A REVIEW OF THE MANUFACTURING-RELATED PROGRAMS AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

FISCAL YEAR 2012

Panel on Review of the Manufacturing-Related Programs at the
National Institute of Standards and Technology

Laboratory Assessments Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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

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

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

This study was supported by Sponsor Award # 1195 (under SB134106Z0011) between the National Academy of Sciences and the National Institute of Standards and Technology, an agency of the U.S. Department of Commerce. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the agency that provided support for the project.

Copies of this report are available from

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

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

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

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

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

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

www.national-academies.org

PANEL ON REVIEW OF THE MANUFACTURING-RELATED PROGRAMS AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

KANTI JAIN, University of Illinois, Urbana-Champaign, *Chair*
HADI A. AKEEL, Amteng Corporation
JULIE CHEN, University of Massachusetts, Lowell
DIANNE CHONG, The Boeing Company
RANDALL R. GORHAM, JR., Lockheed Martin Aeronautics
JEFF GUST, Fluke Calibration
LAWRENCE L. KAZMERSKI, National Renewable Energy Laboratory
JOHN W. KOZARICH, ActivX Biosciences, Incorporated
DOUGLAS LOY, Deloy, LLC
ROBERT E. SCHAFRIK, General Electric Aircraft Engines
LYLE H. SCHWARTZ, Air Force Office of Scientific Research (retired)
F. STAN SETTLES, University of Southern California
MICHAEL G. SPENCER, Cornell University
MATTHEW J. ZALUZEC, Ford Motor Company

Staff

JAMES P. McGEE, Director
CY BUTNER, Senior Program Officer
LIZA HAMILTON, Administrative Coordinator
EVA LABRE, Program Associate

Acknowledgment of Reviewers

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

John E. Allison, University of Michigan,
Julia Phillips, Sandia National Laboratories,
Kathleen Taylor, General Motors Corporation (retired), and
James C. Wyant, University of Arizona.

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

Contents

Summary

The mission of the National Institute of Standards and Technology (NIST)[1] enables NIST to provide broad support for the advancement of U.S. manufacturing. Research and services supporting manufacturing are intended to be an important component in all of the NIST laboratories. Moreover, since manufacturing is a major part of the U.S. economy, the growth or loss of U.S. manufacturing jobs is a very important issue. Clearly, the successful execution of NIST's programs supporting manufacturing will have a significant impact on manufacturing jobs in the United States. With the multidisciplinary, multisector, and crosscutting nature of manufacturing, the Director of NIST requested that the National Research Council (NRC) assess the manufacturing-related programs at NIST in 2012.

Accordingly, a panel of experts was convened by the National Research Council to perform the assessment. The Panel on Review of the Manufacturing-Related Programs at the National Institute of Standards and Technology visited the NIST campus in Gaithersburg, Maryland, on March 26-28, 2012. This report contains the results of the panel's assessment.

The assessment considered manufacturing research at NIST broadly, with emphasis on the specific advanced manufacturing areas: Nanomanufacturing (including Flexible Electronics); Smart Manufacturing (including Robotics); and Next-Generation Materials Measurements, Modeling, and Simulation. The area of Biomanufacturing also was reviewed as a subset of the Nanomanufacturing review. As is to be expected for programs covering such wide scope, the boundaries among these broad areas are not rigid and there is some overlap among them. On the basis of its assessment, the panel formed the observations and recommendations presented below, among others discussed in detail in this report.

With respect to the technical merit and the scientific caliber of the manufacturing-related research being carried out at NIST, the program teams are highly qualified and comparable to the best in the world. Equally strong, the equipment and facilities that NIST laboratories have designed, procured, and built are a national asset. Work in the Nanomanufacturing area is impressive, much of which is among the best in the world, and it evidences the unique skills and contributions of NIST. Some of the projects represent very significant examples of nanomanufacturing, and some are paradigm shifting; all of the groups are either world leaders in their chosen area or making strong strides toward a leadership position. In all areas of Smart Manufacturing the technical staff members are highly qualified, and their expertise is well matched to the specific areas being studied. Publications are of high quality and related to the areas being researched. In the Next-Generation Materials Measurements, Modeling, and Simulation area, the scientists and engineers at NIST are among the very best at the national laboratories, leaders in their fields, and equal to the best academics at leading universities or the best scientists at industrial laboratories worldwide. NIST continues to be a leading organization—the accuracy and validity of its data are the benchmark for other industries, and its scope, depth, and quality are among the best in the world.

The field of manufacturing is vast, and selection of the projects to be undertaken at NIST will often be a challenge. Whereas most of the projects in progress are of high value and importance, the vetting process for project selection could be improved, with greater attention

[1] The NIST mission 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.

paid to industry needs, manufacturability, and commercial potential. With respect to the organizational aspects of the research efforts, some programs give the appearance of being a collection of projects, lacking a coherent focus that binds them together. Program focus and program alignment under specific managers could be made stronger. In assessing the level of progress in various efforts, the panel found that in a number of cases the program metrics could be more quantitative; some of the stated metrics appear merely to be project milestones.

The interactions of NIST with industry are strong, but they could be further expanded, with more visits to companies and a greater awareness of industry practices. Such interactions would be especially helpful in avoiding research efforts that lag behind the industry state of the art. The coordination among teams across NIST laboratories is broad, although at the same time it often is ad hoc and informal. Greater benefits could be realized with more structured coordination. Finally, for its technical and scientific capabilities and accomplishments in the areas reviewed, NIST deserves more national visibility than it receives—perhaps as a result of service being a core element of its mission, and perhaps also as a result of institutional modesty.

KEY RECOMMENDATIONS

The following sections present the key recommendations of the panel for the three advanced manufacturing areas of NIST: (1) Nanomanufacturing; (2) Smart Manufacturing; and (3) Next-Generation Materials Measurements, Modeling, and Simulation. These and related recommendations are presented and discussed in Chapters 2, 3, and 4, respectively.

Nanomanufacturing

1. NIST should continue to define its vision for its Nanomanufacturing program, making clear choices about what nanomanufacturing should be on the basis of the NIST mission. To have more impact, NIST should focus on the following definitions or aspects of nanomanufacturing:
   - Making nanoscale objects to obtain special properties, and
   - Using nanotechnology to manufacture other things.

2. In addition to the focus in the Nanomanufacturing program on the current CMOS technologies, NIST should work with industry to develop the metrics for benchmarking the new, potential CMOS replacement technologies.

3. In the large CMOS device market, which is dominated by companies with vast resources, NIST should make careful judgments about where it positions itself with respect to device metrology supporting continuation of semiconductor technology advances.

4. To play an important role with respect to the issue of bankability of new technologies, NIST should consider providing methodologies, databases, reference materials, and modeling so as to provide those in the manufacturing community (especially new entrants) with a way to evaluate their approaches independently and objectively.

5. Since the structural determination of biologics may constitute a useful measurement tool for assessing the impact of modified variants on Biomanufacturing, future work

should focus on developing clear goals that will test the robustness of the approach for specific protein therapeutics.

Smart Manufacturing

6. NIST should be more proactive at partnering with industry—particularly in the areas of Additive Manufacturing, Robotics, and Automation—to decrease the gap between industry needs and the current state of the art at NIST, to decrease the need for NIST to capitalize, and, more importantly, to decrease the gap between industry needs and NIST's data-gathering and standards-development work.

7. To foster the engagement of stakeholders in additional ways besides industry association meetings and workshops, focused visits to stakeholders to determine needs and challenges in each of the Smart Manufacturing programs should be undertaken.

8. NIST should increase the engagement of stakeholders in the development of the appropriate Smart Manufacturing program goals and metrics.

9. The competitiveness of the Smart Manufacturing projects reviewed should be made more appropriate to current industry practices.

Next-Generation Materials Measurements, Modeling, and Simulation

10. As NIST continues its healthy collaboration with industry, its increasing focus on advanced manufacturing should proceed with additional recognition of industrial needs. Most of the projects in the area of Next-Generation Materials Measurements, Modeling, and Simulation should be market-driven, that is, based on market pull rather than on technology push. In establishing its technical portfolio, NIST should continue to seek strong partnerships with industrial consortia when these exist.

11. NIST's key manufacturing researchers should visit several manufacturing facilities each year in order to broaden their understanding of the real-world manufacturing environment.

12. NIST should take advantage of the opportunity to play an important role in the multiagency Materials Genome Initiative as the potential repository and gatekeeper of scientific data from multiple sources. In the design of a next-generation materials database, strong consideration should be given to seeking a full understanding of the queries that will be made against the database so that suitable accuracy and dynamic performance can be obtained. A targeted workshop on handling data should be convened with industry and other stakeholders.

13. In line with its role in external programs involving the characterization of nanoparticles for achieving a greater understanding of environmental, health, and safety issues and development of in-line nanoscale sensing and measurement capabilities, NIST should continue to take a visible role in the coordination of related

external efforts in this area within the scope of its Next-Generation Materials Measurements, Modeling, and Simulation work.

14. In addition to facilitating cross-NIST collaboration in the area of Next-Generation Materials Measurements, Modeling, and Simulation, NIST should continue to strengthen partnerships with other research institutions and industry. The NIST postdoctoral and visiting researcher programs in these areas should be continued or perhaps even strengthened as a significant source of renewal and outreach for the permanent staff at NIST.

1

The Charge to the Panel and the Assessment Process

At the request of the National Institute of Standards and Technology (NIST), the National Research Council (NRC) has, since 1959, annually assembled panels of experts from academia, industry, medicine, and other scientific and engineering environments to assess the quality and effectiveness of the NIST measurements and standards laboratories, of which there are now six,[2] as well as the alignment of the laboratories' activities with their missions. NIST requested that in 2012 the crosscutting area of manufacturing-related programs be assessed. In accord with the multidisciplinary nature of manufacturing, which covers multiple sectors, the manufacturing-related activities at NIST cut across multiple laboratories. Accordingly, the 2012 assessment considers manufacturing activities across the entire NIST organization. Manufacturing-related activities at NIST were assessed by a panel of experts appointed by the NRC. The findings of the Panel on Review of Manufacturing-Related Programs at the National Institute of Standards and Technology are summarized in this report.

The panel's statement of task is as follows:

> An ad hoc panel will conduct a review of NIST laboratory activities related to manufacturing measurements, standards, and technology and will prepare a report that will provide information on scientific, technology and research activities of relevance to NIST laboratories and user facilities in this area. The panel will undertake the following tasks:
>
> - Assess coordination of NIST programs in the targeted discipline
> - Assess relevance of the R&D efforts of the chosen discipline to the current set of national priorities as well as the needs of stakeholders
> - Assess the degree to which the measurement science, standards, and services achieve their stated objectives and fulfill the mission
> - Assess the technical merits and scientific caliber of the chosen discipline relative to comparable programs worldwide.

For this assessment, NIST requested that the panel look at manufacturing research at NIST broadly, with special emphasis on the following specific advanced manufacturing topic areas:

- Nanomanufacturing (including Flexible Electronics),
- Smart Manufacturing (including Robotics), and
- Next-Generation Materials Measurements, Modeling, and Simulation.

NIST further requested that the panel focus on the following broad factors as part of its assessment:

[2] The six NIST laboratories are the Material Measurement Laboratory, the Physical Measurement Laboratory, the Engineering Laboratory, the Information Technology Laboratory, the Center for Nanoscale Science and Technology, and the NIST Center for Neutron Research.

1. Assess the technical merit and scientific caliber of NIST's manufacturing programs relative to comparable programs worldwide. Furthermore, assess NIST's ability to provide leadership in manufacturing technology areas. How effective are current metrics for measuring value and success in manufacturing programs?
   Background: The panel is to assess whether NIST is targeting the appropriate technological maturity level in its research programs. Are the laboratories adequately anticipating technology trends and service delivery methods? Are they effectively measuring their success? Are there different or additional metrics that should be considered?
2. Assess the efficacy of NIST's engagement with outside stakeholders to:
   - Guide definition of the laboratory's priority areas that address key needs within manufacturing
   - Steer development of NIST's programmatic plans within the priority areas to address the high-priority needs of the manufacturing domain
   - Ensure that NIST's programs in measurement science, standards, and services have the necessary impact in advancing the Nation's competitiveness.
3. Assess coordination and cohesion across NIST of programs in the specific Advanced Manufacturing topics (i.e., nanomanufacturing, smart manufacturing, and next-generation materials measurements, modeling, and simulation).

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

In order to accomplish the assessment, the NRC assembled a panel of 14 volunteers who have strong expertise in the areas of the work performed by the NIST staff in the manufacturing-related programs reviewed. The panel members were also grouped into three review teams. The expertise of the members of the respective review teams especially matched that of the work performed in the areas of Nanomanufacturing, Smart Manufacturing, and Next-Generation Materials Measurements, Modeling, and Simulation. As may be expected, the lines of demarcation for programs of such wide scope are necessarily fuzzy. Consequently, although the review of NIST's manufacturing-related programs and this report were organized around these areas, the reader will find several instances of overlap and cross-reference. Also, in conducting this assessment, the panel's view was that the national priorities in manufacturing are synonymous with the priorities of the U.S. manufacturing industry.

The panel members met at the NIST facilities in Gaithersburg, Maryland, on March 26-28, 2012. The agenda for the session with the full panel included the following:

- Welcoming comments by the Director of NIST;
- Overview presentations by the Chief Manufacturing Officer, the Director of Innovation and Industry Services, and the Director of the Program Coordination Office;
- Overview presentations of NIST mission-specific work supporting and advancing manufacturing by the Director of the Physical Measurement Laboratory, the Director

of the Information Technology Laboratory, and the Director of the NIST Center for Neutron Research; and

- Overview presentations and panel discussions on the advanced manufacturing topic areas of Nanomanufacturing, Smart Manufacturing, and Next-Generation Materials Measurements, Modeling, and Simulation.

Following this full-panel session, the panel divided into its three review teams, and each team (led by a team leader chosen from within the panel) then reviewed activities in its respective advanced manufacturing topic area. During these area reviews, the review team members attended presentations, tours, and interactive sessions with NIST staff; they also conducted interactive sessions with NIST managers.

Subsequently, the entire panel assembled for discussions with NIST management. It then met in a closed session to deliberate on its findings and to define the contents of this assessment report.

The approach of the panel to the assessment relied on the experience, technical knowledge, and expertise of its members, whose backgrounds, as noted above, were carefully matched to the technical areas of NIST's manufacturing-related activities. For its assessment, the panel relied primarily on presentations made by NIST managers and staff and on the informational materials prepared by NIST staff for use by the panel prior to and during the deliberations.

The panel reviewed selected examples of the manufacturing-related technological research covered by NIST; because of time constraints, it was not possible to review these programs and projects exhaustively. The examples reviewed by the panel were selected by NIST in consultation with the panel chair and NRC staff. The panel's goal was to identify and report salient examples of accomplishments and opportunities for further improvement. These examples are intended collectively to portray an overall impression of the manufacturing-related programs at NIST while also preserving useful suggestions specific to projects and programs that the panel examined. The panel applied a largely qualitative rather than a quantitative approach to the assessment.

The comments in this report are not intended to address each particular program within the NIST manufacturing-related areas exhaustively, but instead to identify key accomplishments and issues. Given the necessarily non-exhaustive nature of the review process, the omission of any particular program or project should not be interpreted as a negative reflection on the omitted program or project.

The preceding Summary, which highlights issues that apply broadly to several or all of the manufacturing areas or to the manufacturing-related programs as a whole, presents the panel's key recommendations for NIST. Following this introductory chapter, the next three chapters provide overall assessments of the three areas of advanced manufacturing: Chapter 2 presents a detailed overall assessment of the Nanomanufacturing activities, Chapter 3 addresses the Smart Manufacturing activities, and Chapter 4 presents an overall assessment of the Next-Generation Materials Measurements, Modeling, and Simulation activities. Chapters 2 though 4 also present recommendations relevant to their topic areas, including the key recommendations presented in the Summary and others as appropriate. Chapter 5 discusses crosscutting themes identified by the panel, and Chapter 6 offers the panel's overall conclusions.

2

Nanomanufacturing

INTRODUCTION

The panel received an overview presentation on Nanomanufacturing that summarized NIST's nanotechnology strategy, its leadership in providing documentary standards in nanotechnology, several types of nanomanufacturing, and major needs and challenges. This overview was followed by presentations on nanocomposite manufacturing and nano environmental health and safety. The following detailed presentations and tours in the area of Nanomanufacturing were also given during the review:

1. Dimensional Metrology for Semiconductor Nanomanufacturing
2. CMOS Devices Metrology for the Continuation of Moore's Law
3. Flexible Electronics
4. NEMS (nanoelectromechanical systems) Measurement Science
5. Nanoparticle Measurement Methods and Standards
6. Carbon Nanotube Metrology and Standard Reference Materials
7. Nanomechanics Cleanroom Facility
8. Carbon Nanostructure Growth Optimization

In the following section, the panel presents general comments on the overall Nanomanufacturing area. These comments are followed by discussions of the Nanomanufacturing activities in terms of their technical merit and scientific caliber, the efficacy of NIST's engagement with outside stakeholders, and program coordination and cohesion across NIST. The same aspects of the Biomanufacturing program are then discussed. Finally, recommendations are offered.

GENERAL COMMENTS

The technical merit and scientific caliber of the work in the Nanomanufacturing area are impressive. Much of the work is among the best in the world, evidencing the unique skills and contributions of NIST. Some of the projects represent very significant examples of nanomanufacturing, and some are paradigm shifting. For example, one panel member called the "rice-sized" atomic clock developed at NIST the most significant example of nanomanufacturing that he had seen, noting that this is paradigm-shifting work which the automotive industry can use today if the clock can be manufactured cost-effectively.

The specialized facilities that are contained in the NIST nanotechnology laboratories represent a unique collection of advanced tools. One such facility that panel members toured was the nanomechanics measurement laboratory, in which the temperature is controlled to a few thousandths of a degree. This control is necessary in order to provide calibrated atomic force microscope (AFM) cantilevers. It is hoped that access to these tools will be maximized.

However, the panel noted that there was a significant challenge in reviewing the Nanomanufacturing area. Unlike the case with the other two manufacturing areas (Smart Manufacturing and Next-Generation Materials) addressed during this site visit, the overarching ownership of the Nanomanufacturing area did not seem to exist clearly under the authority of a laboratory director. Unlike the presentations given on the topics of Smart Manufacturing and Next-Generation Materials, the overall area report on Nanomanufacturing did not adequately convey the area's self-assessment of strength and weakness in the field or a focus direction. For example, there did not seem to be a consensus in the area as to which of the following descriptions best fits the objectives of the activities in the Nanomanufacturing area:

- Making small features on large objects,
- Making nanosized objects,
- Making nanoscale objects to obtain special properties,
- Incorporating nanoscale objects in larger objects, and
- Using nanotechnology to manufacture other things.

In his overview presentation, the Director of the Center for Nanoscale Science and Technology (CNST) indicated that this area is trying to do work related to all of the above definitions of nanomanufacturing. Since resources, time, and funds must be limited in any scenario, it would be preferable for NIST to make clear choices about which aspects of nanomanufacturing best fit the NIST mission. Note that this selection process must also include what not to do.

Similarly, there was a lack of clarity about the formal or informal organization of Nanomanufacturing-related activities within NIST. Some possible ways of looking at such structure range from a minimalist to an expansionist viewpoint. Nanomanufacturing could thus be viewed in various ways:

1. One possible view would have Nanomanufacturing existing in the five mission-specific laboratories. The work of these laboratories extends by natural progression down the relevant length scales. As problems of scale are encountered, they are solved in the laboratory setting, sometimes with the involvement of the CNST in a role as an enabler.
2. A second possible view of NIST's Nanomanufacturing organization would expand on the first viewpoint by adding two crosscutting program organizations—the Nanocomposite Manufacturing program and the Nano Environmental, Health and Safety (Nano-EHS) program. These crosscutting programs address two specific issues and are National Nanotechnology Initiative (NNI) Nanomanufacturing Signature Initiatives.
3. A third possible view would extend the Nanomanufacturing effort to include selected programs from the mission-specific laboratories. These selected programs would expand the Nanomanufacturing portfolio.
4. A fourth view, and the most expansive, would include all of the NIST programs that contain elements involving nanofabrication techniques. In this view there is a "shared vision" of what nanomanufacturing means, and common crosscutting problems and issues would be drawn out for special attention.

Adopting a particular organizational view has significant consequences for programmatic review. If the most minimalist (first) view were adopted, the Nanomanufacturing effort would not need to be reviewed at all; rather, a detailed review of the CNST would suffice. If the second view were adopted, the merit of the Nanomanufacturing effort would be based entirely on the review of the two crosscutting NNI programs. If the third view were adopted, the portfolio of the Nanomanufacturing effort would increase, but it would be essential to understand how the various programmatic elements were chosen or not chosen for inclusion in the Nanomanufacturing initiative. Finally, if the most expansive view of the organizational structure were taken, a "shared vision" and management structure would have to be clearly articulated to allow for such an enterprise to thrive.

It is clear that NIST is taking the first steps toward articulating its vision for nanomanufacturing technology by drawing together some programmatic elements that contain strong nanomanufacturing components. However, NIST is encouraged to continue to define its vision further.

Photovoltaics (PV) is one area in the Nanomanufacturing activities in which NIST has research, testing, standards, and standards to support PV manufacturing. There should be a coupling between NIST and the two PV manufacturing centers in the country funded by the Department of Energy (DOE) under the DOE Sunshot Manufacturing Initiative)—one is the PV Manufacturing Center (PVMC) under SEMATECH at Albany, New York, and the other is the Bay Area Photovoltaics Consortium (BAPVC) run from Stanford University—because NIST could add value (e.g., technology roadmapping, manufacturing support, etc.), and smart manufacturing is very much needed by the PV industry. (In the PV area, because the industry is heavily driven by end-product pricing—unlike, just to give one example, precision machine tools—resulting from intense cost pressures from offshore competition, the need for smart manufacturing in the United States has become especially critical.)

Since the PVMC and the BAPVC are specifically funded for PV manufacturing, and since they are just getting started, NIST (which leverages much other electrooptical activity in addition to its PV nanomanufacturing focus) could bring value to these two national efforts. These centers have a mission in concert with the PV area of the NIST effort, and they would benefit from the NIST PV nanomanufacturing expertise. The suggested coupling could allow the rather extraordinary level of effort and concentration of expertise at NIST to enhance and assist the DOE manufacturing effort, as well as increasing the exposure and potential for expansion of work at NIST into other technologies.

An important issue for consideration in NIST Nanomanufacturing activities is "bankability." Many new technologies suffer because the emphasis is placed only on demonstrating them at some performance levels. However, if they are too expensive to manufacture, they cannot be commercialized. It would be good for NIST to avoid projects that may provide exciting research opportunities but are weak in manufacturability and/or commercialization potential (e.g., they are too expensive, or there is insufficient market size). Bankability was the issue with Solyndra, for example. NIST can play an important role here in many ways—by providing, for example, methodologies, databases, reference materials, and modeling to the manufacturing community (especially new entrants) so as to enable them to evaluate their approaches independently.

Within the Nanomanufacturing area, it is important to note the excellent and unique capabilities that NIST has built and operates in its shared facilities. The Nanomechanics Cleanroom Facility is an excellent example of how NIST is making important contributions with unique facilities. Particularly impressive (shown during one of the tours) was the millikelvin controlled room used to provide AFM tips standards.

TECHNICAL MERIT AND SCIENTIFIC CALIBER

The technical merit and caliber of the work performed in the Nanomanufacturing area are generally very impressive. All of the groups are either world leaders in their chosen area or making strong strides toward a leadership position. This is particularly evident in the CMOS (complementary metal-oxide semiconductor) device metrology laboratory. The semiconductor industry is the largest nanotechnology industry in the United States, and NIST has strongly contributed to a technology roadmap addressing key issues using advances in measurement. Issues addressed at NIST include mobility degradation, the role of series resistance, and low-voltage reliability. As a result, numerous measurement advances have been made, including the ability to make an advanced reliability measurement on 3,000 devices simultaneously. The technical diversity evident in the research groups is also impressive. For example, the Flexible Electronics program is a leading and visible program supporting the organic PV industry through a wide range of measurement and process research capabilities. The program's researchers are a young, engaged, knowledgeable, and enthusiastic group of scientists and engineers and a well-assembled group of chemists, materials scientists, and, notably, a device physicist/engineer. NEMS Measurement Science appears to be a promising new area of research, but it is not far enough along at this point for evaluation.

The impact that NIST has made on the semiconductor industry, which plays a critical role in the U.S. economy, is particularly impressive. NIST has done an outstanding job in identifying important problems that the semiconductor industry has overlooked or is not in a position to investigate. NIST has addressed several major current issues in semiconductor technology, such as mobility degradation, the role of series resistance, and low-voltage reliability. NIST also has identified some emerging issues of importance, such as single-defect control and random telegraph noise. It is recommended that, in addition to the focus on the current CMOS technologies, NIST should work with industry to develop the metrics for benchmarking the new, potential CMOS replacement technologies.

Flexible Electronics is an important emerging area, particularly as it relates to the photovoltaic industry. One challenge in this area is deciding which problems to focus on solving. The industrial participants themselves are in the throes of figuring out what to measure, what to monitor, and what standard(s) to adopt. It appears that the NIST CNST laboratory is taking the approach of pulling together the key industry players and, in some sense, facilitating cooperation to help elucidate some solutions to these questions. Two potential issues have been identified: (1) *Critical mass:* Is the size of this group sufficient to meet the needs of the program goals? With growing capabilities in the processing support, is there enough technical coverage for different technical approaches—for example, single-junction, tandem, small-molecule, large-molecule, and other technology approaches? (2) *Leveraging:* It is unclear how the group interacts and interfaces with the other PV activities at NIST (although this obviously must exist).

The Carbon Nanotube (CNT) Metrology and Standard Reference Materials activity (involving the production of standards and reference materials, and measurement techniques and methodologies) is an important area for NIST to pursue. It fits squarely within NIST's charge. This program leads the world. The method for selectivity for sorting of single-wall CNTs using deoxyribonucleic acid (DNA) is innovative. There seems to be interest and some preliminary planning for expansion into biological areas (for DNA and ribonucleic acid [RNA] research) using the team's progress with CNT reference development. However, the team does not seem to have committed to this expansion. This may be an excellent area for a contribution by NIST—and NIST may want to consider extending the expertise of this laboratory to engage this area of technology.

The presentation for the review team in the area of carbon nanomaterial composites provided an excellent view of the development of a technique and capability that will enable in situ measurement of nanomaterial growth processes (using a state-of-the-art environmental transmission electron microscope). Raman spectroscopy is being incorporated into the microscope, and the system is currently being developed and qualified. The method for parallel design and development of the special nano-Raman capability is a creative and time-efficient approach, and it reflects the expertise and experience of this group. This is a unique capability with multiple program applications. The review team received an impressive demonstration of the observation of the in situ growth of CNTs. It is clear that the new microscope capability will provide an understanding of exactly how the growth conditions control the morphology and properties.

NIST ENGAGEMENT WITH OUTSIDE STAKEHOLDERS

Overall, the research groups in Nanomanufacturing are significantly engaged with their constituencies. The CNST laboratory is engaged with the "right players" in industry, particularly in the emerging organic photovoltaic (OPV) field, and NIST has positioned itself well within this emerging industry. The most significant impacts to date include helping the OPV industry by elucidating parameters that should be measured in addition to what the industry was measuring. NIST, including the Material Measurement Laboratory (MML) and the CNST Energy Research Group, has established working relationships and interactions with U.S. manufacturers in this technology, as well as critical interactions with leading U.S. PV organic device research groups. NIST has helped establish a plan for certification testing. Addressing issues such as thickness uniformity and compositional uniformity is much needed, and the benefits of contactless measurement contributions can be significant. In addition, NIST is involved in organizing, leading, and participating in workshops and meetings involving both industry and research institutions. Industry scientists at various times have worked in the NIST laboratories. This should be encouraged and enhanced to ensure value and direct feedback into the NIST Flexible Electronics operations. The following are potential issues and questions:

1. How does the NIST staff measure and document its contributions to this fledgling OPV industry? Is the industry itself involved with developing such metrics?
2. Would an industry advisory board be useful to ensuring relevance—as well as serving as an important feedback mechanism to the technical community, the Congress, and to NIST itself as to whether the investments are paying dividends?
3. Can this effort be a "one-stop shop" for OPV manufacturing, measurements, or processing? What reference materials can be provided?

In the CMOS area, NIST seems very engaged with the semiconductor industry in CMOS device metrology for the continuation of Moore's law; samples of devices are regularly sent to NIST from companies such as Intel. The NIST work in this area is addressing key issues using advances in measurement, many of which have been incorporated into various standard semiconductor measurement techniques. In addition, NIST has leadership roles in the International Technology Roadmap for Semiconductors. Clearly, this area has made and continues to make important contributions to national competitiveness. Since the large CMOS device market is dominated by companies with vast resources, NIST should make careful judgments about where it positions itself with respect to device metrology supporting continuation of semiconductor technology advances.

The Carbon Nanotube Metrology and Standard Reference Materials activity serves the CNT community through standards and reference materials, especially the measurement techniques and procedures that this group provides to other groups. This is a very valuable effort. Other nanotechnology activities (e.g., multi-wall CNT [MWCNT]) were identified as being carried out at NIST's Boulder, Colorado, facility, with good reason—the techniques for evaluation are in-house there. Overall, this activity is a true NIST resource, one that fits the NIST mission well. The cooperation and research exchanges between the Boulder team and this group are essential to ensuring the same success with the MWCNT reference activity.

The new instrumentation in the recently established Carbon Nanocomposites project offers unique and important capabilities for providing information for the manufacturing industry.

PROGRAM COORDINATION AND COHESION

The evaluation of the Flexible Electronics program shows evidence of collaboration and coordination across several NIST laboratories and programs. Material measurements, device fabrication, and device characterization leverage resources from several groups. The CNST understands the need for these various elements within this emerging field.

In the area of CMOS devices metrology, the level of coordination of this effort with other Nanomanufacturing-related initiatives was not made clear. The group is urged to explore ways of expanding its silicon-centric efforts to other materials that have the potential to impact the semiconductor industry.

The Carbon Nanotube Metrology and Standard Reference Materials team has a singular focus—the production of reference materials, standards, and measurement techniques and methodologies. It is not difficult to identify the success that this team has achieved. Clear goals were expressed at the beginning of the presentation to the panel—provide CNT reference materials and techniques and methodologies to measure and characterize carbon nanotubes. The team knows the major markets for its reference materials (now and in the near future).

The main question is the following: In addition to the continuing refinement and development of these processes for standards, what areas is this team developing? (The MWCNT work seems to be in the scope of NIST's Boulder facility, although the Gaithersburg staff obviously will play some role in that.)

The Carbon Nanomaterial Composites program and instrumentation are in their initial stages, but the investigators have designed the capability to meet new and special needs in order to advance knowledge that can advance manufacturing. Since the capability is not currently online, it is too soon to comment on the issues of coordination and cohesion.

BIOMANUFACTURING

The Biomanufacturing program at NIST is in its infancy; it was started earlier this year. The program will focus initially on the development of new or improved measurement science, standards, and reference data for more accurately and precisely determining the structures of biologic drugs. Since protein biologics and monoclonal antibodies are emerging as major economic drivers of new drug development and as new therapeutics for unmet medical needs, this focus is ideally suited to leveraging current internal protein science and cell biology programs at NIST.

Three program goals are envisioned in the area of protein therapeutics: protein stability, protein structure, and production cell variability. Based on discussions with the Food and Drug Administration (FDA) and industry, NIST considers these as critical areas in which NIST measurement tools will provide useful data to underpin regulatory decisions scientifically, to support the development of biosimilars, and to increase the knowledge of biopharmaceuticals necessary for improving therapeutics and developing next-generation treatments.

Technical Merit and Scientific Caliber

Work on protein stability has taken advantage of soft-neutron technology at NIST, leading to the development of new tests for the efficacy of proteins stabilized by various glycerol formulations in collaboration with a major pharmaceutical company. The data are early but promising. Measurement methods are needed to analyze protein aggregation and stability in order to monitor product integrity during manufacturing, in bulk drugs, and for final-product release. Developing standard measurements for these complex formulations will provide important guidance to regulatory agencies. This work has considerable promise and future value.

In the area of protein structure measurements, NIST has excellent resources available internally and through its 20-plus-year relationship with the University of Maryland's Institute for Bioscience and Biotechnology Research (IBBR), formerly the Center for Advanced Research in Biotechnology (CARB). New structural analysis methods will provide improved measurements, standards, and reference data in three specific areas:

1. *Primary amino acid sequence and identification of low-abundance variants and unintentionally chemically modified variants.* This is a solid focus of high importance. Low-abundance variants are problematic for the biopharmaceutical industry and new methods for their detection and quantitation. The results should be of broad significance and applicability.
2. *Post-translational modifications (PTMs) of proteins, including glycosylation.* The significance of PTMs in biological processes and in new protein biological therapeutics cannot be overstated. The precise determination of PTMs in biologics and their correlation to issues of efficacy and toxicities will be invaluable data for ensuring standards of composition and potency for manufactured therapeutics.
3. *Three-dimensional (3-D) protein structure.* The structural determination of biologics constitutes another useful parameter for assessing the impact of variants. The required work will likely rely on efforts at both NIST and IBBR. The goal is worthy, albeit loosely defined at this point. Future work should be directed to providing clarity to this goal.

The goal of understanding parameters affecting production-cell variability also has high impact potential; however, the strategies are not clear. As noted by NIST, approximately 70 percent of therapeutic proteins are produced in Chinese hamster ovary (CHO) cells. Thus, NIST believes that developing new methods for understanding and quantifying these complex drug factories will enable the development of new strategies for engineering and controlling CHO cells so as to ensure efficient production and consistent quality of manufactured protein therapeutics. It remains to be seen what these new methods will be and how effectively they will compete against the vast array of molecular biological techniques already employed to reengineer cells and regulate their production profiles.

The Biomanufacturing effort at NIST is early and a bit tentative. The focus in protein therapeutics makes good sense. Careful integration with other complementary NIST efforts will potentially lead to a robust and valuable initiative.

NIST Engagement with Outside Stakeholders

The three program goals (protein stability, protein structure, and production-cell variability) are based on discussions with the FDA and industry and have been determined to be critical areas in which NIST measurement tools will provide useful data.

As stated above, work on protein stability in collaboration with a major pharmaceutical company has taken advantage of soft-neutron technology at NIST to develop new tests for the efficacy of proteins stabilized by various glycerol formulations. Also as noted above, in the area of protein structure, NIST has excellent resources available internally and through its 20-plus-year relationship with the University of Maryland's IBBR.

Work on production-cell variability is the least-developed program goal. The manufacturing of biologic drugs in living cells, such as CHO cells, is a critical process in the pharmaceutical industry, and controlling product consistency is a significant challenge. Thus, identifying new measurement methods and tools for quantifying and controlling cellular machinery is an admirable NIST goal. There is little doubt that NIST technologies could be invaluable here. What remains is to develop a clear strategy to execute, which will engage the appropriate external stakeholders. This strategy should be forthcoming.

Program Coordination and Cohesion

Overall, the Biomanufacturing initiatives are appropriately focused in the short term on protein therapeutics, consistent with the strengths of the Material Measurement Laboratory. The Biomanufacturing group is encouraged to explore and foster crosscutting initiatives with other manufacturing groups, especially Nanomanufacturing. For instance, nanofabrication of engineered therapeutics is an area of emerging importance. Recent breakthroughs using materials specifically designed for imprint or soft lithography have enabled flexible methods for the direct fabrication and harvesting of monodispersed, shape-specific nanobiomaterials. These nanoparticles can be fabricated into numerous shapes and sizes, including nanocylinders, nanorods, or long, filamentous, "worm-like" nanoparticles. The unique control over size and shape leads to a variety of nanomaterials that can accumulate in specific tissues or diseased sites. This area could constitute an important crosscutting effort.

Careful integration with other complementary NIST efforts will potentially lead to a robust and valuable program.

RECOMMENDATIONS

The recommendations for the Nanomanufacturing area, including Biomanufacturing, are the following:

1. NIST should continue to define its vision for its Nanomanufacturing program, making clear choices about what nanomanufacturing should be on the basis of the NIST mission. To have more impact, NIST should focus on the following definitions or aspects of nanomanufacturing:
   - Making nanoscale objects to obtain special properties, and
   - Using nanotechnology to manufacture other things.

2. In addition to the focus in the Nanomanufacturing program on the current CMOS technologies, NIST should work with industry to develop the metrics for benchmarking the new, potential CMOS replacement technologies.

3. There should be a coupling between NIST and the two DOE-supported centers for photovoltaics (the PV Manufacturing Center [PVMC] under SEMATECH at Albany and the Bay Area Photovoltaics Consortium [BAPVC] run from Stanford University). NIST should add value through technology roadmapping or manufacturing support for this area of renewable energy and manufacturing, a priority for the current administration.

4. To play an important role with respect to the issue of bankability of new technologies, NIST should consider providing methodologies, databases, reference materials, and modeling so as to provide those in the manufacturing community (especially new entrants) with a way to evaluate their approaches independently and objectively.

5. In the large CMOS device market, which is dominated by companies with vast resources, NIST should make careful judgments about where it positions itself with respect to device metrology supporting continuation of semiconductor technology advances.

6. Scientists from the flexible electronics industry at various times have worked in the NIST laboratories, and this should be encouraged and enhanced to ensure value and direct feedback into the NIST Flexible Electronics operations.

7. Since the structural determination of biologics may constitute a useful measurement tool for assessing the impact of modified variants on Biomanufacturing, future work should focus on developing clear goals that will test the robustness of the approach for specific protein therapeutics.

3

Smart Manufacturing

INTRODUCTION

As presented to the panel, the Smart Manufacturing area represents current programs in the Engineering Laboratory (EL) and the Material Measurement Laboratory. The Smart Manufacturing program area uses a systems approach. By doing this, the staff are able to see the relationship of discrete elements to the entire system, since changes in the former can impact system performance. Since manufacturing systems can be very large and complex, the staff realizes the need and the challenge in identifying and researching those elements that are of significance to multiple U.S. manufacturing industries and can also provide data for the development of standards in relevant areas. All of the research groups in the overall area of Smart Manufacturing mentioned the need to develop focus for their areas of work.

The Smart Manufacturing staff assess the impact of several areas with respect to manufacturing. Specific programs and areas that were covered during this site visit included the following:

1. Smart Manufacturing Processes and Equipment (SMPE) program,
2. Next-Generation Robotics and Automation (NGRA) program,
3. Smart Manufacturing Control Systems (SMCS) program,
4. Systems Integration for Manufacturing and Construction Applications (SIMCA) program,[3]
5. Sustainable Manufacturing (SM) program, and
6. Manufacturing with Sustainable Materials program.

The following section describes and discusses work in each of the programs and areas listed above. These comments are followed by discussions of the Smart Manufacturing activities in terms of their technical merit and scientific caliber, the efficacy of NIST's engagement with outside stakeholders, and program coordination and cohesion across NIST. The final section presents recommendations.

DESCRIPTION AND DISCUSSON OF PROGRAMS

Smart Manufacturing Processes and Equipment Program

The objective of the Smart Manufacturing Processes and Equipment program targets the development and deployment of advances in measurement science that improve product quality and productivity. This is demonstrated, for example, by projects addressing machine tool performance standards and machining process modeling tools. The SMPE program includes the modeling, simulation, and measurements of equipment and processes to produce complex finished parts. Complexity is defined through geometry, material, part size, and tolerance.

These are worthwhile projects that promote the development of standards for interoperability among production machines of varied sources and better understanding of the

[3] Formerly the Systems Integration for Manufacturing Applications (SIMA) program.

production processes that can eventually be integrated into the design process of the target products. The emphasis on standards supports NIST's mission.

There are three thrust areas in the SMPE program: metal additive manufacturing, smart machining, and micromanufacturing and nanomanufacturing. Additive manufacturing encompasses technologies used to join raw materials together to fabricate three-dimensional objects directly from electronic design data. This technology has the potential to increase the rates of prototyping and thus accelerate the time required to implement new materials and designs onto the product lines. Demonstrations of additive manufacturing with metals were observed by the panel's review team. Based on inputs from the Additive Manufacturing Consortium, the ASTM F42 Committee on Additive Manufacturing Technologies, industry interactions, and the roadmap for additive manufacturing, the NIST group is focused on fundamental measurement science for additive manufacturing processes that is used to evaluate and improve additive manufacturing equipment, standard test methods, physics-based modeling of the process, and in situ measurements of these parts. The group also is developing materials standards for additive manufacturing that include powder characterization, test protocols, and analysis methods.

Current metrics used to measure the progress toward a goal of improving the producibility of additive manufacturing are the project milestones and are not quantitative in nature. The work in additive manufacturing lags behind industry leaders, such as Lockheed Martin and the Boeing Company, which are implementing additive manufacturing onto production platforms with larger parts and more extensively in comparison with what is being researched at NIST. The need for standards on additive processing methods, data, testing, and monitoring is critical in further adoption of additive manufacturing. Additionally, common approaches to how the testing is being accomplished for design allowables development are also needed.[4] The NIST work is aligned well, but it needs to be accelerated to address these issues.

The work of the SMPE group also includes the development of data to support machine tool performance standards. The goals here are to mitigate risks for users of high-end machine tools through the application of standards to machine manufacturers. There also is a project to improve models and simulations for optimization of these machine tools. These are well-established projects with industry partners, and metrics are developed with industry partners.

Next-Generation Robotics and Automation Program

The objective of the Next-Generation Robotics and Automation program is to provide the means for using smart robots and automation systems in production systems regardless of size. The work targets multiple industries. The focus areas are sensing and perception, manipulation, mobility, and autonomy. There is an emphasis on workplace safety in areas where robots are co-located with people. The group applies knowledge of robot safety, perception, autonomous mobility, and situational modeling in order to develop data that will be used in establishing standards. It also develops tests for current and future standards. The group works through key industry associations, such as the Robotics Industries Association (RIA), the U.S. Council for Automotive Research, and the Material Handling Industry of America, to develop broad-based industry adoption of these standards. This group's work is coordinated with the Information Technology Laboratory (ITL) and the Engineering Laboratory. The metrics used are project management milestones and are not quantitative in nature.

[4] *Design allowables* are materials property values that are statistically determined from test data. They represent the limits of stiffness, stress, or strain that are allowed for a particular material, application, configuration, and environmental condition.

Commendable effort is being demonstrated by the Next-Generation Robotics and Automation program in promoting and participating in the development of robot safety standards as a member of the Robotics Industries Association. Beyond safety standards, the program is in its infancy. The human-robotic interaction that is currently being developed for use in industry is much more complex than the situations being studied at NIST. Objectives are yet to be clearly stated and demonstrated with respect to collaboration with humans and dexterous manipulation at microscales and nanoscales. How this effort relates to RIA or ASTM standards for measuring performance is not clear. The pursuit of these activities at NIST should proceed only if they are potentially viable and if constructive standards can be envisioned. NIST need not compete for leadership in the development of robotic technology for industry, but research on characterization of the technology and the development of supporting measurements and controls can be valuable to the developers of robotic technology for industry. NIST should maintain and develop expertise in robotics to a scale supportive of standards development for products or technologies that are already in use or potentially viable, and it should resist the temptation to develop its own innovative products or technologies—endeavors that are better left to industry, universities, and other research-tasked federal laboratories. Otherwise, the effort would not fit well into the mission of NIST. Robotics expertise at NIST could help identify, research, and promote the standardization of modes of interoperability among robots of various manufacturers, as is being done for machine tools. This type of effort would help industry utilize robots more efficiently, and it would continue to support NIST's mission.

Smart Manufacturing Control Systems Program

The purpose of the Smart Manufacturing Control Systems program is to enable real-time monitoring, control, and optimization of manufacturing systems. The program deals with measurement science that utilizes factory networks, information modeling and testing, and performance measurement and optimization. This work requires advanced analytics, modeling and simulation, and the use of real-time production information. The goal of this activity is to utilize measurement science to develop standards to allow real-time sharing of information between manufacturing equipment and the applications that control the machine performance.

This group is actively working with General Motors (GM) and the Boeing Company in pilot production tests. It also is affiliated with the Open Modular Architecture Controls Users Group, the Association for Manufacturing Technology, the Smart Manufacturing Leadership Coalition, and the Dimensional Metrology Standards Consortium, and it collaborates with the ITL at NIST.

The work of the SMCS program is well executed and reflects the input from its industry partners. The systems that were demonstrated for the review team are linked together well. The metrics used are the project milestones, which should be replaced with metrics that measure improvements in productivity, quality, and safety. The technology has a long way to go before it becomes the "plug-and-play" system that the SMCS program is aiming to provide. In this area, the group needs to understand how to accelerate its efforts to keep up with the advances that are being made in industry research. One strategy that should be considered is the gathering of data in industry environments (machine builders and/or users) and the use of these data to develop standards. The goals of the program also need to be clarified so that the connection between the development of standards in control systems and the maintenance and creation of U.S. jobs is clearly stated in view of the fact that many controller manufacturers and machine integrators are overseas.

Systems Integration for Manufacturing and Construction Applications Program

The Systems Integration for Manufacturing and Construction Applications program deals with the integration of information in the development and production of fabricated parts. The program integrates information from model-based definitions, systems, and supply chains, and quality data. The data that are gathered from these areas are integrated into standards for design and production that contribute to highly integrated production networks. The program participates in American Society of Mechanical Engineers (ASME) and International Organization for Standardization (ISO) geometric and tolerancing standards, as well as STEP standards (product data standards; named for the Standard for Product Model Data)[5] and Object Management Group (OMG; systems engineering standards)[6] standards. The SIMCA program has already had a role in developing conformance tests for engineering integration standards. The program has worked closely with industry (Boeing, GM, General Electric Company [GE], and Caterpillar Inc.). It also participates in organizations that deal with standards for systems engineering, such as the Automotive Industry Action Group, the Aerospace Industries Association, the Open Applications Group, and the International Council on Systems Engineering (INCOSE). The program collaborates with the Engineering Laboratory's Smart Manufacturing Control Systems and other Smart Manufacturing programs, the NIST Physical Measurement Laboratory (PML), and the NIST ITL. The program acts as the integrator of information from the other Smart Manufacturing groups and production networks.

The approach that the SIMCA program uses can be utilized for a number of systems and materials, but the focus in the program has been on the machining of metallic materials. The program staff need to decide how much more effort is required with metallic fabrication systems and to make a decision about what it will do, if anything, with other materials systems, such as composites, ceramics, and coatings. It also needs to define what role the program needs to have beyond fabrication. There is a great need for standards in the assembly and integration of industry production systems. If this is truly an integration group, it should be working with its industry partners to develop data for assembly standards. It also needs metrics that truly measure quality and productivity instead of using the project milestones as metrics.

Sustainable Manufacturing Program

The purpose of the Sustainable Manufacturing program is to gather data related to energy consumption in order to enable sustainable processes and practices. The program's stated purpose is to apply the group's technical knowledge and tools to assess the sustainability of existing operations and to predict the impacts of proposed actions related to suppliers, plants, processes, and products. Various group members are aligned with researchers at numerous universities and companies. They also are collaborating with the Engineering Laboratory's SMPE and NGRA programs, the MML's Manufacturing with Sustainable Materials program, and with the ITL, and they participate in outreach events with the NIST Manufacturing Extension Partnership. The Sustainable Manufacturing program partners with multiple universities in work on information modeling, which is the key to what this program offers, and program staff have engaged with key manufacturers to assess the state of the art and to understand the diversity of the needs from different industries.

---

[5] For definition of STEP, see http://www.steptools.com/library/standard/step_1.html. Accessed July 6, 2012.

[6] OMG is an international, open-membership, not-for-profit computer industry consortium involved with setting software standards; see http://www.omg.org/marketing/omg-standards.htm. Accessed July 6, 2012.

The focus of the SM program is on the energy and material efficiencies in an actual manufacturing plant during its operations; the program is still in the early phases of planning what data are to be gathered. The program staff should survey the industry to determine where the greatest needs are in terms of sustainable manufacturing research. Almost all companies that currently have greenfield sites (undeveloped sites set aside for commercial development or industrial projects) are aware of the fiscal and political advantages of being energy-responsible. The models that the SM staff has would be of use; however, most companies have employed historic and current data to design and build their plants. This group is lagging with regard to what it is planning to do. A better focus would be on other parts of the value stream, such as the supply chain, assembly and integration, and post-delivery support. Although the group mentioned supply chain in its purpose, there was no discussion of measuring energy consumption by basic materials suppliers. As an example, what is the energy consumed in making a pound of a composite versus a pound of a metal? All materials should be investigated. The work should cover the entire product life cycle—namely, the fundamental materials production, fabrication, assembly, integration, sustainment, and recycling. Considering that 75 to 80 percent of the life cycle of certain products is outside of the original manufacturing, a better research project would be in the maintenance and recycling areas.

Manufacturing with Sustainable Materials Program

The overall area of manufacturing with sustainable materials is critical to U.S. manufacturing companies. Knowledge and selection of materials that support environmentally compliant platforms are needed in order to comply with or anticipate environmental needs. Data are needed that can be used to perform trade-off studies that support materials selection. The standard technical data are needed to ensure technical integrity and performance of the final products; they include materials, environmental, and structural properties. NIST currently develops tests and data to support the development of standards.

However, additional data related to the environmental impact of the production of a variety of materials need to be determined. Examples include data on the extraction and refining of materials, such as the extraction of metals from ores and comparisons of different fabrication technologies (e.g., forging or casting). Also, as manufacturers use new structural materials such as composites or ceramics, the environmental impact of producing these materials needs to be determined. The environmental requirements for many nonstructural materials, such as coatings, and chemicals used in manufacturing processes, such as cleaning, are currently regulated. In all cases, more information about the recycling processes is required so that these processes can be standardized and the data can be used in materials selection.

TECHNICAL MERIT AND SCIENTIFIC CALIBER

In all areas of Smart Manufacturing, the technical staff members are highly qualified to address the projects on which they are working, and their expertise is well matched to the specific areas being studied. The laboratories are well equipped to meet the program needs of the work that is being done. With respect to publications, the quality is high, and they are related to the areas being studied, indicating that the correct expertise is being applied to the specific areas being researched.

The mission of the laboratories is very clear. All of the employees understand and can communicate the mission—to help improve the quality and productivity of U.S. industry in order to maintain and create U.S. jobs. However, better clarification of how their work relates to keeping and creating jobs needs to be stated.

The thrust areas are relevant to a number of industries in keeping with NIST's mission to provide standards for multiple, diverse industries and not just to serve one industry. The NIST groups have worked with applications that apply to automotive, aerospace, medical, and heavy-equipment industries. This is also true across the Smart Manufacturing program area.

From what the panel's review team observed, for the SMPE and SIMCA programs, manufacturing deals almost exclusively with the fabrication of parts and very little with the assembly and integration of parts and systems. This is a very narrow component of manufacturing. Manufacturing in the United States involves not just the fabrication of parts but also the assembly and integration (drilling, fastener installation, sealing, coating, etc.), as well as the sustainment of products, for which standards are needed.

The level of maturity of the thrust areas needs to be more appropriate to current industrial practice. Although it is understood that there is some lag in identifying the most appropriate thrusts for research and data gathering, industry practices and needs and university research and development have progressed significantly beyond where NIST is gathering data. Unfortunately, all of the areas of Smart Manufacturing that are being researched are lagging behind industry in their research. With additive manufacturing, although parts are being produced and integrated onto production platforms, companies are interested in accelerating and rapidly progressing beyond where NIST is today, in order to use more parts made by additive manufacturing. In the robotics area, the human-robot interface is more than just the physical presence of the two in the same manufacturing cell. Industry cares about this scenario, but there are also many other human-robot and robot-robot interactions that are developing and evolving rapidly; data from these must be gathered to provide standards for these more sophisticated interactions. With respect to the SIMCA program and the controller areas, there is a limited focus on metals and fabrication. Once again, there needs to be more attention placed on the integration and assembly areas and on other materials systems. In the sustainability area, there needs to be more attention paid to the energy considerations for the materials manufacturing and on post-fabrication processes, including product sustainment and recycling. This attention should include all materials systems.

The noted lag in the relevance of the technologies may be due to the need to acquire appropriate capital equipment for gathering data. This is a long-lead-time process that increases the gap between what NIST is measuring and where industry is. NIST should consider working with the industries to acquire data in real production facilities or machine production facilities and forget about obtaining its own equipment, which is a very costly and time-consuming endeavor.

All of the fabrication work was performed on metallic materials. Although fabrication of metallic parts is very important and still in use in a wide variety of industries, the programs should formulate plans for integrating other materials systems as well. This may necessitate obtaining different capital equipment that is used to produce parts from nonmetallic materials.

The metrics being used are project milestones and not quantitative in nature. Even though all of the mission statements note that the projects have goals to improve quality and producibility, none of the metrics measure these. Instead, they measure project schedules. This is true of all of the Smart Manufacturing program areas. The NIST staff should work with industry to develop a better understanding of what realistic, meaningful metrics are. Product and process quality may be measured differently, depending on the needs of the individual production programs.

NIST ENGAGEMENT WITH OUTSIDE STAKEHOLDERS

In all program areas of Smart Manufacturing, integration with industry—including both the equipment manufacturing and the equipment user industries—needs to be strengthened. With SIMCA and the controller research, there is more integration with industry than with the other areas. However, this integration is limited to very specific areas. Surprisingly, although the SIMCA program's role is to provide a systems perspective and systems integration, the program staff are limited by what is defined as a system. In addition, they tend to only look at metals fabrication.

The other areas have limited true collaboration with outside stakeholders. They may hold workshops, which is one method for beginning the collaboration. However, they have not been proactive enough at approaching the various industries for collaboration.

One suggestion for all program areas of Smart Manufacturing is to propose projects in which NIST investigators can use the stakeholder resources to gather the data. It would be a good way to accomplish several things: (1) to promote collaboration with the stakeholders, (2) to gain a better understanding of manufacturing, (3) to avoid the increasing lag behind the industry due to the capital process, and (4) to develop meaningful metrics.

For the Smart Manufacturing Processes and Equipment program, stakeholder engagement is through standards committees, such as the ASTM F42 Committee on Additive Manufacturing Technologies, the Additive Manufacturing Consortium, and the ASME B5 and ISO/TC39/SC2 standards committees. The SMPE program cosponsored a workshop in 2009 to determine the state of the art and the barriers for the use of additive manufacturing. However, the state of the art has continued to advance since that workshop. The SMPE program needs to quickly reassess how much of what it learned in 2009 is still relevant and quickly readjust its research plan. The program would benefit from more proactive engagement with industry in order to determine how and where to accelerate program efforts. Industries, such as aerospace, want to accelerate the use of parts made with additive manufacturing and would like to see the standards efforts accelerated. One possible activity would be to use industry facilities to gather the appropriate data.

In the Next-Generation Robotics and Automation program, the work targets multiple industries. Stakeholder engagement is primarily through industry associations, such as the Robotics Industries Association, the U.S. Council for Automotive Research, and the Material Handling Industry of America. Industry needs are assessed through workshops and standards interactions and through literature reviews. Interaction with industry (GM, Ford Motor Company, Procter & Gamble [P&G], etc.) is in place. However, the NGRA program would benefit from developing a roadmap with industry on the specific needs of industry so that the program can determine what human-robot or robot-robot interactions are relevant in order to focus the program research in relevant areas. The program also would benefit from setting up relationships with industry and universities to use their facilities for research and data gathering. This would accelerate the data gathering and avoid the lags caused by NIST's ordering and using its own robotic equipment, and it would guarantee that the data were gathered from state-of-the-art equipment.

For the Smart Manufacturing Control Systems program, stakeholder engagement was highlighted with a production pilot program with GM and Boeing, demonstrating strong interaction. Other interactions are with industry groups, such as the Open Modular Architecture Controls Users Group, the Association for Manufacturing Technology (AMT), the Smart Manufacturing Leadership Coalition, and the Dimensional Metrology Standards Consortium. There is very good interaction across the board with respect to the development of control systems for metals machining. However, this effort needs to be expanded to cover other materials systems, such as composites fabrication, coatings application, and assembly and integration technologies. These areas are more state of the art and are used to produce major products or components, and they require standards. It would be useful for the SMCS program to partner with original equipment manufacturers (OEMs) or industry users to gather the data, and thus eliminate the need for capital equipment.

In the Systems Integration for Manufacturing and Construction Applications program, industry needs and focus areas are sought by means of hosting meetings and visiting stakeholders. The program staff have had key roles in ASME and ISO geometric and tolerancing standards, and they have helped in the establishment of reference data and test methods. They have worked closely with companies, such as Boeing, GM, GE, and Caterpillar. They contribute to the Automotive Industry Action Group, the Aerospace Industries Association, and the Open Applications Group. They work closely with groups involved with systems engineering standards, such as INCOSE and OMG. The program staff would benefit from expanding their view of how systems are defined in industry. The view of what they are defining as a system is limited to what the other parts of the Smart Manufacturing area at NIST are doing. In industry, the definition of a system and the use of systems engineering are broader than just working on metals machining and fabrication. They include other materials systems, the supply chain, assembly and integration, and post-delivery support.

The Sustainable Manufacturing program partners with many universities (University of Kentucky; Rochester Institute of Technology; University of California, Berkeley; Purdue University; University of Maryland; Wichita State University; Oregon State University; and Georgia Institute of Technology) in work on information modeling, which is the key to what this program offers. The program staff also has engaged with key manufacturers (Stanley Black & Decker, Boeing, GM, Ford, 3M, GE Aerospace, United Technologies, P&G, and Xerox Corporation) to assess the state of the art and to understand the diversity of the needs from different industries. A broader view of the needs of industry is required, since the SM program is focused on the energy requirements for plant operation. It needs to develop models that provide data on the energy considerations for producing various starting materials and for recycling. The researchers do go to actual manufacturing plants, but usually after a project begins. Proactive visits are rare and limited.

PROGRAM COORDINATION AND COHESION

The various project areas in Smart Manufacturing are aligned with the correct standards organizations. They are also aligned appropriately with the MML and ITL—out of necessity, since this is where the testing occurs. Coordination among the different areas of Smart Manufacturing is evident since there is a system approach to how they link together, although not all groups acknowledge this. The SIMCA group is responsible for the systems integration and should provide a strong role in the Smart Manufacturing projects. That group should also be the one to look at and recommend the collaborations with other parts of NIST. It appears that the research projects drive the SIMCA group and what they do. The interactions are limited, since the work they are doing focuses only on metals fabrication. In all project areas, there is a lag behind industry state of the art and industry needs. It seems that the decision of a research topic in one area drives all of the other areas. It would be good to have a stronger tie-in with the advanced materials area so that more relevant materials and manufacturing areas can be researched for standards development.

The Smart Manufacturing Processes and Equipment program coordinates with other NIST laboratories, including the MML, and with other programs, such as the Sustainable Manufacturing program. The additive manufacturing activities are coordinated with the Metallurgy Division of the MML for powder characterization. The Smart Manufacturing Processes and Equipment program collaborates with the Sustainable Manufacturing and the Smart Manufacturing Control Systems programs. The SMPE program also coordinates with the PML, MML, and CNST. It would be further beneficial for the program to interact with other NIST staff who are involved with advanced materials to determine what they could be doing outside of the metals fabrication work.

In the case of the Next-Generation Robotics and Automation program, coordination across NIST occurs with the Information Access Division of the ITL, which covers human detection and tracking, and the Sustainable Manufacturing program in the Systems Integration Division of the Engineering Laboratory, for assessing energy utilization associated with robots. Coordination for the Smart Manufacturing Control Systems program occurs with the SIMCA program to understand how they would fit into a larger production scheme. The program staff have collaborated with the ITL in the areas of control systems cybersecurity and a precision time protocol that contributed to a smart manufacturing testbed.

In the Systems Integration for Manufacturing and Construction Applications program, there is coordination with the Engineering Laboratory's SMCS and SM programs, with the PML for smart inspection, and with the ITL for software testing techniques.

The Sustainable Manufacturing program works closely with the Engineering Laboratory's SMPE and NGRA programs. All of these measure energy consumption during their operations. The Sustainable Manufacturing program participates in outreach events with the Manufacturing Extension Partnership on the Green Supplier Network project. The NIST Sustainable Manufacturing Caucus coordinates activities in the area of sustainable manufacturing across NIST. The Sustainable Manufacturing program also coordinates with the MML's Manufacturing with Sustainable Materials program and the ITL.

Coordination across the laboratories varies with each program and needs to be standardized. There is a lack of coordination with the Physical Measurements Laboratory.

RECOMMENDATIONS

The recommendations for the Smart Manufacturing area are as follows:

1. NIST should be more proactive at partnering with industry—particularly in the areas of Additive Manufacturing, Robotics, and Automation—to decrease the gap between industry needs and the current state of the art at NIST, to decrease the need for NIST to capitalize, and, more importantly, to decrease the gap between industry needs and NIST's data-gathering and standards-development work.

2. To foster the engagement of stakeholders in additional ways besides industry association meetings and workshops, focused visits to stakeholders to determine needs and challenges in each of the Smart Manufacturing programs should be undertaken.

3. NIST should increase the engagement of stakeholders in the development of the appropriate Smart Manufacturing program goals and metrics.

4. The relationship between the work that the Smart Manufacturing laboratories are doing and U.S. industry productivity and costs needs to be stated more specifically, toward the goal expressed by NIST of creating or saving U.S. jobs by improving productivity and costs. Meaningful metrics should be provided to measure this relationship and how industry can benefit from this work.

5. The competitiveness of the Smart Manufacturing projects reviewed should be made more appropriate to current industry practices.

6. A well-defined process should be established for determining and prioritizing projects that should be undertaken in the Smart Manufacturing area.

7. Program metrics that are more meaningful and quantitative than project milestones should be developed.

8. The Systems Integration for Manufacturing and Construction Applications (SIMCA) program should coordinate the other Smart Manufacturing activities. The SIMCA program needs to take the enterprise view that it claims to have and include other areas of manufacturing, not just metals fabrication.

4

Next-Generation Materials Measurements, Modeling, and Simulation

INTRODUCTION

The Next-Generation Materials Measurements, Modeling, and Simulation area represents a well-recognized core area of NIST. Long known for developing the latest advancements in materials instrumentation and measurements, NIST also has developed several new theories and models that are informed and validated by its experimental capabilities. It is these models, measurements, databases, and standards that enable the use of new materials in industrial applications.

During the panel's on-site review, presentations in this topic area were focused primarily on the role of NIST in the Materials Genome Initiative (MGI), on examples in micromagnetics, and on chemical and biochemical reference data. The presentations also included discussion of the role of NIST in establishing data standards, terminology, and other infrastructure needed for effective materials databases. The review included tours of two laboratories: the Center for Automotive Lightweighting and the Virtual Measurement and Analysis Laboratory.

This chapter first addresses the technical merit and scientific caliber of the activities in the Next-Generation Materials Measurements, Modeling, and Simulation area reviewed by the panel. It then discusses the efficacy of NIST's engagement with outside stakeholders, followed by comments on program coordination and cohesion across NIST. Recommendations are presented in the final section.

TECHNICAL MERIT AND SCIENTIFIC CALIBER

The scientists and engineers at NIST are among the very best at the national laboratories. A number of awards have been received and a number of highly regarded publications have been achieved by these researchers, and the quality of the researchers' responses to questions from panel members during the review was impressive. These researchers are leaders in their fields and equal to the best academics at leading universities or the best scientists at industrial laboratories worldwide. As with many research institutions, such expertise in some areas can be dependent on an individual scientist who has built up a wealth of knowledge and experimental capabilities over many years. Higher-level managers are aware of this challenge, and a key crosscutting theme in this area is the importance of continuing to enhance connections within NIST and across other research institutions and stakeholders to support knowledge transfer and impact.

Data Quality, Databases, and Models

As it pertains specifically to the topic of Next-Generation Materials, NIST continues to be a leading organization, where the accuracy and validity of data are the benchmark for other industries, and its scope, depth, and quality are among the best in the world. NIST's high technical caliber is based on fundamental use of first-principles modeling, the use of state-of-the-art modeling tools and analytical equipment, and expert staff conducting the experimental modeling studies. Entrenched in the development of these tools are critically derived and/or critically reviewed data sets used to develop and calibrate models to enable accurate prediction of a material's physical properties.

With increasing ability to modify materials at the nano- and microscale, the need for next-generation materials databases is critical for industry adoption. In the design of a next-generation materials database, strong consideration should be given to fully understanding the queries that will be made against the database. This is also a dynamical issue in the sense that query response time is an important requirement. For instance, the Chemical and Biochemical Reference Dataset is much acclaimed due to its accuracy and completeness but it is implemented in an object-oriented database that makes it difficult to search across substructures.

In addition to measuring physical science data that are critical to the successful application of advanced materials and process models and simulations, NIST has undertaken the task of developing a database that would provide for the ready retrieval and updating of the data. This task has several challenges, which include the following: (1) the database can be quite large and heterogeneous, containing not only physical property data but associated metadata, such as microstructure photomicrographs, specification of testing parameters, and results of a simulation; (2) the same material is often given many different names, which presents an ontology challenge and the need to compile a thesaurus of synonyms; and (3) the database should implement a data model that is flexible and readily extensible in order to accommodate new data and legacy data that are stored in a variety of different database types.

In addition to its own modeling tools and generation of data, NIST could build on its connections to both industrial research laboratories and academic institutions as a means to supplement its measurements and the development of next-generation modeling tools. As data accessibility faces fewer technical barriers (e.g., utilizing cloud computing and big-data advances), databases could be designed to allow many input sources but would also require oversight to ensure consistency, completeness, and quality control. NIST has an important role to play in establishing the infrastructure for such databases and model dissemination, and in quality control.

Considering the current portfolio of materials characterization techniques now in use, it is apparent that physical property data—ranging from interatomic potential measurements, to detailed thermodynamic and kinetic models of diffusion, to precipitation modeling of complex alloy systems—are all under various stages of development and use. This critically important and unique collection of capabilities is the foundation for supporting future manufacturing initiatives, in which detailed constitutive models can link the computational materials, computational mechanics, and computational manufacturing models needed to derive materials by design and drive materials reinvention.

As is to be expected technologically, there is overlap between the areas of materials and manufacturing. With respect to the development of advanced manufacturing tools, the opportunity exists within NIST to collaborate with industrial manufacturing research, in which focused deliveries of the constitutive materials and mechanics models are key elements of next-generation computational manufacturing models. The key to the success of these NIST manufacturing programs is to move into new domains, in which manufacturing addresses the needs that include advances in stamping, casting, forging, and injection molding, and services the needs of the transportation industry, including automotive, aerospace, and rail, as well as infrastructure rebuilding and construction industries.

In summary:

- The Next-Generation Materials program merits a high rating for technical expertise and scientific caliber in the areas of first principles, computation, and materials characterization.
- The program is an excellent source of fundamental information and a potential repository and gatekeeper of scientific data from multiple sources in support of the large-scale Materials Genome Initiative.
- The program is uniquely positioned to help co-develop constitutive models with links to industry and academia, targeting specific materials attributes derived through material reinvention.
- The program would benefit by expanding into the development of computational mechanics and computational manufacturing, and by continuing to enhance the program's communication and partnership with industry in order to identify critical technical needs and challenges.

NIST ENGAGEMENT WITH OUTSIDE STAKEHOLDERS

Standards and Measurements Mission

Over the past 20 years, NIST has continued to advance its standards and measurements mission. Developing the basis for standards is an essential service that NIST provides to the country.

As globalization across industries continues, industrial, academic, and national laboratories are collaborating and developing new materials and manufacturing processes on a global scale. NIST could position itself to interface with other international standards agencies to consolidate and simplify the many standards that exist. Such an initiative has the potential to control the substandard materials and associated products developed and sold by economically less developed countries.

Mission and Criteria for Selection of Research Topics

In all of the presentations made during the review, NIST scientists emphasized their clear understanding of their role as a measurement laboratory, and they spelled out in great detail the processes that they use to identify the technical agendas that they represented. NIST also provided the panel with a more comprehensive summary of the materials systems being studied and the manufacturing sectors being addressed**,** as well as a concise description of its internal criteria for funding decisions. The criteria are very sound, and NIST is currently covering seven main manufacturing sectors: (1) Materials for Electronics, (2) Biomanufacturing, (3) Energy Materials, (4) Automotive and Transportation, (5) Structural Materials, (6) Nanomaterials, and (7) Specialty Chemicals and Materials.

The Material Measurement Laboratory's "5+1" criteria for the selection and continuation of projects are as follows:

1. Magnitude and immediacy of industrial and/or National Need
2. Match to mission
   MML is responsible to meet customer needs for measurements, standards, and

data in the areas broadly encompassed by chemistry, materials and the biosciences

3. Contribution from MML is needed and will make a difference
   MML contribution is unique and critical for success
4. The nature and size of the impact of MML's contribution…
   The measure of anticipated impact on stakeholders relative to investment is evaluated, including anticipated impacts on quality of life
5. MML can provide a timely and high quality response

+1. Scientific and/or technological opportunity
   Emerging scientific and technological advances present an opportunity that warrants investigation by MM.[7]

The review could not address in detail each of the seven main materials systems and manufacturing sectors. However, the examples provided by NIST represented multiple paths by which projects were initiated—for example, initiated by industry, by joint NIST-industry discussion, and by enthusiasm on the part of the technical community—and for the most part, they were consistent with the stated criteria in terms of the match to mission and focused technical contribution. Less detail was provided with respect to NIST's role within the larger landscape of what other groups were doing.

One good example is the Micromagnetics research effort. In this program, a simulation tool has been developed that facilitates elucidation and exploration of the underlying physics, allowing many different magnetic storage schemes to be quickly evaluated. The impact to the data storage industry has been quite significant, aided by an active user group and the use of realistic challenge problems to validate the simulation tool. NIST's long-standing success in this area also raises the question about the natural sunsetting of projects—that is, how much further work at NIST would be beneficial versus focusing NIST resources on newer opportunities identified by the data storage industry given emerging data storage technologies.

In many instances, project or program initiation has involved industry input through organized workshops. However, in the case of the very specific area of the Materials Genome Initiative, this multiagency program is in the early stages, and it is not clear if the program is currently being constructed with sufficient industry input. This technical area has a long history. NIST has been involved in several ways during that history, and as a consequence, the program, as stated, does seem to be generally on target. In fact, based on its experience and history, NIST has much support in the community to play a central role in data management for this program. However, many subtle issues were discussed with regard to handling the vast array of materials data involved, and NIST recognizes that it does not yet have good answers to these questions. In particular, the issues of how to handle proprietary data and how to share results of the output database are still being addressed. A targeted workshop on handling data should be convened with industry and other stakeholders.[8]

---

[7] Source: Provided by staff of the NIST Material Measurement Laboratory.

[8] NIST, in collaboration with the National Science Foundation Center for Hybrid Multicore Productivity Research, convened a Big Data Workshop on June 13-14, 2012 (http://www.nist.gov/itl/ssd/is/big-data.cfm), that starts to address some of the questions of how to handle large data sets, security, and other important factors. The panel believes that a workshop specifically targeted at the data challenges for the Materials Genome Initiative is still needed.

The Role of NIST in Multiagency Programs

A stated goal of NIST is to identify areas in which the agency can have the greatest impact, rather than just "jumping on the latest bandwagon" or spending limited resources in overlapping areas pursued by others with more resources. One example is in nanotechnology, an area in which the National Nanotechnology Initiative, a 26-agency program, has had investments totaling $18 billion since its inception in 2001 through FY 2013. An important area that NIST has identified for emphasis is its role in characterizing nanoparticles to contribute to a greater understanding of environmental, health, and safety issues and in developing in-line nanoscale sensing and measurement capabilities for nanomanufacturing. The presentations for the panel gave a limited example of NIST's efforts in this area. NIST leads the Nanotechnology Signature Initiative "Sustainable Nanomanufacturing," and it was a significant contributor in the development of the 2011 NNI EHS research strategy. NIST is encouraged to continue to take a visible role in the coordination of such appropriate multiagency collaborations.

It is clear that some of what was reviewed in the Next-Generation Materials Measurements, Modeling, and Simulation area can properly be characterized as programs, although much of what was reviewed was instead an aggregate of various projects that could be identified as having some relation to manufacturing. NIST should take the next steps required to characterize its internal program organization and management. While such an effort may or may not lead to changes of emphasis within the programs, it may facilitate two critical issues that were not well addressed in the presentations on much of the effort reviewed: (1) explaining the strategic decisions behind the chosen focus (Note: Stated criteria were provided after the on-site review.), primarily with respect to the areas in which many groups are working in the same broad field, and ensuring that NIST's role and contributions are fully recognized by the external community; and (2) identifying metrics to be used to judge progress toward stated goals.

In describing their role in the MGI, the speakers had the benefit of the highlights of the excellent multiagency efforts that went into defining the MGI and were able to identify the clear role that NIST plays on this national stage. In other program areas, however, it was not as well articulated as to why NIST was engaged, why these areas of engagement were selected, and what role NIST has with respect to others in the field. Some of the follow-up discussion explained that the programs had different initiators—some were defined by specific industry request, whereas others were identified by NIST staff based on their understanding of current technical advances and needs.

Connections to Industry and Federally Funded Research Laboratories

A healthy collaboration exists between NIST and industry. A strong point to note is that most of the projects should be market-driven rather than based on technology push. Also, key NIST researchers in manufacturing areas should visit several manufacturing facilities each year in order to broaden their understanding of the realities of the commercial manufacturing environment. NIST should define the research projects, but it can do this best by direct observation of the challenges facing industry and by helping to transfer knowledge across industries. This approach is clearly in line with the current administration's policy to develop scientific initiatives to strengthen the economic and intellectual security of the United States.

Relative to materials characterization, modeling, and simulation, existing programs have loose ties to the needs of the industry, but there is a huge potential for expanding or redirecting materials characterization measurements to specific materials systems. One excellent example is the NIST Center for Automotive Lightweighting. This existing, strong collaborative effort underway with the United States Council for Automotive Research, the United States Advanced Materials Partnership, and Federally Funded Research Laboratories (FFRLs) in the characterization of advanced high-strength steels and aluminum alloy sheet is the foundation and benchmark for further collaborative efforts.

The willingness of the Center for Automotive Lightweighting to work on technical problems targeting lightweight materials systems for both the aerospace and automotive industries is impressive and is seen as being proactive with respect to industry needs. Some extraordinary examples of unique measurement capabilities in the metal-forming area were presented. The collaboration included materials and manufacturing experts from automotive companies, as well as experts from the steel industry and academic institutions. Consequently, the NIST center staff well understood the need to be able to design complex geometric car-body shapes with minimal iteration of sheet-metal-forming die configurations. As a result, the staff designed unique laboratory equipment to measure the true biaxial behavior of automotive sheet materials, directly supporting the development of sheet-metal formability constitutive laws. The end result will be much improved accuracy in predicting micromechanical properties and sheet-metal response to complex die-forming operations, saving both time and money. (Additional efforts targeting Gamma/Gamma-prime superalloys for high-temperature applications are underway in the Metallurgy Division of the MML.)

This program is well planned, heavily coordinated with industrial needs, and without a doubt capable of providing singular assistance to U.S.-based companies participating with NIST in developing the test methodologies and standards that will transform the metal-forming business. Such efforts in continuous improvements to maintain top-quality manufacturing research, to ensure standardized materials measurements, and to create next-generation manufacturing processes can be measured, repeated, and implemented at various production volumes from aerospace to high-volume automotive production.

The panel's tour of the Virtual Measurement and Analysis Laboratory included an example of a highly sophisticated supercomputer effort that is producing exciting results in predicting shear and particle-particle interactions in concrete (this is a collaborative effort between the ITL, MML, and EL). In contrast to the example above of the Center for Automotive Lightweighting, this team does not seem to have a clear picture of how to bring the new information to the actual users in the building and construction community.

The visualization of data can provide significant insight into physical phenomena, beyond that obtainable through an analysis of the data themselves. The research in the Virtual Measurement and Analysis Laboratory on the flow of suspensions is being done for the building and construction industry to provide insight into how aggregate size in concrete mixtures affects the ability of the concrete to be pumped into molds at the job site. The three-dimensional data visualization techniques developed by this laboratory present dramatic evidence of the critical role that aggregate morphology and size distribution play in the flow of concrete, and these techniques will lead to improved concrete standards. Despite the potential, however, it was not clear from the presentation whether the topic of flow of suspensions was suggested as a top priority for the industry and whether the industry-NIST communication was strong enough that industry understood how the results could be used to improve their materials and processes.

Other fields could also benefit from this unique and powerful data-visualization technique. It would be directly extensible to improve the understanding of other flow-of-suspension problems, such as how nanoparticles flow during the injection molding of a nanoplastic, or how a dislocation moves through and interacts with a nanoparticle in a nano-reinforced metallic system.

Continuing to Enhance Other Connections

The NIST postdoctoral and visiting scientist programs are a significant mechanism of renewal and outreach for the permanent NIST staff in the area of Next-Generation Materials Measurements, Modeling, and Simulation, and should be continued or preferably even strengthened. NIST actively hosts visiting researchers who provide complementary expertise and longer-term collaborations that not only strengthen NIST's relationship with academia and industrial research, but they also expose resident staff to the new ideas and technical opportunities at these institutions and in the broader technical community.

To summarize, the examples viewed demonstrated the strength of the NIST Next-Generation Materials program. It is particularly impressive in cases in which collaborative efforts are in place with industrial and academic consortia and FFRLs, such as the work on sheet-metal formability and materials characterization. There is great potential for expanding efforts to link first-principles materials models into constitutive models for casting, extruding, and forging metal systems, and to injection and compression molding of complex polymeric systems. These are used across multiple industries and can have significant impact in strengthening the competitiveness of U.S. manufacturing. NIST is also well qualified to expand in the development of first-principles modeling of polymeric, elastomeric, and thermoset composite materials systems, with complementary constitutive models linking fundamental mold flow models with injection molding models of plastic flow.

Metrics

NIST's varied accomplishments in manufacturing research are impressive from several perspectives. The publications and the awards received by NIST researchers are always impressive. NIST's industry collaborators, as can be expected, are even more impressed by the reduction in development time and risk that they can attribute to NIST assistance. Impact metrics can also include NIST's role as a leader in aspects of multiagency programs that support NIST's mission.

A key challenge is the identification of intermediate metrics to help judge whether progress is being made at a sufficient rate. Clearly, the creation of widely used standards (e.g., hardness) and databases (e.g., the Chemical and Biochemical Reference Dataset) serves as an outstanding example of the impact of NIST's efforts. But such contributions (and related metrics) often require a number of years before they can truly be appreciated. Therefore, NIST also needs intermediate status checks with academic and industrial collaborators to recognize if it is on the right path. One suggestion is for NIST to track both external contributions to, and users of, databases and models that are in development. This means that NIST researchers also would be responsible for publicizing and promoting their programs.

PROGRAM COORDINATION AND COHESION

Positive Impact of Reorganization

The panel considers it encouraging to find the close relationships developing between the materials research staff and the chemistry staff. Collaboration with the ITL is strong and has been significant for years. Collaboration with the researchers who run the ThermoData enterprise in chemistry is well underway and a clear indication that the reorganization of the laboratories

2 years ago is having a positive impact through enhanced collaboration. It is anticipated that further benefits of the reorganization will continue to emerge.

Breadth of Responsibility

One of the greatest challenges for the NIST Next-Generation Materials Measurements, Modeling, and Simulation program is covering the entire intellectual space of materials used in all manufacturing industries. Certainly the panel's review could not address all of the relevant programs at NIST in the time available; it was more important to ensure that the quality of what is done remains high rather than to cover all areas. Generally, NIST management has done an excellent job in starting to define programs that relate to U.S. manufacturing sectors, from high-volume automotive and infrastructure needs to high-value aerospace and electronics industries. Of course, at the foundation for all of these is the metrology focus in which NIST has been a clear leader for decades.

Coordination of the Next-Generation Materials program represents an opportunity to develop synergistic research efforts; it is noted that today some groups still appear to be working independently of one another. Elements of fundamental first-principles materials characterization, nanoscale materials development, and smart nanoscale process development can be found in the development of key materials systems. A few examples of such nanoengineered surfaces include the following: low-cost, high-volume, infrared thin-film reflective coatings for glass; engineered thin-film-based lithium-ion batteries scalable for high-volume manufacturing; unique organometallic surfaces to control corrosion, adhesion, and friction; and thermal electric devices with high ZT and non-rate-limiting interfaces.

RECOMMENDATIONS

The recommendations for the Next-Generation Materials Measurements, Modeling, and Simulation area are as follows:

1. As NIST continues its healthy collaboration with industry, its increasing focus on advanced manufacturing should proceed with additional recognition of industrial needs. Most of the projects in the area of Next-Generation Materials Measurements, Modeling, and Simulation should be market-driven, that is, based on market pull rather than on technology push. In establishing its technical portfolio, NIST should continue to seek strong partnerships with industrial consortia when these exist.

2. In establishing its technical portfolio in the area of Next-Generation Materials Measurements, Modeling, and Simulation, NIST should continue to seek strong partnerships with industrial consortia when these exist.

3. NIST's key manufacturing researchers should visit several manufacturing facilities each year in order to broaden their understanding of the real-world manufacturing environment.

4. NIST should define the research projects in the Next-Generation Materials Measurements, Modeling, and Simulation area, and it should do this by direct understanding of the challenges facing industry and by helping to transfer knowledge across industries.

5. NIST should maintain regular communications and interactions with industry to facilitate faster knowledge and technology transfer.

6. NIST should take advantage of the opportunity to play an important role in the multiagency Materials Genome Initiative as the potential repository and gatekeeper of scientific data from multiple sources. In the design of a next-generation materials database, strong consideration should be given to seeking a full understanding of the queries that will be made against the database so that suitable accuracy and dynamic performance can be obtained. A targeted workshop on handling data should be convened with industry and other stakeholders.

7. In line with its role in external programs involving the characterization of nanoparticles for achieving a greater understanding of environmental, health, and safety issues and development of in-line nanoscale sensing and measurement capabilities, NIST should continue to take a visible role in the coordination of related external efforts in this area within the scope of its Next-Generation Materials Measurements, Modeling, and Simulation work.

8. NIST and its industry partners should identify metrics to assess the benefits that industries have received in terms of development acceleration and risk reduction attributable to their interaction with NIST in the area of Next-Generation Materials Measurements, Modeling, and Simulation.

9. NIST should take the next steps required to continue integrated coordination of its internal program organization and management. The success of the collaboration between the materials, chemistry, and information technology researchers should be considered as a model for the similar integration of other groups.

10. In addition to facilitating cross-NIST collaboration in the area of Next-Generation Materials Measurements, Modeling, and Simulation, NIST should continue to strengthen partnerships with other research institutions and industry. The NIST postdoctoral and visiting researcher programs in these areas should be continued or perhaps even strengthened as a significant source of renewal and outreach for the permanent staff at NIST.

5

Crosscutting Themes

Themes that cut across the three manufacturing areas covered in this assessment fall generally into three categories—(1) organization and management, (2) interaction with industry and stakeholders, and (3) industrial impact and national priorities.

With respect to the first category, the organization of NIST's manufacturing programs into three areas—Nanomanufacturing, Smart Manufacturing, and Next-Generation Materials Measurements, Modeling, and Simulation—is highly desirable. However, it is clear that these three areas have not yet been working together sufficiently under these headings for very long. NIST is not a formal matrix-managed enterprise; nonetheless, the three broad manufacturing areas should draw on the extensive knowledge base and expertise that exist for successful matrix-managed structures on such issues as the management of priorities, program planning, and metrics for judging progress.

In all three manufacturing areas, some of the programs can properly be characterized as programs although many others give the appearance of being a collection of projects that relate to manufacturing. Program alignment under specific managers and program focus could be made stronger. Internal project coordination across NIST laboratories is broad, but it seems ad hoc and informal. Greater benefits could be realized with more structured coordination and management. NIST should take the next steps required to characterize its internal program organization and management.

In the second category, interaction with industry and stakeholders, the process for selecting and prioritizing the projects that NIST pursues in all three manufacturing areas could be improved. The vetting process would benefit if greater attention were paid to the needs of industry and its current state of the art, as well as to the factors of manufacturability and commercial potential.

There is a clear need for NIST to expand and enhance its engagement with industry, which would result in better alignment of NIST programs with industry needs and would avoid having projects that lag behind the industry state of the art. In this regard, for example, more visits by NIST staff to industry and greater use of stakeholder resources in measurements would be helpful. Engagement with industry should also include identifying metrics to help judge whether progress is being made at a sufficient rate in projects, as well as assessing the impact of NIST programs on industry and having collaborating industrial partners report on the impact within their own spheres.

The area of national priorities broadly ties together some of the key findings of this review. Because the vast scope of manufacturing encompasses a wide array of disciplines, systems, applications, and environments, contributions made by NIST impact U.S. industry in a multitude of ways. As a result of its highly qualified researchers and advanced facilities that are a national asset, NIST is uniquely positioned to support U.S. manufacturing broadly. Perhaps in recognition of these capabilities, in the recent launch of the Advanced Manufacturing Partnership initiative by President Obama at the recommendation of the President's Council of Advisors on Science and Technology, NIST has rightfully been accorded a leading role in being selected for the Advanced Manufacturing Partnership National Program Office. NIST should and will receive more national visibility as it continues to pursue its mission of service to U.S. manufacturing.

6

Conclusions

NIST is well positioned to broadly support U.S. manufacturing advancement, and research and services supporting manufacturing currently cut across multiple NIST laboratories. NIST considers its support of manufacturing to be a central part of its mission.

The manufacturing program teams at NIST are highly qualified and comparable to the best in the world. Moreover, the equipment and facilities that the NIST laboratories have designed, procured, and built represent a national asset. These factors hold great promise for NIST's continuing support of U.S. manufacturing.

Because manufacturing covers such a wide array of disciplines, systems, applications, and environments, advancements can be made in a multitude of ways. Recognizing these opportunities and their potential impact, companies and other organizations also are investing heavily in the pursuit of manufacturing advancements. This complex mix makes the selection of projects to pursue at NIST quite challenging. It is important for NIST to have a process in place that carefully considers industry needs and inputs when selecting and planning the projects to pursue. NIST interaction with industry is strong, and with further expansion and enhancement, it could provide even more mutual benefits and alignment.

Benefits also come from a unified programmatic focus, supporting management, and the use of metrics designed to measure progress when coordinating the efforts of multiple, technologically diverse projects. The current, significant collaborations among teams across NIST could also garner increased benefits through more structured coordination.

NIST can be proud of its technical and scientific capabilities and accomplishments. Hopefully, NIST will receive more of the national visibility that it so well deserves as it continues to pursue its service to U.S. manufacturing and to the nation.