thermal storage, since the thermal time constants have scales of minutes or hours. Storage can be added intentionally with extra mass, such as ice, or by integrating hot water systems into energy management. A motor in an HVAC system, for example, can be controlled on millisecond time scales. Altering fan speeds or turning heaters or coolers on and off can implement fast dynamic load management, potentially offsetting rapid variations of solar resources.12 It is clear that energy elements and sources in a building (e.g., electrical, water, gas, oil, and solar) as well as building operations need to be measurable and controllable. At a campus or community level, concepts

7 See Architecture 2030, “The 2030 Challenge,” https://architecture2030.org/2030\_challenges/2030-challenge.

8 See, for example, City of Seattle, “OSE Building Tune-Ups Ordinance,” [http://www.seattle.gov/Documents/Departments/OSE/OSE%20Building%20Tune-Ups%20ORD.pdf;](http://www.seattle.gov/Documents/Departments/OSE/OSE%20Building%20Tune-Ups%20ORD.pdf%3B) City of New York, “Energy Audits and Retro-Commissioning,” <http://www.nyc.gov/>html/gbee/html/plan/ll87.shtml; City of Philadelphia, Bill No. 190600, http[s://ww](http://www.imt.org/wp-content/uploads/2020/02/Final-legislation-)w[.imt.org](http://www.imt.org/wp-content/uploads/2020/02/Final-legislation-)/w[p-con](http://www.imt.org/wp-content/uploads/2020/02/Final-legislation-)t[ent/uploads/2020/02/Final-legislation-](http://www.imt.org/wp-content/uploads/2020/02/Final-legislation-) CertifiedCopy19060001.pdf.

9 N. Fernandez, W. Katipamula, W. Wang, Y. Xie, and M. Zhao, 2018, Energy savings potential from improved building controls for the US commercial building sector, *Energy Efficiency* 11(2): 393-413, https://doi.org/10.1007/s12053-017-9569-5.

10 P.J. Hart, R.H. Lasseter, and T.M. Jahns, 2019, Coherency identification and aggregation in grid-forming droop-controlled inverter network, *IEEE Transactions in Industry Applications* 55(3): 2219-2231, doi: 10.1109/TIA.2019.2891555.

11 M. Sinha, F. Dörfler, et al., 2017, Uncovering droop control laws embedded within the nonlinear dynamics of Van der Pol oscillators, *IEEE Transactions in Control of Network Systems* 4(2): 347-358, doi: 10.1109/TCNS.2015.2503558.

12 H. Hao, Y. Lin, et al., 2014, Ancillary service to the grid through control of fans in commercial building HVAC systems, *IEEE Transactions in Smart Grid* 5(4): 2066–2074.

of building energy integration can be expanded. Mitigation of dynamic imbalance between supply and demand will require more sophisticated algorithms to coordinate operations with the electric grid. This is an important opportunity for standards and measurement, especially directed at interoperability.

### TECHNICAL MERIT OF THE PROGRAM

**Accomplishments**

The NIST EIB team has been recognized with several major awards that affirm their leading contributions to intelligent building controls. The dominant professional organization related to the program is the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). A staff member received the 2017 ASHRAE Standards Achievement Award.13 This is one example of this program’s major role in emerging standards for high-performance building. Several other team members have received industry-related awards or Department of Commerce leadership recognition. The NIST team’s work on BACnet verifies their global leadership. BACnet, the building automation and control network protocol that has become ASHRAE/ANSI Standard 135, and standard ISO 16484-5, which enables disparate building systems to exchange information.

The NIST team’s publications and products include major contributions such as HVACSIM+, the “HVAC SIMulation PLUS other systems” computation tool.14 The NIST Data Alignment Tool helps users analyze building system fault and commissioning information.15 The current research on failure detection and diagnostics is leading new directions for industry and has strong promise for positive impact on building system performance and energy reduction. The industry engagement on these programs is strong and foundational to projects in building performance.

The work on semantic interoperability for intelligent buildings is excellent and paves a path toward an exciting future for the EL and for the early-career personnel running the project. The work on smart-grid integration and on fault detection and diagnostics is ongoing. These important projects need to be integrated into a long-term strategic plan. The nation clearly benefits from NIST as the premier global organization for testing and measurement. The enormous impact of buildings and the built environment makes the EIB program and its planning and personnel a vital national investment likely to have large- scale returns.

### Challenges and Opportunities

The EIB program information did not present a well-formed strategic pathway to ensure that projects and personnel are part of a larger multidisciplinary path toward common goals for intelligent buildings. Many projects appeared to be initiated in an ad hoc manner, contributing to the program mission but with limited inter-project cohesion. Projects need to build synergy to guarantee relevance, timeliness, and the ability to lead industry toward 21st century intelligent building excellence. There was limited evidence of rigorous metrics and assessment of individual projects relative to overall program goals. The evidence presented seemed to rely on conventional academic metrics such as technical publications, conference papers, and service to technical organizations. While these are an important

13 ASHTAE, 2017, “ASHRAE Celebrates Contributions, Achievements of More than 100 Members at the 2017 Long Beach Annual Conference,” <http://www.ashrae.org/about/news/2017/ashrae-celebrates-contributions-> achievements-of-more-than-100-members-at-the-2017-long-beach-annual-conference.

14 NIST, 2020, “HVAC SIMulation PLUS Other Systems (HVACSIM+),” <http://www.nist.gov/services-> resources/software/hvac-simulation-plus-other-systems-hvacsim.

15 The tool is available to the public at NIST, “The NIST Data Alignment Tool,” updated June 18, 2019, [http://www.nist.gov/services-resources/software/nist-data-alignment-tool.](http://www.nist.gov/services-resources/software/nist-data-alignment-tool)

starting point, metrics are needed to establish impact on industry practices and on rapid and widespread adoption of effective intelligent building systems. NIST needs to articulate a long-term strategic plan to make sure that the spectrum of projects remains strong and bold and fits into a larger roadmap for intelligent buildings.

Given the modest program budget and project portfolio, wide impact is difficult to achieve, but Americans spend more than 90 percent of their time in buildings, and effective building systems have large-scale quality-of-life impacts. The program has an opportunity to articulate the large return on investment for the full range of EIB goals. Basic objectives such as establishing interoperability practices and programs for industry can help restore U.S. leadership in building systems technology and equipment. The impact is immense. The extreme return on investment will help communicate the opportunities and the urgency.

### PORTFOLIO OF SCIENTIFIC EXPERTISE

**Accomplishments**

The EIB programs as presented by the NIST team showed strong expertise and overall technical excellence. The individual projects were well thought out and executed competently. The principal investigators were goal-driven and had specific, clear deliverables for each project. A concern is limited evidence of a unifying strategic plan to ensure coordination and cross-fertilization of present and future projects.

### Challenges and Opportunities

NIST EL has an opportunity to make sure that the entire spectrum of projects and personnel feeds into a long-term vision. The laboratory has established a formal mentoring program, which appears to be having strong positive impact. There are several areas in which informal collaboration across NIST has been beneficial. There is an opportunity to encourage more formal collaboration. For many projects, it was observed that relevant expertise resides beyond the EED.

The Intelligent Building Agents Laboratory (IBAL) is state of the art and employs advanced technology, although there was a clear shortage of personnel and long-term resources to support potential long-range strategic directions. Many key personnel were transient or short-term employees, such as postdoctoral researchers or term assignees. This revealed a need for personnel pipeline planning to bring in, sustain, and support a diverse workforce. This diverse workforce will benefit from well-defined career paths to guarantee successful matriculation of key personnel at NIST. Given the relatively low turnover at NIST—generally an advantage—a clear plan to grow, train, and support early-career hires is essential.

Along these lines, the NIST EL has established a formal mentoring program for its new hires, but it could expand the impact of this activity. The mix of the later- and earlier-career researchers is advantageous, but some of the interactions seem incidental with no planned structure. A more experience-diverse workforce will yield a more diverse set of solutions that will foster and present new solutions to challenging problems.

### ADEQUACY OF RESOURCES

**Accomplishments**

The EIB program has developed several unique national laboratory resources for high- performance buildings. The new IBAL has set up a rigorous measurement environment for building

systems and devices. One of its strengths is the ability to perform reproducible tests under nearly any plausible operating condition. The facility can simulate exterior weather through control of temperature, moisture, and other factors. It can evaluate, in depth, the performance of devices or controls.

The program has access to the Net-Zero Energy House (NZE House). In contrast to more conventional test houses at various locations, the NIST NZE House is set up for careful, highly reproducible, testing and measurement. In the renewable energy arena, the lack of reproducible test conditions and consistent measurement methods have been barriers to progress. The thorough scientific approach at NIST confirms their global leadership in rigorous science-driven data generation and analysis.

### Challenges and Opportunities

Thermal and environmental test chambers are crucial tools for evaluation and testing at the device and subsystem level. Facilities such as IBAL and the NZE House are exceptional tools for large-scale system tests, but they are not intended to support quicker evaluation and analysis of components or subsystems. The existing chambers for this purpose are dated and do not support the range of necessary tests and measurements. Enhancement of these aspects of laboratory infrastructure is vital to support strong national impact.

A few relevant national laboratories within the Department of Energy (DOE) portfolio, notably the National Renewable Energy Laboratory (NREL) and the Pacific Northwest National Laboratory (PNNL), have equipment-intensive work related to renewable energy integration, intelligent electricity grids, and building-integrated renewable energy. The EIB program might be able to take advantage of some related facilities, bringing NIST’s unparalleled excellence in test and measurement to bear on projects that could return high-impact results suitable for NIST. The team has the opportunity to explore potential collaborations, including collaborations with universities.

### DISSEMINATION OF OUTPUTS

**Accomplishments**

The EIB Program personnel and project work is known and respected in the professional community. Products such as software tools and models are available to the public and effectively supported by the NIST team. BACnet in particular is a dissemination highlight, with wide adoption in industry and substantial impact. The program disseminates many of its activities through technical publications and journal articles. The research productivity is on par with other leading laboratory programs.

### Challenges and Opportunities

As of 2012, the United States has more than 5.6 million commercial buildings.16 Microsoft has created a building outline database with more than 125 million entries.17 A major challenge is that architects, builders, owners, occupants, and other end users often have disparate objectives for building systems and their operation. In residences, occupants have primary control. The growth of consumer intelligent tools such as Nest thermostats suggests that user-friendly interfaces with informative feedback

16 U.S. Energy Information Administration, 2012, *Commercial Buildings Energy Consumption Survey (CBECS)*, [http://www.eia.gov/consumption/commercial/reports/2012/buildstock/.](http://www.eia.gov/consumption/commercial/reports/2012/buildstock/)

17 Microsoft, 2020, “US Building Footprints,” [http://github.com/microsoft/USBuildingFootprints.](http://github.com/microsoft/USBuildingFootprints)

can have profound impact on building operation and performance. NIST has an opportunity to influence end-user interfaces, standardize data collection and reporting, and inform citizens about high-performance building systems and the benefits of commissioning. There is an opportunity for the EIB program to seek a variety of ways to inform consumers and develop outreach materials to disseminate useful information to the public.

### CONCLUSIONS AND RECOMMENDATIONS

**Technical Merit of the Program**

The NIST EIB Program demonstrates global leadership in measurement science and its application to building operations and to intelligent building systems. This small program has outsized impact because of leadership on BACnet, on fault detection and diagnostics (FDD) tools, and on validation of intelligent building controls.

Efforts in intelligent and high-performance buildings and building systems require years or even decades of consistent effort. Although successful outcomes from the individual projects will advance the mission and vision of the EL, strategic thinking and planning to support long-term efforts is critical and essential.

### RECOMMENDATION: The Engineering Laboratory should articulate and plan more activities around a long-term strategic research plan, developed with input from independent outside advisory panels.

Intelligent building operations reach beyond temperature and indoor air quality management; operations also include lighting quality, acoustics and noise, active energy management, and the whole range of issues directed to improved human productivity and quality of life. Emerging issues include pathogen monitoring and mitigation, active noise reduction, daylight emulation, and others.

### RECOMMENDATION: The Engineering Laboratory should consider aspects of intelligent buildings and their operation to include all attributes aimed at enhanced human productivity and quality of life.

**Effectiveness of Dissemination of Outputs**

In intelligent building systems, the industry continues to rely on proprietary interfaces and has provided limited interoperability beyond basic data exchange from BACnet. The lack of interoperability of building devices and systems is a serious threat to U.S. industry. As competitors in Europe, Korea, and other places introduce more open-source interoperable systems, they are likely to overtake U.S. vendors with closed systems quickly. Communication networks and protocols, including BACnet, have limits on dynamic interoperability. For example, IEC 61850, although developed in a different context (utility substations), seeks fast data exchange for real-time intelligent grid operation. Comprehensive interoperability is being explored in health care contexts.18

18 M. Glickman and A. Orlova, 2020, “Building Interoperability Standards and Ensuring Patient Safety,” American Health Information Management Association, [http://bok.ahima.org/doc?oid=107799#.X38RIe17m70.](http://bok.ahima.org/doc?oid=107799&.X38RIe17m70)

### RECOMMENDATION: The Engineering Laboratory should work with relevant U.S. organizations and industrial partners to push for broad adoption of building systems interoperability before it is too late.

Several U.S. national laboratories are currently pursuing research and development in intelligent buildings and intelligent electricity grids. The EIB program has an opportunity to interface with facilities and projects in certain DOE national laboratories, notably the grid interface and renewable energy work at NREL and the transactive energy work at PNNL. The EL is engaged with some efforts at relevant national laboratories, but there is an opportunity to strengthen this interaction. The NIST team has the opportunity to raise the level of data-driven work at relevant national laboratories, at the same time benefiting from collaboration in some DOE facilities.

### RECOMMENDATION: The Engineering Laboratory should consider closer engagement with other relevant national laboratories, specifically on intelligent buildings and intelligent grids.

Broader adoption of AFDD and “grid friendly” features in building systems and appliances will have significant impact in improving operating efficiency and reducing operating costs. Factory installation of these features rather than retrofitting after they are built will reduce cost, enhance reliability, promote interoperability, and set a more level playing field for these vital features. Integration of grid interfaces into these will be required to balance energy generation and usage in the future. It would also be worthwhile to explore the economics of control element retrofitting.

### RECOMMENDATION: The Engineering Laboratory should work with industry, including utilities and energy providers, to encourage factory installation and standardization of automated failure detection and diagnostics features and practices. Integration of grid interfaces into these devices should be considered.

Dissemination of critical outcomes, best practices for building systems, for guidance about preventative maintenance, and for other information is critical to the success of the program and for greater impact. Given the massive installed base of residential buildings, homeowners and other occupants can play a critical role in intelligent building operation.

### RECOMMENDATION: The Engineering Laboratory should work toward broader interface with homeowners and other end users to collect and review requirements, disseminate information from its programs, influence improved user interfaces, and help end users get the best results in building operations.

This is best done in coordination with other federal agencies (for example, the DOE and EPA are active in this area also). Without coordination, the end result would duplicate work done in different ways.

## 9

**Crosscutting Conclusions and Recommendations**

The previous chapters have presented detailed conclusions and recommendations for each program reviewed. This chapter presents conclusions and recommendations that apply to two or more of the programs reviewed, first, in general and second, by the factors considered by this panel (i.e., technical merit of the programs; portfolio of expertise; adequacy of budget, facilities, equipment, and human resources; and effectiveness of dissemination of program outputs).

### GENERAL CONCLUSIONS AND RECOMMENDATIONS

The seven NIST programs reviewed—Community Resilience Program (CRP); Structural Performance Under Multi-hazards (SPUMH) Program; Earthquake Risk Reduction in Buildings and Infrastructure (ERR) Program, Engineered Materials for Resilient Infrastructure Program; Fire Research Programs, Net-Zero Energy, High-Performance Buildings Program; and Embedded Intelligence in Buildings (EIB) Program)—have contributed major advancements in measurement science, standards, and technology over the past decade, which have strongly advanced U.S. competitiveness and innovations. Current national conditions, including the international COVID-19 pandemic, major wildfires throughout the western United States, a record number of hurricanes in the Atlantic Basin, and numerous other recent high-hazard events have heightened awareness of an urgent need for NIST’s work in these specific areas. For example, the Net Zero Energy High Performance Buildings Program quickly incorporated the CONTAMX engine in the FaTIMA tool to assist in evaluating risk due to COVID-19 transmission in buildings. The Fire Risk Reduction in Communities Program rapidly developed and disseminated its current fire assessment and prediction models and is actively working with the California Department of Forestry and Fire Protection (CAL FIRE) and other on-the-ground wildland-urban interface (WUI) firefighters. These contributions and others are of increasingly high value to the United States, both in ensuring health and safety of communities as well as enabling production and commerce.

Several common themes arise across these programs. As the complexity of current extreme conditions increase, explicit collaboration and coordination across these seven NIST programs and the NIST community as a whole, as well as with external organizations, will be critical to achieve significant advancements in the future. Multidisciplinary and multi-organizational teams can effectively pursue long- term, highly interdependent research roadmaps aligned with NIST’s mission to enhance economic security and improve the quality of life.

While the demands of the nation on these divisions increase, and as NIST’s research agenda expands in response, NIST staff reported that the personnel, equipment, and facilities have not substantially increased over time and that these programs are stretched thin in expertise and resources to meet growing needs. NIST staff also reported that critical equipment and campus infrastructure are now constraining necessary facility and equipment upgrades. Internationally recognized experts within these seven programs possess unique capabilities, but as needs evolve and as staff retire, NIST’s preeminence in these fields may be jeopardized without strategic human resource planning, including recruiting, mentoring, and retaining diverse engineering and technical personnel.

While these seven programs contribute to new standards and codes, new measurement methods and standards, and new computer models and equipment, the effective dissemination and implementation of these important advancements is hindered by a lack of coordinated outreach. Accelerating the co- development and diffusion of results through employing advanced communications and marketing approaches, particularly targeting end users, could save lives, protect the economy, and improve the quality of life in the United States. Measuring the outcomes of the work by these seven programs, focusing on demonstrated benefits to safety, quality of life, and economic security, could further ensure NIST’s future contributions in these fields through apprising the U.S. public and industry of this critical and important resource. In addition, the necessary remote collaboration and outreach brought on by the pandemic response provides an opportunity to increase the effectiveness of NIST in the eyes of the public by making it possible for more stakeholders to participate in and observe the activities at NIST.

### TECHNICAL MERIT OF THE PROGRAMS

NIST EL has a long and distinguished record of technological leadership, innovation, and experience in providing analysis and solutions to large and small problems. EL research quality is exemplified by the programs’ science-based tools and outputs. The EL programs show an evolution over the past few years, which indicates a positive attitude toward adaptation to evolving needs. However, in response to these evolving needs, outside collaborations should be sought if expertise does not exist within NIST. In addition, insularity may at times be a risk.

Additionally, emerging technologies (e.g., artificial intelligence, machine learning, and increases in computational capabilities) are likely to impact these programs, and it is important to maintain continuous assessment of the applicability of such technologies to EL programs.

Except for the Fire Research Division, there appears to be a research focus on the structural resilience of concrete, steel, and polymer building materials. However, wood-frame buildings are also subject to damage or collapse from hurricanes, tornadoes, and earthquakes, and so it would be worthwhile to address the resilience characteristics of wood as a building material.

### RECOMMENDATION: The Engineering Laboratory should establish formal procedures to assure interaction with practicing professionals and researchers at other institutions, including federal agencies and universities, to assure that the program does not become overly insular.

The NIST EL programs demonstrate global leadership in measurement science and its application. While successful outcomes from the individual projects advance the mission and vision of the EL, strategic thinking and planning to support long-term efforts is critical and essential.

### RECOMMENDATION: The Engineering Laboratory should articulate and plan more activities around a long-term strategic research plan, developed with input from independent outside advisory panels.

There are frequently good communications with technical peers and standards groups. At the same time, EL staff did not present a clear consensus understanding of the EL’s policy on the importance of publications of various types (e.g., peer-reviewed, technical notes, training documents, and conference proceedings). However, where publications are encouraged, it should be clear to the researchers whether they are measured by the number of publications or the number of citations from their publications.

### RECOMMENDATION: The Engineering Laboratory should communicate to staff clear goals for the rate of annual publications of various types.

**PORTFOLIO OF EXPERTISE**

The high quality of the EL portfolio of expertise is evident in its impact on national and international codes and standards and its strong industry reputation. As programs evolve and new programs are introduced, additional areas of expertise will be needed to enable significant EL contributions and thought leadership. NIST EL contributions address a full range of issues directed to improved human productivity, safety, and quality of life, and the EL portfolio of expertise could be enriched to explicitly incorporate those competencies. For example, the areas of human behavior and health in residential and community settings do not appear to receive the same attention as other technical aspects of programs.

### RECOMMENDATION: The Engineering Laboratory should assess gaps in its expertise and add new competencies as needed, such as adding social scientists and medical scientists to the technical staff.

**ADEQUACY OF RESOURCES**

In some areas, the resources of programs seem to be stretched very thin. The prospect of future retirements suggests a challenge for ensuring the longevity of programs.

### RECOMMENDATION: The Engineering Laboratory should ensure longevity of programs through succession planning to ensure areas of expertise are not lost within NIST.

The EL resources also have challenges related to its relatively limited size and the expanding, diverse demands on its program areas. Because of the imbalance between potential demands and available resources, it is difficult to have a profound effect on the industry.

### RECOMMENDATION: The budget, human resources, facilities, and equipment resources required for both continuity and growth of these programs should be reviewed, and adequate resources should be provided to ensure they continues to develop.

A diverse staff often yields insights and perspectives that enhance the quality of research.

### RECOMMENDATION: The Engineering Laboratory should ensure an appropriate level of diversity of qualified researchers and managers as older members retire and new talent is brought on board.

The EL has long been the industry leader in the metrication and standardization materials, equipment, systems, and processes. To maintain this leadership position, the research and testing facilities need to be maintained and upgraded to match the innovation occurring in the industry.

### RECOMMENDATION: The Engineering Laboratory should seek adequate funding of facilities maintenance to ensure that NIST can continue its industry leadership position in measurement and standardization.

**EFFECTIVENESS OF DISSEMINATION OF OUTPUTS**

Greater awareness of the programs’ products outside of NIST and its immediate stakeholders would significantly benefit the recognition of the value of the products and the awareness of the important

role NIST can play nationally and globally. Working more directly with stakeholders and end users would provide valuable feedback to NIST’s efforts, which can be used iteratively to improve the NIST EL outputs and products.

The lack of a clear Internet communications strategy for the NIST programs is a serious one that needs to be addressed. This includes information about the programs, their roles, the impact they have had and intend, and opportunities for industry and academics to engage the programs. There is also a need for a strategy for using social media.

### RECOMMENDATION: The Engineering Laboratory should develop and actively promote a Stakeholder Engagement and Dissemination Strategic Plan that makes use of a broad range of traditional and emergent media to report and interpret results and solicit user input.

**RECOMMENDATION: The Engineering Laboratory should consider establishing a primary point of contact for outreach and dissemination to its diverse stakeholders, including companies, professional organizations, communities, regional and state agencies, and universities and community colleges.**

### RECOMMENDATION: The Engineering Laboratory should consider an enterprise evaluation system that would promote a holistic approach toward product development, implementation, and user feedback and would promote community engagement early and throughout the process of design through dissemination.

**RECOMMENDATION: The Engineering Laboratory should consider developing programs and tools that are user-driven, not developer-driven.**

### RECOMMENDATION: The Engineering Laboratory should develop stronger relationships with diverse portions of industry, such as design firms, utilities, manufacturing firms, facility owners, local governments, and other agencies, to help ensure that its products are responding to the needs and cultures of different types of organizations.

**RECOMMENDATION: The Engineering Laboratory should distribute its products directly to actual and potential users, and the outcomes of these dissemination efforts should be evaluated.**

### RECOMMENDATION: The Engineering Laboratory should increase its development of partnerships with international organizations.

Dissemination of critical outcomes, best practices for building systems, guidance about preventative maintenance, and other information is critical to the success of the program and for greater impact. Given the massive, installed base of residential buildings, homeowners and other occupants can play a critical role in intelligent building operation.

### RECOMMENDATION: The Engineering Laboratory should work toward broader interface with homeowners and other end users to collect and review requirements, disseminate information from its programs, influence improved user interfaces, and help end users get the best results in building operations.

This is best done in coordination with other federal agencies (e.g., the Department of Energy and the Environmental Protection Agency are active in this area also). Without coordination, the end result would duplicate work done in different ways.

# Acronyms

3DCP three-dimensional printing of concrete

AFDD Automated fault detection and diagnostics

AFM atomic force microscopy

AISC American Institute of Steel Construction

AM additive manufacturing

ARC alternatives for resilient communities

ASCE American Society of Civil Engineers

ASHRAE American Society of Heating, Refrigerating, and Air-Conditioning Engineers ASMI Athena Sustainable Materials Institute

ASR alkali-silica reaction

ASTM American Society for Testing and Materials ATLSS Advanced Technology for Large Structural Systems AWC American Wood Council

BACnet Building Automation and Control Networks

BEES Building for Environmental and Economic Sustainability

BIRDS NEST Building Industry Reporting and Design for Sustainability Neutral Environmental Software Tool

BOB burn observation bubble

BRI Building Research Institute of Japan

CAL FIRE California Department of Forestry and Fire Protection CASA chemical assessment of surface and air

CFD computational fluid dynamics

CoE Center of Excellence

CONTAM Contaminant transport analysis software CPSC Consumer Product Safety Commission

CREME concrete rheology enabling metrology

CRP Community Resilience Program

CWE computational wind engineering

DAD data-assisted design

DoD Department of Defense

DOE Department of Energy

EDGe$ Economic Decision Guide software

EIB embedded intelligence in buildings

EL Engineering Laboratory

EPA Environmental Protection Administration

ERI engineered materials for resilient infrastructure

ETABS A structural analysis software platform

FaTIMA fate and transport of indoor microbiological aerosols FDS Fire Dynamics Simulator

FEMA Federal Emergency Management Administration

FRD Fire Research Division

GEER Geotechnical Extreme events reconnaissance

GWP Global warming potential

HFC hydrofluorocarbon

HP heat pump

HVAC heating, ventilation, and air conditioning

IAQ indoor air quality

IBAL Intelligent Building Agents Laboratory

IBHS Insurance Institute for Business and Home Safety

ICC International Code Council

IDIQ indefinite delivery indefinite quantity

IN-CORE interdependent networked community resilience modeling environment IoT Internet of Things

KED light-emitting diode

MB-HP mini-breadboard heat pump

MSSD Materials and Structural Systems Division

NCSTAR National Construction Safety Team Report NEES Network for Earthquake Engineering Simulation

NEHRI Natural Hazard Engineering Resilience Institute NEHRP National Earthquake Hazards Reduction Program NFPA National Fire Protection Association

NFRL National Fire Research Laboratory

NIST National Institute of Standards and Technology

NRC Nuclear Regulatory Commission

NREL National Renewable Energy Laboratory

NSF National Science Foundation

NZE net-zero energy

NZERTF Net-Zero Energy Residential Test Facility

OA other agency

OSTP Office of Scientific and Technology Policy

PBD performance-based design

PCI Precast/Prestressed Concrete Institute

PE polyethylene

PERFORM Performance-based engineering research for multi-hazards PETG polyethylene terephthalate glycol

RUF residential upholstered furniture

|  |  |
| --- | --- |
| SPHERE | Simulated photodegradation via high energy radiant exposure |
| SPUMH | Structural performance under multi-hazards |
| SRM | standard reference material |
| SSRC | Structural Stability Research Council |
| TMAP | Technology Maturation Accelerator Program |
| TRNSYS | Transient system simulation |
| USFDA | U.S. Food and Drug Administration |
| USGS | U.S. Geological Survey |
| V2G | vehicle-to-grid |
| WUI | wildland urban interface |

79