AN ASSESSMENT OF SELECTED DIVISIONS OF THE PHYSICAL MEASUREMENT LABORATORY AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

FISCAL YEAR 2021

Panel on Assessment of Selected Divisions of the Physical Measurement Laboratory
at the National Institute of Standards and Technology

Committee on NIST Technical Programs

Laboratory Assessments Board

Division on Engineering and Physical Sciences

A Consensus Study Report of

The National Academies of
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THE NATIONAL ACADEMIES PRESS
Washington, DC
www.nap.edu

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

This activity was supported by Contract No. SB13411CQ0017 with the National institute of Standards and Technology Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project.

International Standard Book Number-13: 978-0-309-09371-2
International Standard Book Number-10: 0-309-09371-6
Digital Object Identifier: https://doi.org/10.17226/26312

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

Printed in the United States of America

Suggested citation: National Academies of Sciences, Engineering, and Medicine. 2021. *An Assessment of Selected Divisions of the Physical Measurement Laboratory at the National Institute of Standards and Technology: Fiscal Year 2021*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26312.

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PANEL ON ASSESSMENT OF SELECTED DIVISIONS OF THE PHYSICAL MEASUREMENT LABORATORY AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

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Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

Carlos D. Bustamante, Stanford University,
Jordan J. Green, Johns Hopkins University,
Max G. Lagally, NAE,[1] University of Wisconsin, Madison,
Nadya Mason, NAS,[2] University of Illinois, Urbana-Champaign, and
Robert Schoelkopf, NAS, Yale University.

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

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Contents

Summary

At the request of the Director of the National Institute of Standards and Technology (NIST), in 2020 the National Academies of Sciences, Engineering, and Medicine formed the Panel on Assessment of Selected Divisions of the Physical Measurement Laboratory at the National Institute of Standards and Technology and established the following statement of task for the panel:

> The National Academies of Sciences, Engineering, and Medicine shall appoint three panels to assess independently the scientific and technical work performed by the National Institute of Standards and Technology (NIST) Physical Measurement Laboratory, Information Technology Laboratory, and Center for Neutron Research. Each panel will review technical reports and technical program descriptions prepared by NIST staff and will visit the facilities of their respective NIST laboratory. Visits will include technical presentations by NIST staff, demonstrations of NIST projects, tours of NIST facilities, and discussions with NIST staff. Each panel will deliberate findings in closed session panel meetings and will prepare a separate report summarizing its assessment findings. The Panel on Assessment of Selected Divisions of the Physical Measurement Laboratory at the National Institute of Standards and Technology will review the following divisions of the NIST Physical Measurement Laboratory: Quantum Measurement Division, Radiation Physics Division, Sensor Science Division, Microsystems and Nanotechnology Division, and Nanoscale Device Characterization Division. This panel will not access restricted information; the report summarizing its assessment will contain only public release information.

The Director of NIST requested that the panel consider during its assessment the following factors:

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

To accomplish the assessment, the National Academies assembled a panel of 24 volunteers whose expertise matched that of the work performed by the Physical Measurement Laboratory (PML) staff.[1] On May 17-20. 2021, the panel conducted a virtual review (via Internet media), a restriction imposed by the risks associated with the COVID-19 virus pandemic. During a plenary session, the panel received overview presentations by the acting NIST Director and the Director of the PML. Subsequently, the panel spent approximately 1.5 days receiving presentations from and engaging in discussions with the staff at the five divisions reviewed. On the third day, the panel met in a closed session to deliberate on its findings and to define the contents of this assessment report. The panel met with NIST management on the fourth day to clarify open questions. The choice of projects to be reviewed was made by the PML. The panel applied a largely qualitative approach to the assessment. Given the nonexhaustive nature of the

[1] See the NIST Physical Measurement Laboratory at https://www.nist.gov/pmlfor information on PML organization and programs.

review, the omission in this report of any particular PML project should not be interpreted as a negative reflection on the omitted project.

TECHNICAL QUALITY OF THE WORK

The Quantum Measurement Division has six groups, each with significant accomplishments. These include single-photon sources (sources that produce streams of single photons) and detectors, quantum optics using laser cooling, the redefinition of the kilogram, and a graphene-based Quantum Hall Resistance Standard. Other notable achievements include the development of a Josephson-junction–based waveform synthesizer for power and energy applications, a unique magnetic suspension mass comparator, and the investigation of photon momentum for laser power and force measurements. Some of the best technical programs in the world are located in this division.

The Radiation Physics Division provides a unique resource to the United States, serving industrial, medical, and national security needs through its three groups. Its new gamma-radiation dosimetry calibration facility, detector calibration, and brachytherapy source traceability have produced improved calibration capability. The neutron physics program provides unique capability in the United States and is on par with the best neutron facilities worldwide. The neutron/X-ray tomography imaging facility offers the best simultaneous imaging available. The division has also developed a unique photon-assisted neutron detector for fast-neutron dosimetry. The division's excellent technical capability provides outstanding service to the nation developing important new radiation detection and calibration methods.

The Microsystems and Nanotechnology Division is focused on advancing nanofabrication tools, technologies, and measurement systems. The three division groups work together to improve uncertainty in International System of Units (SI)-traceable calibration, fabricate devices such as accelerometers and atomic clocks, and develop nano-fluidics for biomedical applications. The study of the fundamental interactions of photons and phonons in nanostructures enables new tools while nonlinear optics enables new optical applications.

The Nanoscale Device Characterization Division is organized into five groups whose goals are to transform nano-scale and atom-scale technologies, engineered materials, and solid-state devices. The division's strategic areas of research are as follows: theory and measurements for alternative computing; microscopies for quantifying emergent properties in quantum materials and devices; advanced microelectronics integration, characterization, and authentication; and atom-scale solid-state device theory, fabrication, and measurements. The quality of the division's work is excellent as judged by the significant number of peer-reviewed publications and conference presentations.

The Sensor Science Division has responsibility for three of the seven base units of the International System of Units: the meter, the kelvin, and the candela. Its seven groups are aligned to support this significant assignment plus additional activities and programs. The technical quality of the division's work is recognized worldwide through awards and commendations from multiple technical societies and organizations such as NASA and ASTM International (formerly the American Society for Testing and Materials). The division has an international reputation for technical excellence and is known and respected worldwide. It is highly involved in regional and international key comparisons that help to establish worldwide agreement on measurement standards.

TECHNICAL EXPERTISE OF THE STAFF

The technical expertise of the staff in the Quantum Measurement Division is outstanding and among the best in the world. Its research is at the forefront of the field in both theory and experiment.

The Radiation Physics Division has scientists and engineers with world-leading capability, high-impact publications, and strong international recognition, including American Physical Society (APS) fellows.

The Microsystems and Nanotechnology Division staff seem fully qualified to accomplish the various program goals.

The caliber and expertise of the senior researchers and associates in the Nanoscale Device Characterization Division is impressive. While the division staff are excellent device engineers and scientists, it would probably be helpful to add some systems design and engineering expertise to the team.

The highly respected technical expertise of the Sensor Science Division staff is the foundation for the division's excellent international reputation. As an example, the International Organization for Standardization publishes the most important standard for calibration and test laboratories, the revision of this standard was co-convened by a division staff member.

ADEQUACY OF RESOURCES

The excellence of the staff and technical output at the PML has been maintained despite challenges that include, for some divisions, concerns about staffing shortages and the need for succession planning; and the need for facilities and equipment maintenance, upgrading, and replacement.

Two of the groups in the Quantum Measurement Division have been integrated with the Joint Quantum Institute (JQI) at the University of Maryland. This facilitates collaboration with other researchers and enables NIST researchers to have easier access to students. However, this has also led to the migration of much of the Quantum Optics and Laser Cooling and Trapping Groups from the NIST campus to the University of Maryland Campus, although efforts and collaborations remain on the NIST campus. This geographical separation is exacerbated by the loss of NSF funding for the Physics Frontier Center associated with the JQI, and by the deferred maintenance issues back at the NIST Gaithersburg site, both of which impact needed space expansion. HVAC and flooding issues at the aging Gaithersburg facilities have also impacted the division and its overall progress; this needs to be addressed.

The Radiation Physics Division has benefited from recent facility upgrades in their area, such as the Building 245 modernization project, the new high-dose-rate brachytherapy vault, and the future 10 MeV electron beam accelerator facility. There is concern, however, that maintaining this level of expertise may be difficult going forward, given the loss of senior staff and the competition for new hires. The recent loss of senior staff has led to more time spent on immediate needs than on long-term research for some senior staff, which may be counterproductive in the long term. It would be productive and cost effective to strengthen student and post-doctoral training to help mitigate this problem.

The Microsystems and Nanotechnology Division has extensive facilities, including two cleanrooms and a wide variety of fabrication and characterization tools. The PML maintains two fabrication facilities: one in Boulder and the other in Gaithersburg. The Microsystems and Nanotechnology Division has access to the Gaithersburg facility directly, and the Boulder one via collaboration. As with all such facilities, significant resources are required to keep the facility and tools at state-of-the-art levels.

The Nanoscale Device Characterization Division has excellent resources with outstanding equipment. The new photo emission microscope system and planned ultraviolet femtosecond light source will add to a well-equipped division.

Facilities available to support the Sensor Science Division are reported by staff to be inadequate to the task, and building renovations are planned to rectify this. However, the time scale for these fixes is such that aging infrastructure will severely limit for years the effectiveness of the division to achieve its goals and accomplish its mission of fostering the next generation of SI-traceable standards.

EFFECTIVENESS OF DISSEMINATION OF OUTPUTS

The Quantum Measurement Division has been highly effective in disseminating the results achieved in the division, notably including atomic spectroscopy data in the NIST Atomic Database, publication in peer-reviewed journals and scientific conferences, and invited lectures explaining the new kilogram standards and the Quantum SI Revolution.

The Radiation Physics Division regularly publishes in top-tier peer-reviewed journals. The Neutron Physics Group sets an excellent example with strong collaborations, summer schools and workshops, and a high publication rate. Given the division's technical accomplishments, more engagement with universities and professional societies may benefit the dissemination of the division's output in some areas.

The Microsystems and Nanotechnology Division publishes extensively in both peer-reviewed journals and conference proceedings. In the previous 2 years, the division has published over 100 such articles. Collaborators include more than 40 top universities and research centers. The division staff are highly involved on conference committees, review panels, and standards bodies.

The Nanoscale Device Characterization Division is using not only traditional means of distribution for its outputs, it is also using new methods such as GitHub for making new software available to a wide audience. The division had over 100 publications and more than 130 conference presentations over the past 2 fiscal years, which indicates that other researchers are well aware of the progress being made in the division.

The Sensor Science Division is very effective at disseminating its results. The division staff publishes in high-impact journals and gives invited talks at key conferences around the world. Over the past 3 years, SSD staff published 240 archival journal papers, technical reports, conference proceedings, and book chapters. In addition, the division is proactive in organizing workshops and interlaboratory comparisons.

CROSSCUTTING CONCLUSIONS

The following conclusions apply to more than one group or program in the PML that was reviewed.

Technical Quality of the Work

The accomplishments of the PML's staff are many and significant, spanning an extremely broad array of topics and including both research and support of the practical development of measurement standards. The staff innovatively develop and apply novel devices and techniques to solve important problems that affect industry, academic researchers, federal government agencies, and society in general. The work of the PML staff is effectively aligned with the NIST mission and is frequently performed in collaboration with researchers from those organizations.

The PML staff made commendable contributions during the COVID-19 pandemic. From March 2020, when staff were required to work remotely, PML staff ensured that essential services were performed for their customers, in support of national security, national well-being, and commerce. PML staff also answered the call to address measurement issues relating to combatting the virus, such as disinfecting agents and storage of vaccines.

Technical Expertise of the Staff

All the divisions of the PML have scientific and engineering staff with the appropriate level of expertise to deliver on their mission. In many cases, the staff are the best or among the best in their field of research. Staff have received numerous awards from professional organizations and from the Department of Commerce, which houses NIST.

The gender and minority employment gaps that are still strongly and broadly plaguing science, technology, engineering, and mathematics (STEM) fields remain an acknowledged, significant challenge at NIST as well. The PML has implemented a plan to improve equity, diversity, and inclusion that involves the following features: monitoring promotion and salary data to ensure an equitable process; publishing promotion criteria so that staff know what is expected; mentoring by supervisors on how to advance; reviewing the pay level of all staff members with more than 8 years of service; participating in the APS's Inclusion, Diversity, and Equity Alliance (APS-IDEA) in partnership with Howard University; sponsoring of and participating in conferences to increase women and minority participation in physics and other STEM fields; and supporting the PML Inclusivity Council, an internal grassroots organization working to identify barriers to inclusion and propose remedies. Addressing the challenge of staff attrition could provide opportunity to address diversity challenges as well. It is expected that in future years PML will demonstrate greater efforts and progress in diversity, equity, and inclusion.

Adequacy of Resources

Generally, but with significant exceptions, the PML staff are provided with adequate equipment and facilities to perform their tasks to a high degree of quality. Noteworthy exceptions include aging facilities in urgent need of upgrade, delayed maintenance on aging equipment, and an apparent lack of supercomputing support. All divisions reported concern about the adequacy of staffing levels, particularly given an aging workforce and severe competition for postdoctoral researchers and other new hires. Each division indicated initiation of strategic planning exercises with an eye toward addressing the current and predicted challenges associated with the limitations of equipment, facilities, and human resources.

Effectiveness of Dissemination of Outputs

PML staff are effectively disseminating the results of their work through appropriate means that include publication of research results; delivery of standard reference materials and standard reference data; performance of calibrations for industrial, academic, and government customers; participation on standards committees; sponsorship of workshops; and educational programs. Some customers, however, have complained about the amount of time it takes and the cost associated with purchased calibration services. They have also complained about the inadequate information provided by the web-based NIST Storefront interface for purchasing measurement services and about the lack of information about which services are currently available.

1

The Charge to the Panel and the Assessment Process

At the request of NIST, the National Academies of Sciences, Engineering, and Medicine has, since 1959, annually assembled panels of experts from academia, industry, medicine, and other scientific and engineering environments to assess the quality and effectiveness of the NIST measurements and standards laboratories, of which there are now six,[1] as well as the adequacy of the laboratories' resources.

At the request of the Director of NIST, in 2020 the National Academies formed the Panel on Assessment of Selected Divisions of the Physical Measurement Laboratory at the National Institute of Standards and Technology and established the following statement of task for the panel:

> The National Academies shall appoint three panels to assess independently the scientific and technical work performed by the National Institute of Standards and Technology (NIST) Physical Measurement Laboratory, Information Technology Laboratory, and Center for Neutron Research. Each panel will review technical reports and technical program descriptions prepared by NIST staff and will visit the facilities of their respective NIST laboratory. Visits will include technical presentations by NIST staff, demonstrations of NIST projects, tours of NIST facilities, and discussions with NIST staff. Each panel will deliberate findings in closed session panel meetings and will prepare a separate report summarizing its assessment findings. The Panel on Assessment of Selected Divisions of the Physical Measurement Laboratory at the National Institute of Standards and Technology will review the following divisions of the NIST Physical Measurement Laboratory: Quantum Measurement Division, Radiation Physics Division, Sensor Science Division, Microsystems and Nanotechnology Division, and Nanoscale Device Characterization Division. This panel will not access restricted information; the report summarizing its assessment will contain only public release information.

The NIST Director requested that the panel focus its assessment on the following factors:

1. Assess the organization's technical programs.
    - How does the quality of the research compare to similar world class research in the technical program areas?
    - Is the quality of the technical programs adequate for the organization to reach its stated technical objectives? How could it be improved?
2. Assess the portfolio of scientific expertise within the organization.
    - Does the organization have world-class scientific expertise in the areas of the organization's mission and program objectives? If not, what areas should be improved?
    - How well does the organization's scientific expertise support the organization's technical programs and the organization's ability to achieve its stated objectives?
3. Assess the adequacy of the organization's facilities, equipment, and human resources.
    - How well do the facilities, equipment, and human resources support the organization's technical programs and its ability to achieve its stated objectives? How could they be improved?
4. Assess the effectiveness by which the organization disseminates its program outputs.

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

- How well are the organization's research programs driven by stakeholder needs?
- How effective are the technology transfer mechanisms used by the organization? Are these mechanisms sufficiently comprehensive?
- How well is the organization monitoring stakeholder use and impact of program outputs? How could this be improved?

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, enable new scientific and technological advances, and improve and refine existing measurement methods and services.

NIST specified that 5 of the 10 divisions of the PML would be reviewed—Quantum Measurement Division, Radiation Physics Division, Microsystems and Nanotechnology Division, Nanoscale Device Characterization Division, and Sensor Science Division. The following PML divisions were not reviewed because they had previously been reviewed (NIST may request their review in the future): Applied Physics Division, Quantum Electronics Division, Quantum Physics Division, Time and Frequency Division, and Weights and Measures Division. In order to accomplish the assessment, the National Academies assembled a panel of 24 volunteers whose expertise matches that of the work performed by PML staff.[2]

On May 17-20, 2021, the panel conducted a virtual review (via Internet media). During a plenary session, the panel received overview presentations by the acting NIST Director and the director of the PML. Subsequently, the panel spent approximately 1.5 days receiving presentations from and engaging in discussions with the staff at the five divisions reviewed. On the third day, the panel met in a closed session to deliberate on its findings and define the contents of this assessment report. The panel met with NIST management on the fourth day to clarify open questions.

The panel's approach to the assessment relied on the experience, technical knowledge, and expertise of its members. The panel reviewed selected examples of the technical research performed at PML; because of time constraints, it was not possible to review PML programs and projects exhaustively. The examples reviewed by the panel were selected by PML. The panel's goal was to identify and report salient examples of accomplishments, challenges, and opportunities for improvement with respect to the factors suggested above by the NIST Director. These examples are intended collectively to portray an overall impression of the laboratory, while providing useful suggestions specific to the projects and programs that the panel examined. The panel applied a largely qualitative rather than quantitative approach to the assessment.

Given the necessarily broad and non-exhaustive nature of the review, omission in this report of any particular PML program or project should not be interpreted as implying any negative reflection on the omitted program or project. Because the divisions reviewed by the separate teams address separate specific missions and tasks, the type of information provided by each division was inconsistent with respect to some metrics. The lack of discussion of a metric, such as publications, in one division but not another should not be taken as an indication that there was a difference in performance on the given metric between the divisions.

[2] See on the NIST Physical Measurement Laboratory homepage for information on organization and programs at https://www.nist.gov/pml accessed May 17, 2921.

2

Quantum Measurement Division

The mission of the Quantum Measurement Division is to provide the foundation for the International System of Units (SI), test its limitations, and develop the measurement infrastructure to disseminate SI units related to electrical and mechanical properties. The Quantum Measurement Division covers a wide breadth of interests, including fundamental science and everyday needs and applications. The division's strategic goals are to explore fundamental aspects of the quantum nature of light and matter; develop quantum metrology and the Quantum SI; create the foundations for electrical, mass, and force metrology from first principles; deliver improved measurement services; and disseminate critically evaluated atomic reference data.

The division is organized into the following six groups: the Atomic Spectroscopy Group; Quantum Optics Group; Laser Cooling and Trapping (LCT) Group; Fundamental Electric Measurements Group; Applied Electrical Metrology Group; and Mass and Force Group. Many staff from the Quantum Optics Group and all staff from the Laser Cooling and Trapping Group are participants in the Joint Quantum Institute (JQI) and the Joint Center for Quantum Information and Computer Science (QuICS), both located on the University of Maryland campus. All of the groups, except the Fundamental Constants/CODATA (Committee on Data for Science and Technology) Center group, were reviewed by the panel.

TECHNICAL QUALITY OF THE WORK

The accomplishments of the division's groups are many and significant.

The work of the Atomic Spectroscopy Group's experimental team includes the spectroscopy of highly charged ions and high-resolution precision spectroscopy of atomic lines. Among the group's accomplishments are applications of newly developed calorimetric sensors recently developed by PML's Quantum Electrodynamics Division that offer ultrawide bandwidth at an excellent resolution similar to crystal spectrometers. The Atomic Spectroscopy Group collaborates actively and effectively with several university groups.

The Quantum Optics Group addresses a wide variety of topics. On the applied side, these include single-photon detectors with improved time resolution, integrated single-photon sources on a chip, and studies of biophotonics at the single-photon level. On the fundamental side, the Quantum Optics Group studies important questions such as quantum metrology beyond the classical limits and possible implementations of secure quantum communication in a future quantum network. The group is undertaking a significant theoretical effort toward understanding fundamental aspects of entanglement propagation in many-body systems, in particular in systems with long-range interactions. Other noteworthy theoretical work includes quantum-enabled novel detectors for searching for the elusive dark matter and new physics beyond the Standard Model. Staff from this group also contributed significantly to the Quantum Economic Development Consortium (QED-C), which seeks to align research in the quantum field with industry needs.

The Laser Cooling and Trapping Group works on fundamental research at the intersection of atomic, molecular, and optical physics, condense-matter physics, and quantum information science. A unifying theme across these different subfields is the study of coherent quantum phenomena. The research programs are driven by the need to understand quantum physics in the context of information science and the importance of developing approaches to exploit quantum physics for new technologies. The scientific work of this group is well aligned with the National Quantum Initiative Act, and the research outcomes are important to the broader quantum ecosystem across the world.

The LCT Group's research portfolio is wide-ranging and includes some of the best programs in the world on ultracold atom physics and quantum many-particle physics. Ultracold atoms, created via laser cooling and trapping, provide a powerful platform for quantum simulation. Quantum simulation is one of the central applications of quantum information science and involves tuning one quantum system to behave like another. This group has pioneered methods to study new and exotic many-particle quantum states relevant to solids using optical-lattice quantum simulators. The work on topological order has spawned new research programs around the world and driven the field forward. The LCT Group is also at the forefront of new technical developments, including sub-wavelength microscopy in optical lattices and applying modern machine learning to optimize the experiments and analyze data. The methods are extremely useful to others in the field. Group members have also pioneered the development of approaches to create superfluid circuits and analogues of the expansion of the early universe using laser-cooled, ultracold atomic gases.

The LCT Group also studies quantum optics and produces some of the best results in this area in the world. Quantum optics is important to creating new devices. A key accomplishment is the demonstration of a high-fidelity, narrow-band photon source and demonstrating interference from photons produced using different species of laser-cooled atoms. This hybridization of two types of atoms and photons at different wavelengths could provide an important platform for devices needed to develop and deploy quantum networks. This group is also at the frontier of nonlinear optics and has produced important results on using atomic systems to produce correlated states of light. These quantum states can be used to improve interferometric measurements.

The LCT Group has a strong theory component that supports activities around the world and the development of new metrology instruments. Key contributions include atomic-structure calculations, which are needed at the frontier of laser cooling and trapping research and are critical to the development of next-generation, optical-lattice clock standards. The group also computes collision properties of atoms and molecules that are critical for the cold-atom vacuum sensor, which is a unique project to provide an absolute standard for ultra-high vacuum pressures. The work of the LCT Group is well aligned with the National Quantum Initiative Act and positions the team to capitalize on opportunities for scientific collaboration with, for example, The National Science Foundation's (NSF's) Quantum Leap Challenge Institutes and the Department of Energy's (DOE's) National Quantum Initiative Centers.

The Fundamental Electrical Measurements Group provides the foundation of the nation's electrical infrastructure through measurement services in the general areas of resistance, impedance, and related quantities. As part of its mission, the group maintains an active research program in precision measurements based on fundamental constants and in the development of quantum electrical standards. The group's laboratory program is competitive with other top-level, similarly focused national measurement institute (NMI) groups worldwide. Among the most notable achievements, the group had a significant role in the redefinition of the kilogram, leading to the official redefinition of the SI on May 20, 2019. Part of this contribution came in the form of the internally developed Kibble balance, which brought together many disciplines inside the PML to measure the Planck constant to an astonishing accuracy.

Another major innovation, the transition from a GaAs to a graphene implementation of the Quantum Hall Resistance Standard (QHR) has resulted in superior performance, a smaller footprint, and lower build cost. This has enabled industry partners to commercialize these types of instruments. As a necessary step in building the graphene QHR, the group developed and optimized in-house graphene production. This helps further support commercialization of the QHR. A measurement traceability link from the QHR to the Calculable Capacitor has been established, adding additional confidence to the evaluated performance of both measurement standards.

The Applied Electrical Metrology Group supports the nation's infrastructure by providing calibration services in the general areas of AC and DC voltage, current, phase, and power. As part of this mission, the group maintains an active research program in precision measurement systems based on quantum voltage standards to support calibration services within the group.

The Applied Electrical Metrology Group is competitive with similar groups at other top-level NMIs. The group has advanced the performance of electrical standards beyond any peers within the field. The Group utilizes a Josephson-junction based arbitrary waveform synthesizer (JAWS), developed by PML's Quantum Electrodynamics Division, that continues to increase output range while lowering costs and physical footprint. New thermal voltage converters have been developed and added to the Standard Reference Instrument (SRI) catalog. Research has started on a new nano-photonic thermal converter that may lead to a self-calibrating device with a zero-traceability calibration chain. Development of a metrology-grade radiofrequency (RF) buffer amplifier could lead to greater accuracy in AC current and RF measurement areas.

With the new definition of the kilogram and the realization of its consensus value, the Mass and Force Group is faced with a number of new challenges. The application of the new kilogram, its realization and dissemination, involves a number of steps ranging from the realization of a high-precision mass comparator, the calibration of standards in vacuum, the transfer from vacuum to air, the establishment of working standards under atmospheric pressure, and the dissemination of mass scales. Noteworthy are a rolling vacuum system designed to transfer weights in high vacuum between stations, and a unique magnetic suspension mass comparator that is essential for the transfer of mass realizations from their vacuum environment to air, with a demonstrated standard uncertainty of 15 micrograms.

The Mass and Force Group also develops an electrostatic force balance that provides a link between milligram-scale masses and the Planck constant. This approach is superior to the alternative of determining small masses by comparing them directly to the kilogram, in which case the associated subdivision of mass process results in accrued uncertainty. The electrostatic force balance approach promises orders-of-magnitude reduction in the uncertainty of masses at the microgram level and could possibly be miniaturized for implementation in a NIST-on-a-chip (NOAC) device.

The photon momentum yields a fundamental relation between mass, force, and laser power that can be used for laser power metrology and force measurements. A miniaturized version of this system using calibrated weights could provide a self-contained NOAC force reference for femtonewton resolution. Small-mass and small-force metrology, in particular in connection with NIST-on-a-chip, offers considerable potential for synergy and cross-fertilization, also with groups with related interest at NIST-Boulder.

TECHNICAL EXPERTISE OF THE STAFF

All the groups have the scientific and engineering staff with the appropriate level of expertise to deliver on their mission. In particular, the technical expertise of the staff in the Quantum Measurement Division is outstanding. The Quantum Optics and LCT Groups are among the best in the world, and their research is at the worldwide forefront of the field. The nearly equal mix of researchers in theory and experiment in the LCT Group is a unique strength that drives the research forward.

The quality of the staff has been recognized by a number of prestigious awards. Recent recipients of federal awards include eight awardees of Gold Medals and three awardees of Bronze Medals of the U.S. Department of Commerce, one recipient of a Presidential Early Career Award, and a Presidential Rank Award. External awards include an Arthur S. Flemming Award and an Arthur S. Flemming/Katherine B. Gebbie Lifetime Achievement Award; a George Snow Award; an International Union of Pure and Applied Physics Young Scientist Prize in Atomic, Molecular, and Optical Physics; and a Clarivate Analytics recognition for highly cited researcher.

ADEQUACY OF RESOURCES

The Quantum Optics and LCT Groups have the appropriate level of scientific expertise to deliver on their mission. A strength of the Quantum Optics and LCT Groups is their integration with the JQI, which includes 15 NIST principal investigators (PIs) out of 32 research staff, with about 40 graduate students working with NIST JQI Fellows. This association enables the NIST researchers to have easier access to students on the University of Maryland campus. The JQI also brings together researchers from different subdisciplines, which has led to new and productive directions for the laser cooling and trapping program. With their wide-ranging interests, they are well-positioned to take advantage of collaborations and new funding opportunities in the field. This is particularly easy for NIST researchers who also have adjoint faculty status at the University of Maryland through JQI.

On the flip side, a substantial part of the research effort of the Quantum Optics and LCT Groups has migrated to the University of Maryland campus, and the resulting geographical separation from NIST can lead to isolation. This issue is mitigated by former students and postdoctoral researchers who become permanent NIST employees and drive collaboration. Lessons learned from the COVID-19 pandemic about remote work have also been beneficial in addressing this issue.

On the financial side, The JQI was supported for 10 years as a NSF Physics Frontier Center. The program was not renewed. This loss provides a challenge to financially supporting the research effort, although the loss of NSF Physics Frontier Center funding is an opportunity to explore new research directions. The LCT Group is highly aligned with the National Quantum Initiative Act and well positioned to capitalize on new federal funding programs in this area.

The JQI research facilities on the University of Maryland campus are among the best in the world but are at physical capacity. Expansion space is needed for the research programs to grow and remain at the frontier. The facilities at the NIST Gaithersburg site have significant deferred-maintenance issues. A recent air-handling failure significantly disrupted research progress.

The Fundamental Electrical Measurements Group has the facilities, equipment, and human resources to support the stated objectives of the organization’s technical program. However, because of the COVID-19 pandemic and the resulting closures and limited physical capacities, the facilities’ malfunctioning HVAC systems have been a source of issues that are blocking progress.

The Applied Electrical Metrology Group has the facilities and equipment to support the stated objectives of the organization’s technical program. However, it suffers from a shortage of available human resources to support the group’s calibration services. Some of the less central activities appear to be understaffed. The flood damage to the Kibble balance laboratory is problematic.

The Atomic Spectroscopy Group is somewhat understaffed, considering the scope, importance, and broad application of its task serving a wide variety of stakeholders from industry, with applications in fundamental science. Critical issues include difficulties hiring, given the small numbers of students trained in spectroscopy at universities, and knowledge transfer when experienced staff retire. There is also a shortage of available human-resource support for the group’s calibration services, on which DOE, the Department of Defense (DoD), NASA, and the commercial industry rely heavily The Group does not have sufficient resources to meet demand for multijunction thermal converters (ac/dc voltage converters).

A hiring challenge is that there is no broad university training for metrologists, who need to understand basic science and engineering. Few universities offer this kind of training. The alternative solution of working with short-time visitors does not help with maintenance continuity and corporate memory.

The excellence and worldwide reputation of a number of staff members of the Quantum Measurement Division result in significant recruitment efforts and attractive job offers by top universities and research institutes. It speaks highly for NIST that it has been largely successful in countering these offers and retaining these superstar researchers.

EFFECTIVENESS OF DISSEMINATION OF OUTPUTS

The Atomic Spectroscopy Group generates, critically evaluates, maintains, and distributes atomic spectroscopy data. It serves a broad community that includes astronomy, chemistry, and extreme ultraviolet (EUV) lithography. The NIST Atomic Database is unique in the world in that it enables a critical evaluation of published data to compile a database.

The Quantum Optics and LCT Groups disseminate products via publication in peer-reviewed journals and at scientific conferences. The publication rate is strong, and results appear in top journals with high impact factor. Many of the publications are frequently cited in the field, which demonstrates the importance of the fundamental and applied research performed at NIST. The LCT Group also plays an important role in collating data on precision measurements to improve knowledge of the fundamental constants of nature and on quantum neutron interferometry at the NIST Center for Neutron Research (NCNR).

The Fundamental Electrical Measurements Group has outputs in the form of publications in peer-reviewed journals and at scientific conferences, and in-house manufactured standards in the form of resistors, scaling resistors, and intrinsic QHR systems. Although still costly, the recent development of graphene-based QHRs has halved the cost of the previous GaAs-based version. The operation cost will also be reduced due to using a closed-loop cryostat that replaces the need of buying liquid helium, a limited resource. Overall, this group serves as an excellent example of balancing the need to research and develop the latest technologies with working with industry to produce practical, cost efficient, standards.

The Applied Electrical Metrology Group has also developed many robust standards that are sold to government and commercial customers through the SRI program. The Group serves as an excellent example of turning research into actual, practical, useful technology that benefits industry. However, success at offering a state-of-the-art standard at a price below similar commercially available standards has pushed demand beyond what the group can supply. Other outputs of the Applied Electrical Metrology Group include publications in peer-reviewed journals and at scientific conferences.

The Mass and Force Group disseminates its results in the form of publications in peer-reviewed journals and at scientific conferences and in-house development and measurement of standards. The group also represents U.S. interests in national and international metrology communities through participation in and leadership of consultative committees, working groups, and standards organizations.

The establishment of the Quantum SI, and in particular the introduction of the new mass standard in terms of Planck's constant, was accompanied by an outstanding range of outreach and educational activities, including in particular the NIST do-it-yourself LEGO® Kibble balance, which permit a broad audience of students and science enthusiasts to build their own working Kibble balances out of LEGO® bricks. Noteworthy also are the superb lectures by Nobel Laureate W.D. Phillips explaining the Quantum SI revolution to broad audiences worldwide.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The activities of the Quantum Measurement Division cover a remarkably wide range of topics, including basic research on the foundations of quantum measurements and quantum information science, and their applications to the redefinition and Mise en Pratique of the Quantum SI. The division provides critically evaluated spectroscopic data important for broad areas of science and technology and conducts fundamental and applied research toward the development of electric standards. Division staff is highly qualified. It compares favorably with the best groups worldwide working on related areas, and in a number of activities it is truly world leading. Generally, the division effectively disseminates the results of its work; the Applied Electrical Metrology Group could improve the transfer to industry partners of the technology it develops.

The most significant highlight of the Quantum Measurement Division is its key role in an achievement of historical importance, namely, the establishment of a revised SI unit in 2018. Central to this paradigm shift away from a mass artefact was the development of a Kibble balance that exploits fundamental electrical metrology: the quantum voltage characteristic of the Josephson effect and the von Klitzing resistance characteristic of the quantum Hall effect. In this way, the Kibble balance realizes a new definition of the kilogram based solely on fundamental constants. The resulting mass standard replaces the International Prototype of Kilogram, a cylinder of platinum-iridium which had served as the standard unit of mass of the metric system ever since 1899. As a result, all SI units have now been put on a fundamental, prototype-free footing and are now defined by giving exact numerical values to seven fundamental constants: the speed of light, the hyperfine transition frequency of Cesium atoms, the Planck constant, the electron charge, the Boltzmann constant, the Avogadro number, and the luminous efficacy. This development is having a profound impact on many of the programs of the Quantum Measurement Division of NIST. In particular, the Mise en Pratique and distribution of the new mass standard requires a number of novel steps that are currently being successfully developed by the group.

The division played a pivotal role in the establishment of the National Quantum Initiative Act and the Quantum Economic Development Consortium. In terms of measurement devices and standards, noteworthy is the development of the new graphene-based quantum Hall standard that operates at higher temperatures and smaller magnetic fields than the GaAs standard. Regarding new quantum technologies, significant achievements have been the development of an integrated single-photon source with a rate of 20 million photons per second; the development of a quantized arbitrary waveform synthesizer that can produce fundamentally accurate signals; and the generation, critical evaluation, and maintenance of an essential and widely used atomic spectroscopic database.

Aging facilities are suffering from delayed maintenance or urgent maintenance interrupted by the COVID-19 pandemic.

RECOMMENDATION: The Quantum Measurement Division should continue to pursue resources needed to address deferred maintenance, including air-handling issues, for the Advanced Measurement Laboratory Complex on the NIST Gaithersburg campus, and to repair the flood damage to the Kibble balance laboratory.

The division is experiencing difficulty in recruiting, especially in areas where universities do not provide a training ideally matched to the division's needs. Most undergraduate students are not aware of the broad range of science and engineering opportunities at NIST. Graduate students are not generally aware of the research opportunities and permanent positions that NIST offers. Attending campus recruiting events, giving seminars within university departments, and connecting with the Quantum Leap Challenge Institutes, DOE National Quantum Initiative centers, and other center-scale programs could provide a pathway to higher visibility

RECOMMENDATION: The Quantum Measurement Division should become more proactive in outreach to universities with a goal of developing a recruiting pipeline.

No plan was presented to the panel for improving the NIST Calibration Services, which is a unique service that NIST provides to industry. NIST is the sole provider of calibrations that are directly compared to U.S. national standards, and the service has been stagnant with diminishing quality over the last decade. Division staff attribute this to external budget cuts and loss of support personnel.

RECOMMENDATION: The Quantum Measurement Division should collaborate with other NIST organizational units in analyzing, assessing, and rejuvenating the NIST Calibration Services.

3

Radiation Physics Division

The mission of the Radiation Physics Division is to develop, maintain, and disseminate the national measurement standards for ionizing radiation and radioactivity, and methods and models needed to address related applications. The goal of the division is to provide accurate measurement in service to industry and in related basic science essential to its mission as the nation's precision measurement laboratory. The division provides a unique resource to the United States based on its one-of-a-kind facilities and expertise housed within its component groups—the Dosimetry Group, Neutron Physics Group, and Radioactivity Group.

TECHNICAL QUALITY OF THE WORK

The dosimetry program primarily serves stakeholders in radiation protection, industrial radiation processing, national security, and therapeutic and diagnostic medical physics, fundamentally supporting required calibrations and quality assurance of nationally mandated programs and efforts. A key mission of the dosimetry program is to develop and maintain national air kerma (kinetic energy released per unit mass), air kerma rate, and absorbed-dose calibration standards based on the derived International System of Units (SI) unit—the gray—for homeland security, medical, radiation processing, and radiation protection applications. This is accomplished through the provision of calibration services utilizing the dosimetry of kilovolt (kV) and megavolt (MV) X rays; ^{137}Cs and ^{60}Co gamma rays; ^{90}Sr/Y and ^{85}Kr beta particles; ^{125}I, ^{103}Pd, ^{131}Cs, ^{192}Ir, and ^{137}Cs brachytherapy; and electron beam sources and measurement instruments.

The quality of the work conducted by the Dosimetry Group is excellent, as demonstrated by the streamlined practices for maintaining the existing radiation dosimetry standards while anticipating new approaches to meeting calibration standards in emergent and in-demand fields such as brachytherapy calibration and electron beam calibration. While the activities are predominantly service-oriented, meeting calibration needs for critical programs and activities supported by associated regulations, the group has demonstrated technical accomplishments in designing and building a new therapy-level, gamma-radiation dosimetry calibration facility that improves NIST's ability to deliver state-of-the-art measurement capabilities for air kerma and absorbed-dose-to-water calibrations to a wide stakeholder base, and in pioneering research and development of new objective methods to assess image quality in security X-ray systems.

The Dosimetry Group has performed detector calibration for homeland security systems, as well as occupational-radiation areas, survey, and personnel dosimetry capabilities using a highly reproducible (~0.1%) ^{137}Cs irradiator source as established by the National Council on Radiation Protection and Measurements (NRCP) Report 160, making this facility critical across multiple national mission areas. The Dosimetry Group is further tasked with fulfilling the American Association of Physicists in Medicine (AAPM) Task Group 56 recommendation that all brachytherapy sources be directly traceable to NIST by automating the Wide-Angle Free-Air Chamber, to measure key quantities in the calibration process of radioactive material in brachytherapy seeds (i.e., air-kerma strength, well ionization chamber response, photon energy fluence spectrum, air-anisotropy ratio, and radiochromic film contact exposure). The culmination of these processes ensures accurate clinical dosimetry while maintaining the dosimetric traceability of these sources, enabling the three accredited dosimetry calibration laboratories (ADCLs) to maintain secondary, NIST-traceable standards. In the support of medical dosimetry standards, the bilateral benchmark activities between NIST and the Bureau International des Poids et Mesures (BIPM) has ensured harmonization of air kerma and absorbed dose standards with high fidelity, resulting in journal publications. Interest expressed by the group in improving the state of the art in nano-sensor and microchip dosimetry beyond long-established alanine-based, EPR-based (electron paramagnetic resonance–based) methods, resulting in two patents, demonstrates research interests that could beneficially be conducted collaboratively with the NIST-on-a-chip (NOAC) initiative.

The Dosimetry Group primarily works with its large stakeholder community. Alternative mechanisms other than radiological-based calibrations using ^{137}Cs and ^{60}Co could be applied, given movements to non-radiological source calibration in-field, thereby aligning calibration with field practices. Calibration and measurement associated with new modalities in medical physics (e.g., proton and heavy-ion therapy), with associated facilities and staffing expertise, are absent in the established activities of the group, and these capabilities need to be anticipated. While current calibration services harness established techniques, active research engagement is critical to ensure integration of new technologies that will supersede current methods and equipment. In addition to seeking extramural funding, the division could leverage initiatives such as NOAC in, for example, EPR dosimetry research.

The neutron physics program is at the forefront of neutron measurement science. It maintains facilities and capabilities that are unique in the United States and, in many cases, on par with the premier neutron institutes around the world. The single-crystal neutron interferometry facility at NIST is the only one in the United States and has achieved the best phase contrast in the world. The neutron/X-ray tomography (NeXT) imaging facility is the world's best for offering simultaneous tomography with neutrons and X rays. The neutron beam line at the NCNR, used by the Neutron Physics Group, is the preeminent resource for cold-neutron fundamental physics in the United States, and the group is pioneering the measurement of the neutron lifetime using the beam method (to be compared to the bottle method, thereby resolving the neutron lifetime puzzle). The NG-C beamline, after the planned cold0source upgrade in 2023, will increase the neutron flux by a factor of two; it might be the only high-flux beamline available to users in the United States, because the fundamental neutron physics beamline at the Spallation Neutron Source at the Oak Ridge National Laboratory will be dedicated to the nEDM (neutron electric dipole moment) experiment. In addition to the neutron flux calibration services, the group is carrying out a diverse research program, including fundamental physics, nuclear power monitoring, national security, manufacturing, and radiation protection.

The Neutron Physics Group has improved the technique for calibrating neutron flux. The group has been operating a $MnSO_2$ bath to calibrate neutron source emission rate for a variety of radioisotopic sources (with up to 10^{10}/s and 0.8% precision). With it, all U.S. neutron metrology is traceable to a reference source, NBS-1, maintained by NIST. Over the past decade, the Neutron Physics Group developed an Alpha-Gamma device to improve the neutron metrology precision to 0.06%. This expertise in neutron flux calibration directly supports the basic science program to measure the neutron lifetime (and other beta-decay observables) using the cold-neutron beams at the NCNR to test the standard model of particle physics and Big Bang nucleosynthesis. The recent work on the Alpha-Gamma device improves the knowledge of the neutron capture cross-section on ^{6}Li to 0.3% precision, with an ongoing effort to improve the neutron capture cross-section on ^{235}U to 0.2% and other isotopes relevant to nuclear sciences and national security.

The neutron imaging program supports applied research on hydrogen fuel cells, energy storage, and porous media in geology and other civil engineering materials (like concrete). The thermal neutron imaging station (BT2) is fitted with an X-ray system, making it the world's first such facility. The simultaneous tomography of neutrons and X rays enhances the capabilities to resolve small features, which is critical to studying material degradations and lithium-ion transport in batteries. A new cold neutron imaging instrument, installed in 2015, enables studies of magnetic structures using polarized neutrons and four-dimensional (4D) tomography to reach a spatial resolution on the micron scale. The ongoing effort to develop Wolter optics and a neutron imaging far-field interferometer, with a large acceptance of neutron flux, will reduce the exposure time by a factor of 1,000 while achieving high resolutions in both space and time.

Neutron interferometry provides a versatile tool to probe new knowledge, including nuclear physics and characterization of quantum materials. It uses the interference of matter-waves of the neutron to probe the four fundamental forces of nature with high precision. Recent work includes high-precision measurements of the scattering length of n-^{4}He (0.06% precision, 2020), the neutron charge radius, and the creation of entangled neutron states (spin and orbital angular momentum) to characterize quantum materials. Ongoing development of far-field interferometry using nanofabricated phase diffraction gratings aims to probe the weak gravitational force to extract the fundamental constant "G" using single neutrons with a precision comparable to the torsion balance–based experiments.

To support the NIST mission relating to neutron calibrations and metrology, the group members are developing new neutron detectors. Recent work includes a photon-assisted neutron detector (PhAND; U.S. patent) and segmented fast-neutron detectors to meet the national needs for fastneutrons dosimetry in homeland securities, underground sciences, and health physics. This expertise in fast-neutron detection enables the Neutron Physics Group to address the needs of a reactor-based neutrino experiment, PROSPECT (Precision Reactor Oscillation and Spectrum experiment), which measures the flux and energy spectrum of neutrinos from the high-flux isotope reactor fission reactor, with a highly enriched uranium fuel, to search for the sterile neutrinos, which are theoretically new particles.

The Radioactivity Group's key mission is to develop and maintain radiation detection methods, often based on first-principles methodology, that directly measure radioactive emissions. The group is required to develop relevant standards and methods of assay for industrial and medical radioisotopes. The group defines protocols for measurement of radioactivity on the national and international level and for other government agencies such as the Nuclear Regulatory Commission, the Department of Homeland Security, and the Food and Drug Administration, frequently linking radioactivity measurements to NIST standards.

Since the advent of the nuclear era, the use of radioactive isotopes has brought tremendous benefits to society in a multitude of ways, from expanding our knowledge of the world around us to improving the lives of millions of people through medical diagnoses and treatment. The use of radioactive isotopes has allowed researchers to answer a myriad of questions about wide-ranging subjects, from the behaviors of ancient peoples to the movement of carbon through the environment. The use of radioactive materials by industry allows the analysis of material densities, the inspection of critical systems, product sterilization, and oil and gas exploration. In health care, radioisotopes have been instrumental in diagnosing and treating disease, improving the lives of millions of people. One isotope alone (technetium-99m) is used in over 16 million people per year in the United States as an imaging agent.

TECHNICAL EXPERTISE OF THE STAFF

The staff of the Dosimetry Group is distributed among core expertise areas in accelerator physics, computational dosimetry, high-dose dosimetry, X-ray dosimetry, gamma-ray dosimetry, calorimetry/photonics, and brachytherapy.

The scientific expertise in the Neutron Physics Group is evidenced by its success in several areas of activities. The area of calibration and metrology includes neutron source calibrations, absolute neutron fluence, standard cross-sections for thermal neutrons, and high-dose irradiation with neutrons. The area of basic physics research includes fundamental neutron physics, interferometry, and reactor neutrinos. The area of applied research includes neutron imaging, polarized ^{3}He spin filters, neutron detection, dosimetry, and spectroscopy. The caliber and expertise of the staff in all activities and at all levels is outstanding. Four of the staff have been recognized as fellows of the APS. Senior staff members are leading the standardization of precision measurements in neutron sciences in the United States.

There is strong synergy among the groups in calibrations and metrology, basic sciences, and applied research, with the staff supporting multiple areas of the program. In particular, the neutron imaging program supports many leading industrial research and development program, s as evidenced by the impressive numbers (approximately) of unique experiments (416), patents (40), papers (200), and Ph.D. dissertations (66) since its inception. The basic research program on beta-decay physics involves a handful of difficult measurements; each takes multiple years of data collection to acquire the counting statistics and to perform many checks on systematic effects, which also requires running times of comparable lengths. The interferometry program has developed a versatile tool that produces significant scientific results. Several high-impact publications, many with external university collaborators, showcase the unique niche of this approach. The ^{3}He laboratory continues to support the fundamental neutron physics and neutron scattering programs in the NCNR by providing state-of-the-art large vapor cells to polarize cold neutrons.

The Radioactivity Group leads the nation in the development of new methods and instruments for determining the absolute activity of a radionuclide or mixture of radionuclides. The group is publishing and disseminating information on new approaches for determining the absolute activity of a radionuclide, and the group is fulfilling its mission of advancing measurement science and providing standards for the use of radioactive materials in medicine and industry.

The Radioactivity Group continues to develop new methods for creating primary radioactive standards. This includes live-timed $4\pi\alpha\beta$-γ anti-coincidence counting and Monte Carlo simulation analysis. The group is part of a NIST Innovations in Measurement Science–funded proposal to develop leading-edge technology that can be used to determine the absolute activity of a mixture of radionuclides using 4π decay energy spectrometry with ultracold transition edge sensors. In the area of medical applications, the group developed a methodology for calibrating Ge-68 activity content in a commercially available calibration source that is traceable to a national standard for positron emission tomography isotopes, and it developed standards for the complex decay chain targeted-alpha therapy radioisotopes Ra-223 and Ra-224.

ADEQUACY OF RESOURCES

Maintenance of facilities and infrastructure is a necessary foundation for mission accomplishment, as exemplified by the modernization project for Building 245, one of the world's premier laboratories for ionizing radiation measurement science and research. Recent infrastructure upgrades have increased efficiency of operations, with fewer interruptions in calibration service work due to environmental conditions (e.g., temperature and humidity stability in air kerma–based standards and calibrations). Investment in critical facility improvements in X-ray calibration, relocation of the ^{60}Co source for medical dosimetry standards, building a new high-dose-rate brachytherapy vault, and upgrading to 10 MeV the electron beam accelerator used in industrial irradiation processes are all demonstrated commitments to facility modernization and sustainability. Movement to new H-wing laboratories dedicated to general dosimetry calibration activities is under way; these activities include photon and electron, brachytherapy, and radiation-processing dosimetry facilities and instruments, collocated with mechanical and electronics shops.

The Building 245 modernization project has imposed demands on division finances and resources, which has detracted from staff time and regular duties (e.g., moving equipment and escorting construction workers). It will be necessary to anticipate the impacts on resources, staffing, and budget to mitigate interruption of activities during (1) the migration to facilities in the new H-wing; (2) the move to a renovated laboratory in the existing building for the EPR dosimetry facility; (3) renovation in place for the A-wing medical industrial radiation facility (MIRF) and 10 MeV industrial accelerator, scheduled in the 2022-2024 timeframe; and (4) renovation of the B-wing ^{137}Cs and ^{60}Co radiation protection, accelerator, and high-dose calibration facilities in a currently undetermined timeframe.

The Neutron Physics Group occupies two research buildings. In the NCNR, it is running eight neutron beam lines and the thermal column; in Building 245, there are several laboratories, including the Mn (manganese) bath room, the polarized ^{3}He laboratory, a low-scatter room for dosimetry, and a machine shop. The decaying infrastructure of the neutron calibration and setup laboratories in Building 245 is being renovated. The renovation, however, presents a major challenge to all operations, with an uncertain timescale for completion. In the NCNR, the high-flux neutron beam lines, the imaging stations, and the interferometry facilities are the best in the world. However, the COVID-19 lockdown in 2020, followed by a recent safety incident in the NIST reactor, triggered by an over-temperature of one fuel rod, prevented the reactor from coming online and had disruptive impacts on the neutron physics programs. Delays associated with the planned cold source upgrade in 2023 will inevitably reduce the scientific productivity of the group.

In the Dosimetry Group often one dedicated staff member is assigned to each of the core areas; mitigating this reliance on a single individual could improve capacity for performing mission-critical work and additional research. The training program that involves students and postdoctoral researchers in each of the critical standards activities could be strengthened. Fostering a program to share equipment and facilities with users at national laboratories and universities would be useful. It will be important to ensure sustainability of succession planning and knowledge retention by prioritizing allocation of resources in a manner that appropriately addresses the requirements of human capital development and infrastructure improvements.

Research staff in the Neutron Physics Group are world-leading experts in neutron measurement sciences. However, considering the large scope of work, loss of staff, and difficulty hiring replacements, there will be a challenge in sustaining an adequate level of staffing. The group lost several senior staff members recently due to departure and retirement, but there is no plan to replace them, due to budgetary constraints. Understaffing has significantly increased the service-base workload of current staff in order to meet the NIST mission. As such, Ph.D.-level scientists are deprived of time and opportunities for doing innovative research. Many recent and current postdoctoral researchers have demonstrated credentials to do outstanding science; however, the group reported that there is apparently no funding available to retain and promote them at NIST. Currently, the National Academies/National Research Council (NRC) postdoctoral program is the main channel for the group to recruit postdoctoral fellows, but there is significant competition among the sciences represented by the applicants and the selection committees. The understaffing situation remains the major risk to the program to meet its core missions while pushing the advancement of neutron metrology. Without increasing the number of staff, NIST risks losing its leadership role and its competitiveness with other neutron facilities in the United States and around the world.

The Radioactivity Group has successfully moved multiple detection systems to the new laboratories in the H-wing. The group has demonstrated that these unique instruments with over 40 years of operational history are operating as well after the move. The group has also demonstrated reduced ambient backgrounds for many of the instruments in the new laboratories. The staff for many of the activities within the group are served by single researchers with very little backup. Because of this, the Radioactivity Group is at risk of depleting its expertise through an ageing workforce and staff departures.

EFFECTIVENESS OF DISSEMINATION OF OUTPUTS

Since 2018, the Dosimetry Group has published 10 manuscripts in peer-reviewed journals and proceedings, including two publications with the Radioactivity Group, and selected publications with international counterparts. Some staff are active in professional societies, notably the AAPM, but there has been limited dissemination of capabilities and results in the scientific community. Expanded engagement with professional societies would promote scientific exchanges and enhance state-of-the-art practices in areas including, but not limited to, Monte Carlo simulation tools, nuclear data science, and detection science. Expanded engagement with university partners, stakeholder programs, and international counterparts resulting in joint publication would also be beneficial. Engagement with professional societies could help promote participation in the Council on Ionizing Radiation Measurements and Standards by students, postdoctoral researchers, and faculty.

The Neutron Physics Group's training of postdoctoral researchers and students, both within and outside NIST, is highly effective. The group maintains strong collaborations with outside institutions. The group has been hosting a large number of graduate students and postdoctoral researchers, academic users, and industrial users from the isotope production industry, fuel cell and energy storage industry, national laboratories, and the Navy. In recent years, the group hosted summer schools on fundamental neutron physics and the 9th Workshop on Neutron Wavelength Dependent Imaging in 2017. The dissemination of the group's program is effective, as evidenced by its 27 publications since 2018. The interferometry team has produced 22 publications since 2015. The imaging team, benefitting from a large number of external collaborations, has published almost 99 papers since 2015.

In addition to its basic-science activities, the major way in which the work of the Radioactivity Group is disseminated is through the development and availability of standards and standard reference materials. From 2009 to 2021, the group completed 30 new standard reference materials and recertified 22 standard reference materials. The Radioactivity Group participated in international comparisons of standards for Cu-64, F-18, Ba-133, Ra-224, tc-99m, and tc-99. From 2017 to 2021, the group published 37 papers in the peer-reviewed literature. The majority of these papers appeared in the premier journals for this type of work.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The Dosimetry Group has made major contributions to improved precision of dosimetry metrics through Monte Carlo computation improvements, nuclear-data science, and detection science, which in aggregate have greatly contributed to the precision of dosimetry measurement. Expanded dissemination of this knowledge outside NIST, through greater engagement with university partners, and international stakeholders, would accelerate widespread application of this outstanding technology.

RECOMMENDATION: The Dosimetry Group should expand dissemination of its knowledge of radiation metrics through greater engagement with university partners, and international stakeholders.

Staffing of the critical service and research activities within the Dosimetry Group is very top heavy, with senior scientists compelled to take on support functions to sustain key activities. It would be advantageous to strengthen the student and postdoctoral training functions to help mitigate this problem. It would also be useful to give consideration to analyzing and identifying resource allocation priorities in a manner that ensures the sustainability of succession planning and knowledge retention, while balancing the needs of human capital development and infrastructure improvements.

The Neutron Physics Group is integral to the Radiation Physics Division through their work on neutron calibrations and metrology. Within the group, there is a virtuous cycle connecting the basic research with neutrons to the applied research that often benefits from the operationalized products of basic research (such as polarized ^{3}He spin filters) and to the core NIST mission in metrology and calibration. Each of these applications benefits from the synergy of technology and staff across the focus areas.

The group's neutron imaging program provides a set of unique capabilities to multiple applications as evidenced by numbers of unique experiments, patents, papers, and RD100 2018 (neutron X-ray imaging), awards. Neutron interferometry has transitioned from an artifact of quantum mechanics to a versatile tool addressing issues, including nuclear physics and characterization of quantum materials. The group is publishing significant papers, many with external collaborators. The beam line used by the Neutron Physics Group is the preeminent resource for cold-neutron fundamental physics in the United States (based on overall results), and the group is the world leader in the beam measurement of neutron lifetime.

The Neutron Physics Group has made very few new hires over a number of years. The group is small for the scope of work for which it is responsible, and this constitutes a risk for a national resource essential to maintaining the state of the art in neutron-related measurement and applications.

RECOMMENDATION: The Radiation Physics Division should examine the ratio of the Neutron Physics Groups' staffing to its workload and consider means of achieving and maintaining an effective ratio by increasing staff if appropriate.

The Radioactivity Group leads the nation in the development of new methods and instruments for determining the absolute activity of a radionuclide or mixture of radionuclides. The group is publishing and disseminating information on new approaches for determining the absolute activity of a radionuclide. The group is fulfilling its mission of advancing measurement science and providing standards for the use of radioactive materials in medicine and industry. However, the Radioactivity Group is at risk of depleting its expertise due to an ageing workforce and staff departures.

RECOMMENDATION: The Radiation Physics Davison should address predicted staff departures as part of its staffing plan.

4

Microsystems and Nanotechnology Division

The mission of the Microsystems and Nanotechnology Division is to advance nanofabrication technologies and use them to develop innovative integrated measurement microsystems. The division is organized into the following three groups: the Nanostructure Fabrication and Measurement (NFM) Group, Photonics and Optomechanics Group, and Biophysical and Biomedical Measurement (BBM) Group.

TECHNICAL QUALITY OF THE WORK

The generally impressive work of the Nanostructure Fabrication and Measurement Group is broadly focused on improving quality and efficiency in nanofabrication and measurement through emphasis on a closed-loop iteration process (virtuous cycles). Group presentations emphasized the traceability chain and the ways that a detailed understanding of nanofabrication and measurement impacts this chain. For example, the point was made that the transitioning of calibration tools to the field typically involves multiple steps, with each step introducing compounding errors. Therefore, nanoscale fabrication and measurement provide a direct way of improving commercial calibration tools by greatly reducing the uncertainty in the root calibration. Even measurement devices as simple as a tape ruler, which typically would be manufactured to have an accuracy less than 1 mm, rely upon root calibration at the nanometer scale. Of course, this precision is even more critical in quantum information, such as for the precise and accurate placement of quantum emitters within chip-based microcavities and also in medicine, where more efficient and higher-accuracy measurements are required in development, testing, and production of nanomedicines such as DOXOrubicin.

The NFM Group is working effectively with the Biophysical and Biomedical Measurement Group, and the Photonics and Optomechanics Group. The NFM Group expressed the belief that continued improvements made possible by the virtuous cycle will strongly impact nanophotonics in particular, where new application areas, such as frequency microcombs, are already demanding nanoscale control of macroscale resonant structures for dispersion engineering. This collaborative approach to solving problems is commendable.

The Photonics and Optomechanics Group interacts with other NIST groups and is rapidly expanding the range of research to address a wide variety of NIST problems, such as NOAC and miniaturized, integrated atomic clocks. The group has achieved a number of recent breakthroughs, such as integrated beams in multiple wavelengths for the next generation of Strontium magneto-optical traps for atomic optical clocks. The group demonstrated an accelerometer with an order of magnitude better sensitivity, based on combining their photonic expertise with their micro-electromechanical systems (MEMS) expertise. This is likely to have a significant impact on the inertial-navigation field, and like many of its other projects, it will have a large commercial impact. The photonics team is engaged in exciting projects, engineering devices at ever-higher frequencies and achieving record high Qs and using them for quantum measurements at room temperature. The scientific depth of the group’s scientists, the quality and control of the fabrication processes, and the exciting world-record research results that are being generated are impressive.

The science of biology has critical length scales, from nanometers to meters and beyond. Biology is also incredibly complex at every one of these scales. The Biophysical and Biomedical Measurement Group is tasked with the formidable challenge of performing triage on critical problems over this range of lengths and finding critical technologies and problems to address. One of the great challenges in biomedical measurement is moving from the culture dish to the three-dimensional (3D) physiological world of tissue, and probing with microelectronic sensors the chemical and physical state of tissue, both diseased and healthy. There is a unique effort by the Biophysical and Biomedical Measurement (BBM) Group in the Microsystems and Nanotechnology Division, in collaboration with the Advanced Electronics Group within the Nanoscale Device Characterization Division, to develop ultra-sensitive nanofabricated field-effect transistor pH sensors, which can ultimately be deployed in a clinical setting to probe the interior of tissue.

In collaboration with the electron-spin paramagnetic sensors being developed within the BBM Group, the researchers will begin to develop 3D models of the oxygen, pH, and other critical metabolites in tissue. It is very exciting that there is a collaboration developing with AstraZeneca, one of the COVID-19 vaccine developers using the technologies being developed here.

Micro-nanofluidics plays a central role in biomedical technologies, including biological object sorting by size in a range from the nanoscale to the millimeter scale, and in developing fluidic connectivity between modular biological units. The team addressing fluidics and cytometry is developing new high-throughput, high-precision sorting technologies and measurement technologies to provide precise quantitative measurement of the extremely low flow rates often found in these systems. A challenge in the field of micro-nanofluidics is the complex and often unknown structure of the objects being transported and how they interact with other objects and surfaces. DNA nanotechnology offers an ability to design biological structures using well-defined rules that can create both novel materials and reproducible complex structures that can be used as transporters in biological systems and as precision standards.

The team researching microphysiological systems is bringing all of the above technologies together in a major effort to put a “body on a chip,” which consists of a number of interconnected modules that have tissue cultures of various organs (e.g., liver and bone marrow) to which various drugs and physiological stressors (e.g., oxygen, pH, and temperature) may be applied to ascertain in a longitudinal manner the way that the various tissue components interact with one another. This is a daunting challenge, and it would be beneficial to achieve more integration of the technologies discussed above in a 3D manner within this modular assembly of intercommunicating tissues. The impact of this technology would be vast, because so many drugs fail with increasing environment complexity.

TECHNICAL EXPERTISE OF THE STAFF

The staff of all groups within the division is well organized and well qualified, with impressive scientific depth and clear definitions of responsibility and good synergy across groups within the division.

ADEQUACY OF RESOURCES

The NFM Group operates in conjunction with the Gaithersburg cleanroom facility, vital to its mission that supports focus areas in electron-beam lithography, focused ion beam, scanning electron microscopy, atomic force microscopy, super-resolution optical microscopy, and biomolecular assembly. Work within NFM and the clean-room facility directly impact the Photonics and Optomechanics Group and the BBM Group. It will be important to maintain the cleanroom nanofabrication and characterization facilities at a state-of-the-art level. Continued support and investments in this facility will be broadly leveraged across technical groups. These facilities will also directly support NIST initiatives such as NOAC.

EFFECTIVENESS OF DISSEMINATION OF OUTPUTS

The NFM Group is doing an excellent job of disseminating the results of its work through publications, direct engagements with industry and universities, distribution of nanofabrication tools such as the nanolithography Toolbox, and the development of the JMONSEL simulator tool for precision calibration of nanoscale features in scanning electron microscopy. Dissemination of research results on the subject of nanoplastics, which is emerging as an environmental challenge with direct consequences for human health, will grow in importance.

The Photonics and Optomechanics Group's publication rate in top-tier journals is excellent, and the rate of patent filings indicates the novel aspects of their research. The group seems tightly coupled with the NFM Group in particular and interacts with other NIST groups. Staff members also have collaborations with scientists outside of NIST and seem to be leveraging their skills in other groups to secure outside funding and expand the visibility and impact of their research.

GENERAL CONCLUSIONS

The programs within the Microsystems and Nanotechnology Division are of high quality and are well aligned with the NIST mission. The researchers are generally superb and frequently among the world's best researchers in the areas of microsystems and nanotechnology, as evidenced by the citation data for their publications. The facilities and equipment are top notch, although there are some concerns about maintaining expensive processing systems at state-of-the-art levels. The dissemination of outputs is reasonable and appropriate, including publication in top-tier journals, cooperative research and development agreements (CRADAs) and other relationships with industry, and a steady flow of associates into and out of the organization, to and from academia, industry, and national and government laboratories. These interchanges occasionally yield permanent appointments at NIST.

RECOMMENDATION: The Microsystems and Nanotechnology Division should perform a forward-thinking analysis to address the concerns about maintaining expensive processing systems at state-of-the-art levels.

The division chief presented a plot that effectively made the point that the division staff is working in a strongly interdisciplinary manner within the division and with many other divisions across NIST. This indication that the activities within the division are not siloed—a concern for many technical organizations—was borne out by the reviews of the division's groups.

5

Nanoscale Device Characterization Division

The Nanoscale Device Characterization Division is home to scientists and engineers with deep expertise in design, fabrication, and characterization of novel nano- and atom-scale engineering solid-state materials and devices. The vision of the division is to transform nano- and atom-scale technologies by advancing measurement science and fundamental knowledge. The division's mission is to develop and advance the measurement and fundamental knowledge needed to characterize nano- and atom-scale engineered materials and solid-state devices for innovation in information processing, sensing, and future quantum technologies.

The division is organized into the following five groups: the Advanced Electronics Group, Alternative Computing Group, Atom Scale Device Group, Nanoscale Processes and Measurements Group, and Nanoscale Spectroscopy Group. The division's strategic areas of research are as follows: theory and measurements for alternative computing; microscopies for quantifying emergent properties in quantum materials and devices; advanced microelectronics—integration, characterization, and authentication; and atom-scale solid state devices—theory, fabrication, and measurements.

TECHNICAL QUALITY OF THE WORK

Overall, the quality of the technical programs is impressive; much of the scientific work at the division ranks among the best of the world in its field of research.

Among the highlights of the division's technical accomplishments, the extraordinary scanning probe effort is a standout. The Alternative Computing Group has developed an impressive platform to enable testing of prototype artificial intelligence hardware, available to NIST and its partners. By allowing new computing prototypes, such as cross-bar or neuromorphic chips, to be physically integrated onto a foundry-fabricated CMOS wafer, to be probed, packaged, and tested as a system, new levels of system-level testing have become available. Donor and dot platforms in the quantum area have also made great strides and are clearly positioning themselves to make important contributions.

In a forward-looking research area such as the development of future nanodevices, it can be very difficult to assess the needs of industry with respect to NIST's mission. The division needs an improved understanding of which nano- and atom-scale engineered materials and solid-state devices are of greatest interest to industry, and what measurements and fundamental knowledge gaps exist with respect to their characterization. Division researchers are pursuing promising initiatives whose proposed directions are aligned with cutting-edge research and NIST mandates. However, in some instances, there are other research groups that are pursuing similar directions and that are ahead or in better institutional positions to succeed, by virtue of funding and/or infrastructure. The division's researchers need to better define their current complementary or competitive role, vis a vis external research efforts, and where their research needs to be in the future, so that leadership can strategically align resources and laboratory mandates to position the researchers for success in these new initiatives. The division needs to develop clearer metrics and strategic planning to define and accomplish success and growth goals. It is important to clearly link the choice of metrics to the NIST mandates such as advancing U.S. competitiveness, being the laboratory for industry, and supporting development of measurement standards. Given the newness of this division after a recent reorganization, such gaps in metrics and strategic planning are not unexpected.

In the area of quantum computing, increased interaction with industry would beneficially inform the work being carried out at the division. The phosphorus atomic precision platform could significantly help further understanding of control limits (i.e., manufacturing inaccuracy and imprecision) and benchmarking of Hamiltonian translation to physical systems. In addition, the unique capabilities in low-temperature scanning tunneling microscopy (STM) could provide new information on two-level systems (TLS) that impact the ever-important issue of T_1, qubit energy relaxation time. While there is an extensive literature regarding TLS providing a phenomenological framework and conjectures for sources of TLS, the atomic-scale sources of energy relaxation have yet to be identified and characterized conclusively particularly for next-generation materials of interest. By combining 8 mK temperatures and 7–8 micro electron volt energy resolution, using the STM tip to identify defects (e.g., TLS) and then carry out spectroscopy on these defects could lead to unprecedented understanding and characterization of TLS.

The common thread across the division's work in alternative computing appears to be at the device level, as embodied in the non-volatile memory crossbar/platform work. The impending end of Moore's Law seems to imply that today's emphasis on machine learning based on graphics processing units (GPUs) and their huge attendant energy consumption will necessarily end. With this alternative computing effort, the division is placing a bet that what will follow GPU- and accelerator-based machine learning will be similar to what came before it—biology-inspired neuromorphic, low-energy arrays of nonlinear memory elements such as memristors. Crossbar neuromorphic devices utilizing memristors of either magnetic tunnel junctions or WO_3 (tungsten oxide) are of significant interest in a number of companies. The stochastic nature of filament formation and control to vary resistance is actively being investigated and is a challenge in issues of control, but importantly an opportunity for ultralow-power artificial intelligence computing.

TECHNICAL EXPERTISE OF THE STAFF

The caliber and expertise of the senior researchers and associates in the Nanoscale Device Characterization Division are impressive.

ADEQUACY OF RESOURCES

In general, the facilities of the division are excellent. Much of the equipment is state of the art with some pieces being one of a few in the world or one of a kind. The installation of the photoemission electron microscopy (PEEM) system and planned inclusion and coupling of a ultraviolet (UV) and deep UV femtosecond light source constitutes an exciting addition to the suite of nanoscale analytical tools. PEEM can be used to investigate differences in the work functions of individual grains, for example, and the inclusion of a femtosecond source could provide information on key dynamics at the nanoscale and femtosecond time domain.

During the review, there was little mention of supercomputing (or even large-scale computing) resources available to support the division's technical work. One theorist said he did not need much support, and another researcher said he had adequate access to computing support. Other national laboratories, such as Lawrence Berkeley National Laboratory, however, point to their onsite supercomputer as being a fundamental required resource for analytics and modeling and argue that continuing development of even more capable supercomputers is essential to scientific progress at all levels, including basic research. In that context, the division's apparently modest computing resources appear minimal by comparison. One presenter suggested that the COVID-19 pandemic had helped his research by making more computing cycles available. "Doing the best with what you have" is a generally laudable attitude, and it is in evidence here, but under-resourcing the computing systems available to the division's scientists could effectively limit the scope of their work or delay its completion. If more advanced and capable computer systems were to be made available, the division may benefit from adding additional skill sets to their current mix. In particular, algorithms experts can be extremely helpful in matching what domain experts (the division's current personnel) know to the tools and methods that best suit high-end computing systems.

During the review, insufficient time was made available for discussion of the adequacy of human resources. One apparent inadequacy might be a need to add a person with systems expertise to the team. This gap may affect the group's ability to address issues relating to wear-out mechanisms of non-volatile memories. Accessed enough times, any given cell can no longer reliably retain state. Flash memory of the kind in USB keys have this characteristic, and the general solution (a systems level approach) is to provide a wear-leveling controller that reassigns addresses as needed, to keep any one cell or group of cells from being overused. Presentations by division researchers mentioned this problem of wear-out in passing, but there was no concerted effort to address it directly. There are both system reliability and security implications to this problem that will require higher-than-device-level research to solve.

EFFECTIVENESS OF DISSEMINATION OF OUTPUTS

The division is using well the traditional methods of output dissemination, including publications in high-quality journals, timely workshops, and direct connections to outside projects. The division is also using impressive new channels of communication. For instance, making the atomic force control software available on GitHub is a very good first step toward disseminating that work to the widest possible audience. A useful follow-up step could be to proactively contact whoever downloads that code to see if support or collaboration would be useful. Another example was the crossbar platform for artificial intelligence. The design of that system was done with an eye toward facilitating its duplication outside of NIST (i.e., using industry standards, appropriate languages, and affordable hardware). This would have the intended effect of making future collaboration much more feasible and effective.

Much of what NIST does is basic research, and fundamental facts about how nature is organized are by definition not patentable. However, the innovative work described to the panel showed ample examples of material that would clear the novelty threshold required of patents by U.S. law. Unless there are legal or policy restrictions at NIST, patenting such work seems worthy of consideration.

In the area of quantum computing, there is an increasing need for standards development. There is a need for standards relating to characterization not only of the qubits but of the elements of the qubits such as properties of quantum dots as well as donor and Josephson junction-resonator structures. For example, standards and reliable technique development for tunnel barrier characterization, charge noise, defect identification, as well as valley splitting (e.g., spatial uniformity) are all areas where groups report results from various methods without any authoritative understanding of the comparisons of accuracy and precision. Benchmarking of novel computing schemes such as analog quantum simulation is also an opportunity, given NISTs present position. Leadership in this area is needed, and perhaps a NIST-led workshop series might be timely to help the community to converge in some of these areas.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

Because NIST is tasked with developing new characterization technologies, U.S. companies would benefit greatly from the capabilities within NIST to develop next-generation tools for addressing a range of technical challenges at the nanoscale for companies without the resources to develop these analytical probes themselves.

> **RECOMMENDATION: The Nanoscale Device Characterization Division should expand its interactions with technology companies within the United States with an eye toward sharing information on characterization instrumentation.**

Adequate computing resources, including supercomputers where appropriate, are essential for conducting research at the advanced levels evident at NIST. Such resources may not be currently available to the division's researchers.

RECOMMENDATION: The Nanoscale Device Characterization Division should conduct an analysis to ascertain whether the capabilities of the computing systems available to the division's researchers reflects an effective balance of cost of acquisition, cost of use, and utility to the researchers. The division should calibrate the results of such an analysis against the capabilities provided to researchers by other national laboratories.

6

Sensor Science Division

The vision of the Sensor Science Division (SSD) is to be the primary driver for innovation in the International System of Units (SI)-traceable measurement of dimensional, thermodynamic, and optical radiation quantities, enabling the next generation of equitable standards to promote U.S. economic growth and security. The mission of the division is to foster the next generation of SI-traceable, dimensional, thermodynamic, and optical radiation measurements and their applications by providing calibrations, standards, and innovations that improve U.S. industrial competitiveness and quality of life.

The division is organized into the following seven groups: the Dimensional Metrology Group, Fluid Metrology Group, Optical Radiation Group, Remote Sensing Group, Surface and Interface Metrology Group, Thermodynamic Metrology Group, and Ultraviolet Radiation Group. The groups work collaboratively on nine major topics—measurement services and documentary standards, large-scale dimensional metrology, metrology for extreme ultraviolet (EUV) lithography, forensics topography and surface metrology, providing SI traceable measurements to support the energy sector, low-background infrared radiometry, climate change and greenhouse gas, thermodynamic metrology, and optical metrology for solid-state lighting.

With its institutional responsibility for the realization and dissemination of three of the seven base SI units—the meter, the kelvin, and the candela—the SSD is tasked with SI-traceable measurements of length, temperature, infrared-to-EUV radiation, pressure and vacuum, surface and interface optical and dimensional properties, gas and liquid flow, liquid volume, and humidity. Across SSD's groups and programs, the division is responsible for developing, maintaining, and disseminating national measurement standards for these physical quantities; performing measurement comparisons internationally to support U.S. competitiveness in the global marketplace; performing research for new measurement technologies, methods, and national needs; and providing measurement services, including the calibration of practical standards and measurement instruments. The list of stakeholders reliant on and requesting NIST impartiality and quality for SI-traceable measurements continues to grow.

TECHNICAL QUALITY OF THE WORK

While it is not the role of NIST to specify technical requirements, NIST plays an important role in measurement services and documentary standards, advising on measurement techniques and collaborating with industry in the development of technical standards. The SSD is engaged in over 25 Standard Development Organizations (SDOs) worldwide. Approximately one-third of the staff are actively involved in producing documentary standards, and they hold about 58 leadership positions in these organizations. Billions of dollars in dimensional metrology equipment are bought and sold using performance specifications from standards developed under SSD leadership and with SSD-developed models serving as the technical foundation. This work has resulted in 16 major documentary standards and draft documentary standards published since 2017. SSD contributions to dimensional metrology have been recognized by the ASTM James A. Thomas President's Leadership Award and the NIST Edward Bennet Rosa Award. NIST staff have also been recognized for their outstanding contributions by awards from the International Commission on Illumination, Acoustical Society of America, American Society for

Mechanical Engineering (ASME), NASA, the American Vacuum Society (AVS), ASTM International, and NIST.

The SSD is currently involved in 19 key comparisons and 16 regional comparisons, which help to establish equivalence of measurement standards across national metrology institutes. The published results of these key comparisons confirm that NIST staff demonstrably are leaders in many measurement disciplines, achieving some of the lowest measurement uncertainties in the world. In terms of impact on advanced manufacturing, it is important to note that nearly all large-scale metrology tools are specified and tested according to standards developed under SSD staff leadership.

Stakeholders purchased $2.2 million of products of SSD measurement services (calibration services, standard reference materials, laboratory accreditation, and training courses) in fiscal year 2020. The measurement services of the SSD account for more than half of the total NIST calibrations performed, corresponding to 4,000 artifacts per year. An impressive example of leverage is that four NIST-calibrated reference flow meters are used by one manufacturer to calibrate 50,000 mass flow controllers.

SSD staff and leadership expressed a concern that they had lost contact with key customers with the implementation of the NIST Storefront, which provides an Internet interface through which NIST measurement services are procured. Both end users and staff expressed displeasure in using the current Amazon-like interface to procure and deliver services. This may have had several detrimental effects. While returning customers provide formal and informal feedback, some traditional customers of NIST (major industry segments, Department of Defense [DoD]) have not been able to obtain some needed services. Specifically, the long times for some calibrations to be completed, the discontinuation of some measurement services, such as the cryogenic liquid flow metrology and the high costs charged to customers, are jeopardizing NIST's position of providing SI traceability for U.S. commerce and national security.

Because NIST typically works with critical, but few-in-number, customers at the top of the traceability pyramid, it may be beneficial to contact these customer segments to understand better their measurement needs, which have significant impact on the industrial competitiveness and on the U.S. security and defense infrastructure. Some NIST calibration services perform well; others could benefit from improvement. It would be beneficial for SSD to consider ways to give customers better estimates of delivery times for calibration services and provide direct, timely notification when services are not available. The SSD might, in collaboration with other NIST divisions, consider having a customer rating system on individual services to identify top performers in terms of service metrics and other areas where customer service might be improved. This would also likely be useful in quantifying the impact of individual measurements performed within SSD, as well as in clarifying the division's priorities. For example, the impact of flow calibration for Brooks was clear. It would be appropriate for the SSD to maintain a record of which measurement services have been phased out and why, as well as those added. SSD staff reported that some measurement services were not available during renovation of laboratory space, and other measurement services have been severely impacted by maintenance issues in aging buildings. Renovation of some of the facilities is planned but will take many years to complete.

The SSD has a worthwhile involvement in the NIST-on-a-chip (NOAC) initiative, which can realize the SI directly or disseminate measurements based on properties of nature, whereby the traceability chain can be short-circuited to allow standard sensors to exist extramurally. This initiative could develop a process that would likely result in significant economic savings for industrial users without compromising measurement standards. This effort is extremely forward thinking, and NIST is to be commended for putting thought and resources behind an initiative that could potentially obviate some of its services and make NIST traceability and error reduction easier.

A key feature of NOAC is the design, fabrication, and dissemination of embedded, SI-traceable sensors that can be incorporated directly into instruments, eliminating NIST as a middleman while minimizing sources of uncertainty. Candidate projects for NOAC were identified organically by SSD scientists through a standard NIST proposal review system, which takes advantage of significant staff enthusiasm and engagement with the NOAC effort. However, there might be missed opportunities for identifying other, more important NOAC targets, or places for improved efficiency in identifying targets that offer more direct or convenient NOAC integration. The enthusiasm of SSD scientists could be channeled into a systematic review of potential targets for NOAC integration to create an overall strategy. Such a review could identify new and deserving targets and also identify targets that could reach technological maturity faster in order to demonstrate NOAC capabilities and accelerate industry acceptance. Thermodynamic metrology capabilities would benefit from such a review, as well as other groups that are pursuing NOAC integration. An additional concern with respect to NOAC development is the need for a reasonable estimate of the cost of delivering an NOAC to a customer and a clear idea of what types and numbers of customers will purchase and use such devices. With its stated goal of creating embedded, SI-traceable calibration chips that can be incorporated directly into instruments, it will be important for NIST to understand the value proposition for specific customers that NIST expects will purchase and embed such chips into their systems. At the end of the review, the panel learned that there had been a strategic planning exercise for NOAC but were not given any details of whether any customers participated. NIST has developed a roadmap for NOAC, but it was not shared with the panel due to confidentiality concerns. As a result, the examples of NOAC within PML seemed unconnected.

Staff scientists and engineers in SSD have been and continue to be pioneers in large-scale dimensional metrology. SSD operates and maintains research and calibration facilities for such measurements that are among the best in the world and have been used as models for other industrial and national metrology institutes (NMIs). SSD staff invented laser scanning methods that enable precision, traceable measurements with on-the-order-of micrometers of uncertainty for length measurements for scales involving tens of meters or more. The identification of the previously unknown source of error in commercial laser trackers led to creation and dissemination of the NIST geometric model through national (ASME B89-4-19) and international (ISO 10360-10) standards. Other outputs of NIST’s research have been embedded in ASME standards for tactile coordinate measuring machines (CMMs), articulated arm CMMs, laser trackers and scanners, and X-ray-computed tomography. NIST has had good collaboration with industry in this area, leading to several CRADAs to build artifacts to test laser scanning systems, and the testing procedures associated with them have also been integrated into ASME standards.

The SSD has been a key driver in metrology for the economically important area of EUV lithography, an essential tool for semiconductor manufacturing and continuation of Moore’s Law, which predicts that the area density of transistors on a chip will double every 2 years. Increasing transistor densities that are represented by the transition from the 10 nm node to the 7 nm node, and now to the 5 nm and 3 nm nodes, require shorter wavelengths of EUV radiation in the lithography tools used to make them. The SSD has been involved in key collaborations in the metrology for EUV lithography, including optics lifetime, photoresist characterization, and source radiometry due to the capabilities of the Synchrotron Ultraviolet Radiation Facility (SURF III). SURF III is an important source of ultraviolet (UV) radiation, with its spectral peak output near the wavelength of EUV lithography (13.5 nm). The SSD used this capability for industry collaborations in the areas of testing EUV optics lifetimes and identifying optics degradation methods; photoresist characterization (e.g., all advanced semiconductor materials lithography) witness samples worldwide are traceable to NIST); and source radiometry (photodiode calibration), which has aided the industry transition. For example, the Apple APU (accelerated processing unit) for the iPhone is made with EUV lithography. The SSD has active CRADAs and precompetitive and proprietary work going on with 11 industry players. Industry testimonials attest to the importance of NIST and the SURF III to this critical industry transition. Specific SSD research and development accomplishments include a model of optic degradation and identification of degradation mechanisms for satellites. Upgrades of the SURF III facility have been beneficial for this strategic work. NIST is prepared for the transition to 6.7 nm with SURF III, with light output at this wavelength though at a lower intensity than at 13.5 nm. The SSD is well connected to this industry and has the opportunity to continue to contribute as the industry transitions to 5 nm and 3 nm, while also providing valuable service to the scientific customer base.

In the area of forensics topography and surface metrology, the SSD conducts calibrations of transfer standards for surface roughness, step height, lateral spacing, and microform geometry for manufacturing, forensics, and science. As an example, it provides the world's lowest measurement uncertainty for the microform geometry of standard hardness Rockwell-C diamond indenters used in certification of NIST hardness standards. The Forensic Toolmark Analysis Project serves as a case study in this area. Firearm and toolmark identification currently relies on subjective evaluation of toolmark similarity. SSD facilitated the transition to repeatable 3D topography measurements, developed objective similarity metrics, and developed initial statistical models for error rate and weight of evidence estimations. It has also created an open-access research database of two-dimensional (2D) and 3D toolmark images from a diverse population of firearms and a reference population database of firearm toolmarks. This fosters the development of further measurement methods, algorithms, and metrics that are likely to offer opportunities for machine-learning methods. The research team is well connected to standards organizations and federal, state, and local laboratories, including the Federal Bureau of Investigation and the National Institute of Justice, which have supported and/or collaborated on these projects.

Challenges in this area include being able to address industry and manufacturing needs while also addressing the toolmark project. Opportunities not met with current resources include optical metrology for rougher surfaces, including the important application of optical surface finish metrology for additive manufacturing. One of the most significant challenges is the rapid pace of change in firearms that require research to address. The ability to address them is limited by staffing resources. The development of the national database is time and labor intensive. The team is trying to develop automated systems for the Federal Bureau of Investigation, but that also will take additional resources.

In the area of providing SI traceable measurements to support the energy sector, the SSD plays a vital role in calibrating custody transfer flow meters for natural gas, affecting the sale and use of $\$300 \times 10^9$ of natural gas per year. The successful collaboration with CRADA partner CEESI (Colorado Engineering Experiment Station, Inc.) has allowed for calibrations with SI traceability to continue. A multi-million-dollar project to reduce uncertainty from 0.35 to 0.2 percent is near completion. The SSD works with the American Petroleum Institute (API) to provide calibration of the approximately $\$5 \times 10^{12}$ per year sale of petroleum products. API documentary standards require recalibration of test measures every 5 years, with SSD involvement in the recalibration due to its impartiality, measurement consistency and quality protocols, and the SSD's continuing research to improve liquid volume measurements. Of particular note are the use and continuing improvement of automation methods for volume transfer.

One concern in this area is the loss of the cryogenic liquid flow meter calibration capability for liquid natural gas. The facility was shut down and transferred to CEESI, the NIST CRADA partner that also performs ambient flow meter calibrations and who agreed to provide calibrations. Due to changing circumstances at CEESI, CEESI is no longer performing those calibrations and has shut down the facility. VSL, the Netherlands NMI, is the only NMI that does such calibrations. Although SSD staff will be working with VSL to establish comparability with NIST measurements when the VSL facility reopens later this year, the lack of a U.S. calibration facility for such an important U.S. industry is of concern, especially given the industry's requests to NIST to reinstate the capability.

The Low-Background Infrared Radiometry program is the primary source of calibrations for a key national security customer, the Missile Defense Agency (MDA). The program includes two main elements—calibration of cryogenic blackbody sources and transfer radiometers for calibration of user test chambers. The SSD's support of DoD programs has been ongoing for over three decades and is gradually evolving because of the requirements for higher sensitivity calibrations. While the direct funding to NIST for this program has remained constant for some time, the MDA provides significant staffing for the effort at NIST. The SSD effectively engages in research to support these increasing demands. For example, there is emphasis on innovation of cryogenic radiometric devices and methods to improve sensitivity and speed. The program interfaces with groups at NIST Boulder to employ novel nanotube radiometers, thus giving it a pathway to be integrated into the NOAC initiative and eventually allow miniaturization and easier traceability.

The main challenge to the program is the lack of diversity in the customer base, with MDA being the principal customer over the entire period of existence of the program. This poses a considerable risk if the customer needs change; hence, it would seem advisable to pursue a more vigorous approach to engage with other potential customers. The recent collaborations with NASA, the International Thermonuclear Experimental Reactor, and the Air Force are laudable and may present a springboard for program diversification.

The Climate Change/Greenhouse Gas program builds upon the mature and successful spectral irradiance and radiance responsivity calibration with uniform sources (SIRCUS) capability, which enabled pre-flight calibration methods for Earth-observing satellites, was transitioned to NASA, and is now used by multiple industrial customers. The satellite calibration service is critical to supporting the global effort to understand and mitigate the effects of climate change through improved measurements of parameters used in climate modeling. An impressive recent accomplishment is the development of the telescope for lunar spectral irradiance calibration, which is suitable for deployment on a high-altitude aircraft and was successfully deployed in a demonstration flight campaign. This facility realized a considerable reduction of lunar spectral irradiance measurement uncertainty, helping to improve climate measurements from satellites. Complementary to space-based observations, the program also developed methods to perform greenhouse gas measurements at industrial facilities. Its success in reducing the uncertainty and increasing the speed of smokestack flow measurements is admirable and highlights the merits of immediate stakeholder engagement, which, in this case, led to a successful field demonstration. Of particular note was the use of the NIST smokestack simulator in enabling design of the NIST hemispherical 3D airspeed sensor, which reduced errors from 17 to 1 percent.

Engaging in new programs such as ocean-color measurements, forest productivity, and solar-induced fluorescence highlights the potential for making key contributions in other areas of relevance to climate. The growing awareness and investment of resources in addressing the climate change challenge globally underscores the need to develop a strategic plan of engagement to prioritize the use of program's resources and enable its growth through staffing and facilities. It appears that such a roadmap currently does not exist, and it could be developed in collaboration with other PML, NIST, and other governmental and industrial programs.

Work on pressure measurement is representative of SSD's strength in the area of thermodynamic metrology. The researchers identified an outstanding need in the area of deepest vacuum, where the existing pressure gauge technology, in the form of ionization gauges, could not quantify this level of vacuum due to the requisite contamination that accompanies this previous state-of-the-art approach. The group responded to this need by developing a new methodology, the cold-atom vacuum standard (CAVS). More nascent efforts that leverage existing SSD strengths in emissive defects, optical cavities, and optomechanics suggest a rich pipeline for further advances in thermodynamics metrology.

SSD researchers in the area of optical metrology for solid-state lighting provided several examples supporting their leadership in this area over the past 15 years. For example, NIST protocols for stray-light correction and temperature-compensation of light efficiency have become industry standards and, in some cases, have helped lay the groundwork for societal acceptance of new lighting solutions. New work on vision science, including color quality of light-emitting diodes, flicker perception, and glare, will continue NIST leadership. Newer facilities and products, including a uniquely massive integrating sphere, automated photometry bench, new transfer standards, and a setup to show the effects of different illumination on human perception, are likely to allow this group to expand their revenue from services, which is already in excess of $300,000 per year. Some of these accomplishments were enabled by industry partnerships via CRADAs, small business innovative research grants, and patents. One demonstration of NIST leadership in this area is best-in-the-world low uncertainty in maintaining the candela standard, as demonstrated in 2018. SSD human resources and technical capabilities in this area continues to be among the best in the world.

SSD staff made commendable contributions during the COVID-19 pandemic. From March 2020, when staff were required to work remotely, division staff ensured that essential calibrations were performed for their customers in support of national security, national well-being, and commerce.

Directly related to the pandemic, SSD staff conducted special projects on germicidal UV (GUV), including measurements of the UV action spectrum for the deactivation of SARS-CoV-2 in collaboration with the Department of Homeland Security; development of documentary standards for UV sources, and a UV–SIM (Inter-American Metrology System) workshop and UV radiometer distribution; N95 mask disinfection using GUV in response to shortages in personnel protective equipment; education on proper calibration procedures and use of ambient radiation thermometers through a workshop with 50 metrologists from 15 countries in the Americas; and standards for vaccine cold storage and transport vaccine with the Centers for Disease Control and Prevention (CDC). There has been a 12-year collaboration between SSD's Thermodynamic Metrology Group and the CDC's Vaccine Supply and Assurance Branch on standards and best practices for vaccine cold storage and transport. This effort illustrates the broad reach of NIST in ensuring national well-being, beyond national defense and economic competitiveness. SSD staff have assisted with the COVID-19 vaccine rollout, addressing critical questions related to the transport and monitoring of frozen vaccine. Division staff are likely to have continuing roles during this pandemic and in potential future crises. This may have an effect on other roles and responsibilities of SSD staff. It is hoped that additional resources can be made available to ensure that other high-priority programs are not affected.

TECHNICAL EXPERTISE OF THE STAFF

The technical staff for the SSD are internationally respected experts in metrology. The staff holds fellowships in the International Society for Optics and Photonics (SPIE), American Physical Society, AVS, ASTM, ASME, Acoustical Society of America, and the Illuminating Engineering Society. Division staff facilitate global best-metrology practices at an international level through the Bureau International des Poids et Mesures (BIPM) consultative technical groups in thermometry, photometry, and radiometry. The researchers' creativity and elite status in measurement science are illustrated by several recent awards, a commendable rate of production of papers and patents, and leadership in high-visibility initiatives to safeguard national artifacts. These efforts are excellent examples of creativity resulting in unique and best-in-world capabilities, and these efforts are likely to result in continued SSD leadership in these areas.

Overall, NIST and SSD support of standards development is impressive. For example, a NIST staff member was a co-convener for the revision of International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) 17025, the most important competency-based standard for calibration and test laboratories. An SSD staff member is a participant in the revision of ISO/IEC 17043, general requirements for proficiency testing, which is used as a reference for both key comparisons and measurement assurance programs that NIST coordinates. The division leads global documentary standards activities for general measurement competency and specific industrial sectors, in support of the NIST, PML, and SSD missions.

ADEQUACY OF RESOURCES

The aging infrastructure has negatively affected performance of mission-critical activities in the form of facilities downtime, burdening technical personnel (because they have to spend time reacting to and compensating for deficient environmental conditions and not in performing measurements), and systematic degradation of performance metrics. Although examples of issues with NIST infrastructure were given throughout the review, some of the most conspicuous were in the Thermodynamic Metrology Group. Poorly controlled laboratory humidity keeps experiments using the CAVS tool from being routinely conducted, often for months at a time. SSD staff also reported having to do makeshift or temporary repairs and solutions to compensate for a lack of long-term environmental upkeep; this constitutes weak temporary solutions that ultimately result in more sudden or catastrophic failures.

Maintenance is funded locally, rather than centrally, and service is generally slow and inadequate. The apparent dearth of proper, environmentally stabilized laboratory conditions and proper building maintenance are significant impediments to performance of mission-critical activities. Building renovations are planned but will take many years at their current pace—a pace that is limited by the NIST budget. Building maintenance is slow and inadequate, with the staff performing makeshift repairs that often delayed, but did not prevent, catastrophic failure.

Hiring of additional technician-level staff would significantly streamline calibrations and other experiments and would elevate the ability to meet industry's measurement needs while maximizing the efficient time for staff at the ZP-level pay band. Division staff mentioned in several groups and programs that productivity would increase if there were additional technicians in the division. This may be a matter of having enough available funding or in how headcount is approved—that is, if one new hire per year can be added, it may be more likely that it will be a Ph.D., even though two technicians are needed. An alternative or complementary strategy could be to provide added support for the continuing development of automation capabilities to streamline routine calibrations, where possible.

Maintaining the high level of expertise over time is a critical concern. SSD staff reported continuing challenges in hiring postdoctoral researchers, which are often the entry-level position for Ph.D. hires at NIST and in succession planning. With respect to postdoctoral researchers, particularly NRC postdoctoral researchers, the issue is the fierce competition for them between base metrology programs and other areas of science. The SSD recently was able to bring on two postdoctoral researchers, but that seems a low number given the size of the division. The difficulty in succession planning is a continuing, serious issue that cannot be addressed without guidance and support from upper management at NIST.

EFFECTIVENESS OF DISSEMINATION OF OUTPUTS

SSD staff published 240 archival journal papers, technical reports, conference proceedings, and book chapters in the past 3 years. Many of those publications appear in prominent scientific journals with high impact. Division staff members have presented over 50 invited talks nationally and internationally in this period. These metrics attest to the high quality of research and development activity and the division culture to widely disseminate the output to the benefit of the public. The division is active in participating in or leading interlaboratory measurement comparisons, which generate cooperative agreements with industry, government, and universities, as well as interagency agreements. SSD staff participate in over 25 standards developing organizations and consultative committees that produce documentary standards, leading approximately 58 of these committees, with 8 documentary standards and draft documentary standards in dimensional metrology published since 2017. Fourteen patents have been issued for innovations developed by the division in the recent period.

Continued engagements in standards organizations, professional society leadership, journal editorship, and conference/workshop organization can have a large multiplying effect on dissemination and personal career development. Additionally, effective outreach to show the importance of measurement science at the K-12 level is an opportunity that could reap long-term benefits to NIST staffing and society as a whole. Maintaining and incentivizing these activities is a prudent practice.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The SSD has excellent programs, with an equally excellent staff, aligned with the SSD and NIST mission. Its impact on industrial competitiveness, public well-being, and national security is significant. The full scope of its activities is broad and diverse. SSD staff hold key leadership roles in national and international standards organizations vital to fulfilling the NIST mission. Their efforts to put themselves out of some current business and open up new opportunities through the NOAC and through new implementations of automation for calibration are commendable. The division has recently started a strategic planning exercise with the staff, with the initial outcomes being more open communication and trust, which are necessary first steps in setting priorities for a division with such a broad portfolio of activities. The SSD staff would benefit from clear metrics for the impacts of the division's portfolio of activities and understanding of division priorities and resource allocation.

RECOMMENDATION: The Sensor Science Division should develop improved metrics for the impacts of the division's portfolio of activities and implement a more formal process for establishing division priorities and resource allocation.

Customers of SSD have expressed dissatisfaction with the timeliness with which measurement services are delivered and with the lack of sufficient feedback during the process of performing the services.

RECOMMENDATION: The Sensor Science Division should develop and apply a qualitative and quantitative assessment of the quality of customer service for measurements and calibrations, using formal and informal feedback on time to completion, quality of measurements, and other relevant parameters at an individual service level.

RECOMMENDATION: The Sensor Science Division should improve communication with measurement service customers, providing them estimated times for completion and notification if a service is not available.

RECOMMENDATION: The Sensor Science Division should reexamine the design and implementation of the NIST Storefront based on conversations with division staff and customers. The division should also perform an assessment of which measurements, calibrations, and standard reference materials are no longer available but are still listed on the Storefront as being offered.

Aging infrastructure is a serious issue. It is affecting performance and will ultimately affect NIST's reputation. This is a NIST-wide issue that is noted here to highlight the urgency with which it needs to be addressed.

Having adequate staffing levels continues to be an issue for the SSD with respect to hiring postdoctoral researchers and technicians and being able to do meaningful succession planning. These require more financial resources and/or a realignment of programmatic priorities.

RECOMMENDATION: The Sensor Science Division should include in its ongoing strategic planning exercise consideration of programmatic priorities in the light of anticipated funding sources and available staffing.

7

Crosscutting Conclusions

This chapter contains conclusions that apply across more than one group or program in the PML that was reviewed.

TECHNICAL QUALITY OF THE WORK

The accomplishments of PML's staff are many and significant, spanning an extremely broad array of topics and including both research and support of the practical development of measurement standards. The staff innovatively develop and apply novel devices and techniques to solve important problems that affect industry, academic researchers, federal government agencies, and society in general. Their work is effectively aligned with the NIST mission and is frequently performed in collaboration with researchers from those organizations.

PML staff made commendable contributions during the COVID-19 pandemic. From March 2020, when staff were required to work remotely, PML staff ensured that essential services were performed for their customers, in support of national security, national well-being, and commerce. PML staff also answered the call to address measurement issues relating to combatting the virus, such as disinfecting agents and storage of vaccines.

TECHNICAL EXPERTISE OF THE STAFF

All the divisions of the PML have the scientific and engineering staff with the appropriate level of expertise to deliver on their mission. In many cases, the staff are the best or among the best in their field of research. Staff have received numerous awards from professional organizations and from the Department of Commerce, which houses NIST.

The gender and minority employment gaps that are still strongly and broadly plaguing STEM fields remain an acknowledged significant challenge at NIST as well. The PML has implemented a plan to improve equity, diversity, and inclusion that involves the following features: monitoring promotion and salary data to ensure an equitable process; publishing promotion criteria so that staff know what is expected; mentoring by supervisors on how to advance; reviewing the pay level of all staff members with more than 8 years of service; participating in the APS-IDEA in partnership with Howard University; sponsoring of and participating in conferences to increase women and minority participation in physics and other STEM fields; and supporting the PML Inclusivity Council, an internal grassroots organization working to identify barriers to inclusion and propose remedies. Addressing the challenge of staff attrition could provide opportunity to address diversity challenges as well. It is expected that in future years PML will demonstrate greater efforts and progress in diversity, equity, and inclusion.

ADEQUACY OF RESOURCES

Generally, but with significant exceptions, staff are provided with adequate equipment and facilities to perform their tasks to a high degree of quality. Noteworthy exceptions include aging facilities in urgent need of upgrade, delayed maintenance on aging equipment, and an apparent lack of supercomputing support. All divisions reported concern about the adequacy of staffing levels, particularly given an aging workforce and severe competition for postdoctoral researchers and other new hires. Each division indicated initiation of strategic planning exercises with an eye toward addressing the current and predicted challenges associated with the limitations of equipment, facilities, and human resources.

EFFECTIVENESS OF DISSEMINATION OF OUTPUTS

PML staff are effectively disseminating the results of their work through appropriate means that include publication of research results; delivery of standard reference materials and standard reference data; performance of calibrations for industrial, academic, and government customers; participation on standards committees; sponsorship of workshops; and educational programs. Some customers, however, have complained about the time taken and cost associated with purchased calibration services and about the inadequate information provided by the web-based NIST Storefront interface for purchasing measurement services, and about the lack of information about which services are currently available.

Acronyms

2D	two dimensional
3D	three dimensional
4D	four dimensional
AAPM	American Association of Physicists in Medicine
API	American Petroleum Institute
APS	American Physical Society
ASME	American Society for Mechanical Engineering
ASTM	ASTM International, formerly the American Society for Testing and Materials
AVS	American Vacuum Society
BBM	Biophysical and Biomedical Measurement Group
BIPM	Bureau International des Poids et Mesures
CAVS	cold-atom vacuum standard
CDC	Centers for Disease Control and Prevention
CEESI	Colorado Engineering Experiment Station, Inc.
CMM	coordinate measuring machine
CODATA	Committee on Data for Science and Technology
COVID-19	Coronavirus disease 2019
CRADA	cooperative research and development agreement
DoD	Department of Defense
DOE	Department of Energy
EPR	electron paramagnetic resonance
EUV	extreme ultraviolet
GPU	graphics processing unit
GUV	germicidal ultraviolet
IDEA	Inclusion, Diversity, and Equity Alliance
JAWS	Josephson-junction based arbitrary waveform synthesizer
JQI	Joint Quantum Institute
LCT	Laser Cooling and Trapping Group
MDA	Missile Defense Agency
NASA	National Aeronautics and Space Administration
NCNR	NIST Center for Neutron Research
nEDM	neutron electric dipole moment

NeXT	neutron/X-ray tomography
NFM	Nanostructure Fabrication and Measurement Group
NIST	National Institute of Standards and Technology
NMI	national measurement institute
NOAC	NIST-on-a-chip
NRC	National Research Council (of the National Academies of Sciences, Engineering, and Medicine)
NRCP	National Council on Radiation Protection and Measurements
NSF	National Science Foundation
PEEM	photoemission electron microscopy
PhAND	photon-assisted neutron detector
PI	principal investigator
PML	Physical Measurement Laboratory
PROSPECT	Precision Reactor Oscillation and Spectrum experiment
QED-C	Quantum Economic Development Consortium
QHR	Quantum Hall Resistance Standard
QuICS	Joint Center for Quantum Information and Computer Science
RF	radiofrequency
SI	International System of Units
SIRCUS	spectral irradiance and radiance responsivity calibration with uniform sources
SPIE	International Society for Optics and Photonics
SRI	Standard Reference Instrument
SSD	Sensor Science Division
STEM	science, technology, engineering, and mathematics
STM	scanning tunneling microscopy
SURF III	Synchrotron Ultraviolet Radiation Facility
TLS	two-level system
UV	ultraviolet