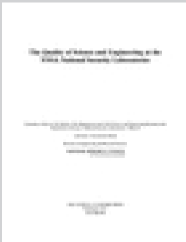

The Quality of Science and Engineering at the NNSA National Security Laboratories

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The Quality of Science and Engineering at the NNSA National Security Laboratories

Committee to Review the Quality of the Management and of the Science and Engineering Research at the Department of Energy's National Security Laboratories—Phase II

Laboratory Assessments Board

Division on Engineering and Physical Sciences

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

Marvin Adams, Texas A&M University,
Michael Anastasio, Los Alamos National Laboratory (retired),
Arden Bement, Purdue University,
Paul Fleury, Yale University,
Paul G. Gaffney II, Monmouth University,
Neil Gehrels, NASA Goddard Space Flight Center,
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Cherry Murray, Harvard University,
Steen Rasmussen, University of Southern Denmark,
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Merri Wood-Schultz, Los Alamos National Laboratory (retired).

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

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APPENDIXES

Summary

The three National Nuclear Security Administration (NNSA) national security laboratories—Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), and Sandia National Laboratories (SNL)—are a major component of the U.S. government's laboratory complex and of the national science and technology base. These laboratories are large, diverse, highly respected institutions with broad programs in basic sciences, applied sciences, technology development, and engineering; and they are home to world-class staff and facilities. Under a recent interagency agreement between the Department of Energy (DOE), Department of Defense, Department of Homeland Security, and the intelligence community, they are evolving to serve the needs of the broad national security community. Despite this broadening of substance and support, these laboratories remain the unique locus of science and engineering (S&E) for the U.S. nuclear weapons program, including, most significantly, the science-based stockpile stewardship program and the S&E basis for analyzing and understanding nuclear weapon developments of other nations and non-state actors. The National Research Council (NRC) was asked by Congress to assess the quality of S&E and the management of S&E at these three laboratories. On February 15, 2012, the NRC released a report on the quality of the S&E management (the "phase I report").[1] This second report (the "phase II report") addresses the quality of S&E.

In order to conduct this phase II assessment, the NRC assembled the Committee to Review the Quality of the Management and of the Science and Engineering Research at the Department of Energy's National Security Laboratories—Phase II, composed of distinguished scientists and engineers, as shown on p. v. Some members of this committee also served on the phase I committee, but most did not. Some of the committee's findings and recommendations are presented in this Summary, and more are found in Chapters 2 through 6 of the report.[2]

Assessing the quality of S&E in a meaningful way within the context of the primary nuclear weapons mission of the laboratories requires a broad perspective, both in substance and in time. Referring to criteria developed by the NRC Laboratory Assessments Board and to other sources, the committee chose to judge the quality of S&E as the capability of the laboratories to perform the necessary tasks to execute the laboratories' missions, both at present and in the future: Are the laboratory mission needs being addressed today? Is there a compelling plan for the future? Are the laboratories recruiting and training the next generation of staff? Are the tools and facilities adequate to meet mission needs? Is the working environment sufficient to attract and retain high-quality staff?

The nation faces major S&E challenges related to the missions of these laboratories that extend well into the future. The country has an aging nuclear weapons stockpile, with many of the weapons being decades old. The last nuclear weapons test was conducted before the United States declared a unilateral moratorium on testing in 1992.[3] Because it is no longer possible to test a complete weapon, understanding of the safety and reliability of the nuclear weapons stockpile must be inferred from relevant S&E knowledge and existing test data. Furthermore, the country faces threats from the development of

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[1] National Research Council (NRC), *Managing for High-Quality Science and Engineering at the NNSA National Security Laboratories,* The National Academies Press, Washington, D.C., 2013.

[2] Findings and recommendations are numbered with the format "X.Y," where X denotes the chapter in which the finding or recommendation appears, and Y is a counter that starts at 1 in each chapter.

[3] See 50 USC 2530. In addition, the United States has signed, but not ratified, the 1996 Comprehensive Test Ban Treaty and is therefore committed under the Vienna Convention on the Law of Treaties to refrain from actions that would defeat the object or purpose of the treaty, pending entry into force.

improvised nuclear weapons (i.e., terrorist nuclear weapons) and nuclear weapons designed by nations seeking to become nuclear powers. Understanding and evaluating the threat from such developments—including those that are based on novel design approaches rather than on designs that the United States or its allies have been able to study first-hand—is of vital importance. Even though we have more than a half-century of experience with nuclear weapons, the need to understand their S&E in detail is likely more compelling today than it has ever been.

An all-encompassing detailed assessment of the quality of S&E at the three NNSA laboratories is a complex task requiring resources far beyond those available to this committee. Instead, the committee chose to sample a set of activities that are central to the core mission of the laboratories, under the assumption that the quality of *all* of the laboratories' S&E work, including research on energy topics, work for others, and basic research, is dependent on the quality of those core capabilities. Moreover, the committee focused on the quality of capabilities rather than on evaluating how well particular projects are being executed. In this way, the report offers a snapshot of the present with an eye to the future. This focus was discussed with and endorsed by NNSA leadership. The committee identified the following as four basic pillars of stockpile stewardship and non-proliferation analysis: (1) the weapons design; (2) systems engineering and understanding of the effects of aging on system performance; (3) weapons science base; and (4) modeling and simulation, which provides a capability to integrate theory, experimental data, and system design. The study committee organized itself into four teams, each of which focused on one of these areas.

The challenge facing the nuclear weapon design community in the coming decades is the certification of the performance of weapons that have aged, and in some cases differ in some details (e.g., due to Life Extension Programs (LEPs)), from designs that have undergone nuclear-explosive testing. Aging—the changes over time in materials and component systems of nuclear weapons—and other alterations may affect the performance of a weapon. In the absence of the ability to test a complete, aged weapon, one must build a knowledge base about how aging affects a weapon's constituent parts and, from that, develop the capability to predict the performance of an aged weapon. LEPs are motivated by aging and by evolving requirements to improve safety, reliability, and security characteristics. LEPs now underway sometimes require the incorporation of components that are not identical to those in the original weapon because the exact material is not available, possibly because its manufacturing process has evolved. Predicting the performance of weapons systems whose components are not exactly the same as they were when tested decades ago requires precise knowledge. A strong systems-engineering function is the core integrating activity for the results of high-quality scientific research, development, engineering, and manufacturing.

Computer modeling and simulation is a key tool that helps weapons designers integrate all the knowledge and information about the safety and reliability of a weapons system. For the present, modeling and simulation capabilities play important and effective roles in informing the process of certifying the performance and safety of the stockpile. The quality of the research staff and the availability of underground test data allow models of key physical processes to be fine-tuned to actual data.

In the judgment of the study committee—across all four of the pillars it examined and across all three laboratories—it did not find S&E quality issues that would prevent certification of the stockpile. In many areas, the S&E is of very high quality when judged in the wider context. As noted in Chapters 2 through 5, the quality of S&E varies somewhat depending on the area, but nothing was observed that would suggest that the S&E underpinning the stockpile stewardship and non-proliferation missions are currently compromised. S&E quality in these four areas of fundamental importance is currently healthy and vibrant.

In recent years much has been said about the aging workforce that maintains the weapons stockpile. Significant progress has taken place in the laboratories and the NNSA to recruit a new generation of weapons designers, scientists, and engineers. The committee was very impressed by the enthusiasm, morale, and capability of the new recruits. Efforts are being made at all the laboratories to transition information from experienced staff members to the next generation that will have never seen a weapons test.

Despite these encouraging trends, deterioration of the work environment for scientists and engineers can limit the quality of their work, and thus the nation's ability to benefit fully from the laboratories' potential. Looking across the four pillars of stockpile stewardship and non-proliferation examined in this study, several major themes emerge. These themes are, to varying degrees, common to each of the pillars. Consistent with the focus of this study, these themes, in most cases, concern aspects of capabilities—impediments to performing experimental work, balance among classes of experimental facilities, maintenance of facilities and infrastructure, strategic planning and workforce allocation, communications, and workforce issues—that will gradually erode the S&E quality. Maintenance of the stockpile is a long-term effort extending at the very least decades into the future. While planning for that future should be possible, S&E professionals at the laboratories are frustrated with inconsistent funding from year to year, which leads to inefficiencies, waste, and in some cases, a discouraged workforce. Many S&E professionals reported having to piece together support from multiple programs. The committee was told by the laboratories' staff that some mid-level managers have left for employment in more stable work environments.

Looking at the longer term, uncertainties in the stockpile certification process will tend to grow unless steady progress is made against S&E challenges. The laboratories recognize the need for new higher-fidelity models to replace some current key models that are based on empirical data from nuclear tests. The new models will have to account for weapons aging due to changes in materials and their properties; this requires state-of-the-art capabilities in a number of areas of S&E. New data will have to be acquired from experiments other than disallowed testing, but the cost of performing the necessary experiments is escalating dramatically. This is a major concern.

Scientists and engineers (and managers) across the three laboratories expressed concern about impediments to performing experimental work. There appears to be a consensus that the amount of experimental work has declined and continues to decline. Laboratory staff cited increasing costs and increasing operational restrictions and controls on experimental work. Necessary experiments are very costly and can require multiple approval steps. This is especially true for experiments using radioactive or otherwise hazardous materials, which are often the key materials in nuclear warheads. For high-explosive-driven hydrodynamics experiments (Hydro Shots), a key part of the primary design and certification process, the time scales involved are months to years, and the costs run into millions of dollars. If the current degree of operational oversight continues, too many experiments will be unaffordable, and that would be very damaging to the quality of S&E. Factors driving experimental costs include the loss of trust, excessive duplicative oversight, formality of operations, and a culture of audit and risk avoidance across the NNSA enterprise without balance from risk/benefit analysis. A number of such factors were discussed in the phase I report.[4] All experimental activities have inherent risk, which must be balanced against the benefits that derive from conducting the experiments if reasonable decisions are to be made. It is in the nation's best interest to stabilize the conditions for safe, secure, cost-effective mission success. The risks inherent in doing an experiment need to be brought into balance with the benefits of doing the experiment and the associated risks of not doing the experiment. This needs to be done on a logically sound basis in order to guide important decisions and resource allocations. The committee does not advocate irresponsible behavior, but the critical need for experimental work must be weighed against the mounting disincentives facing it. Small incremental increases in safety in the conduct of experiments may require a disproportionate increase in time and cost. All experimental activities have inherent risk, and successful organizations manage that risk in a manner that allows the work to be performed cost effectively with proper regard for safely. It must be recognized that not carrying out the needed experiments imposes a risk to the ability of the NNSA laboratories to build the capabilities for stockpile certification down the road, which could increase the risk to national security.

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[4] NRC, *Managing for High-Quality Science and Engineering at the NNSA National Security Laboratories*, 2013, Chapter 4.

Finding 2.1. Experiments that support the nuclear weapons programs often involve hazardous materials or otherwise carry safety risks. Assessing and controlling those risks is necessary, and mechanisms have been put into place to do so. However, this process necessarily adds to the cost of conducting experiments and can slow or deter experimental work, particularly when the process involves multiple overseers (e.g., NNSA, NNSA field offices, the Defense Nuclear Facilities Safety Board, etc.) with overlapping safety responsibilities. Moreover, these assessments generally focus on the safety risks associated with particular experiments rather than weighing those risks against the benefits to be derived from the experiments and the risks to the nuclear weapons program from not conducting the experiments.

Recommendation 6.1. The Department of Energy and NNSA, in conjunction with laboratory management, should review the overall system for assessing and mitigating safety risks and identify opportunities for savings and efficiencies, for example, from reducing redundant responsibilities. They should develop a methodology to assess both risks and benefits and should employ that methodology in ensuring safe and productive experimental work at the national security laboratories.

Congress might consider requesting annual updates on progress in implementing Recommendation 6.1 until such time as the methodology is sound and the implementation process is functional.

The laboratories maintain and operate world-leading major facilities—such as DARHT,[5] NIF,[6] Z,[7] and petascale[8] computing centers. These major facilities are vital to the execution of the laboratories' missions. Smaller facilities are also crucial for executing those missions, and they are an important component of the work environment that attracts new talent and retains experienced staff. Examples of such smaller facilities include specialized capabilities for the production of nuclear weapons components, such as neutron generators; facilities that enable processing and experimentation with plutonium, especially to evaluate its long-term aging; and capabilities for developing radiation-hardened microelectronic components and photonic-related components and for beryllium parts fabrication. The rising costs of building and operating large signature facilities can threaten the continued support of such vital smaller facilities, particularly in periods of greatly constrained budgets. Moreover, because signature facilities have greater public and political visibility and can be seen as being inextricably bound up with a laboratory's fate, there can be understandable pressure on management to sacrifice other capabilities in order to ensure the continuing support of major facilities.

Finding 6.1. World-leading signature experimental facilities are essential to fulfilling the nuclear weapons mission of the national security laboratories, but smaller experimental facilities are also essential to the ability of the laboratories to conduct their work and to attract, develop, and retain staff.

Recommendation 6.2. The laboratory directors, working with NNSA, should ensure a balance between small scientific facilities and the larger signature facilities at the laboratories appropriate for sustaining the nation's nuclear deterrent and addressing related national security threats within a tight budget profile.

The quality of infrastructure is uneven, ranging from world-leading to unsatisfactory. At one extreme, the NIF at LLNL is a world-leading facility of impressive design and engineering. At the other

[5] The Dual-Axis Radiographic Hydro-Test facility (DARHT) at LANL.
[6] The National Ignition Facility at LLNL.
[7] Z Pulsed Power Facility at SNL, also known as the Z machine or the Z-pinch facility.
[8] Computing facilities capable of performance in excess of one petaflop, i.e., one quadrillion floating point operations per second.

extreme, at the same laboratory (and at the others as well) some laboratory staff report having to perform basic housekeeping functions to conduct their work. Examples of old and poorly maintained facilities include the explosives test facilities at LANL. Many important facilities and other infrastructure are deteriorating, including buildings that house important, expensive, and advanced equipment.[9] This situation can erode morale and the ability of the laboratories to recruit the best young people. Funding difficulties resulting from federal budget uncertainties make it difficult to address this issue. Nevertheless, continued careful monitoring by NNSA and laboratory management is essential in order to set appropriate priorities for facility improvement.

Computer modeling and simulation is an important component of the weapons program, In the absence of underground testing, the integrated modeling codes (IMCs) provide the only mechanism for assessing the effect on a whole weapon of differences in materials and manufacturing processes relative to those used in the original design. Thus, as these differences increase and underground test data (UGT) becomes a decreasingly reliable method for calibrating the codes, the requirements for fidelity of physical models and accuracy of the numerical methods in the IMCs will increase in order for them to play their required role in the stockpile certification process. At the same time, the architectures of the processors from which high-performance computers are constructed are undergoing disruptive changes, which will lead to a need for a major software redesign of the IMCs, analogous to that required for migrating to parallel computers in the 1990s. Finally, the IMC development teams and the developers of supporting software have simultaneously seen the resources available to them decrease (the size of the code teams are down by a third relative to the late 1990s), while their missions have increased from the support of stockpile stewardship to include a number of other areas, such as counterproliferation and LEPs.

Finding 5.5. There are substantial needs for higher model fidelity and numerical accuracy in the IMCs. In particular, there are no robustly predictive simulation capabilities (i.e., ones that do not require calibration from UGT data) for multiple key physical phenomena. The staffing levels of the modeling and simulation effort are inadequate to meet the needs of retooling the IMC codes to meet the simultaneous challenges of developing higher-fidelity simulation capabilities, meeting expanded mission requirements, and changing the algorithms and software architecture of the codes to respond to the disruptive changes in computer architecture expected to occur over the next decade.

Recommendation 5.2.` Given the increasingly important role that the integrated modeling codes will play in certification of the stockpile in the absence of testing, the NNSA should undertake a detailed assessment of the needs for simulation and modeling over the next decade and implement an adequately funded execution plan to meet the challenges outlined in Finding 5.5.

All three laboratories maintain highly qualified, productive workforces. As noted in the phase I report, attrition rates are low—about 4 percent per year—and relatively steady.[10] In the course of phase II of the study, the committee met with many people who are enthusiastic and apparently pleased with being at their laboratories. However, the committee notes some reasons for concern. For example, it heard numerous, and widespread, complaints about deteriorating conditions at the laboratories. As recounted in phase I of this study,[11] these complaints focused primarily on declining infrastructure and a perceived increasing burden of rules, regulations, operational formality, constraints and restrictions, and administrative burdens. The committee notes that while there have not been significant negative changes in recruitment and retention, some of this continued success may be due to the state of the economy since

[9] This matter was discussed in the phase 1 report, NRC, *Managing for High-Quality Science and Engineering at the NNSA National Security Laboratories,* 2013.

[10] NRC, *Managing for High-Quality Science and Engineering at the NNSA National Security Laboratories,* 2013, p. 13.

[11] NRC, *Managing for High-Quality Science and Engineering at the NNSA National Security Laboratories*, 2013.

2008; the committee cautions that an improving economy may produce better opportunities outside the laboratories.

NNSA and the laboratories should pay close attention to the problem of hiring and retaining a cadre of first-rate, creative, energetic scientists and engineers that are expert in all aspects of modeling and simulation (M&S), ranging from deep understanding of the underlying physics and mathematics to the most advanced ideas in computer architectures, algorithms, and programming methods. There is uncertainty concerning the staff's ability to make good use of future high-performance computing systems. Expected disruptive changes in computer architectures will require very high levels of computer science expertise in order to create the software to exploit the new capabilities. There is particular concern in core computer science areas, such as computer architecture, systems software, programming models, tools, and the algorithms used in these systems. While there are some outstanding individuals in these areas within the laboratories, there are also signs of difficulty in recruiting and retention. Among laboratory scientists and engineers, computer science researchers are the most mobile because they can easily find challenging and lucrative employment in industry—while their work is necessary to the NNSA mission, they have other good options. These researchers and engineers appear less likely to come to the laboratories and more likely to leave mid-career than those working in other disciplines.

Maintaining a quality workforce in the face of budget uncertainty and competition from other employers will be very difficult. An atmosphere nurturing broad scientific investigation and intellectual excellence, along with salaries that are competitive with industry, are the keys to maintaining the laboratories' M&S capabilities.

A supportive and nurturing work environment fosters the ability of highly creative scientists and engineers to do their work while encouraging the retention of senior staff and the recruitment of young staff. The work environment at the laboratories, however, appears to be deteriorating and is at risk of further deterioration.[12] Early-career people at the laboratories expressed concern to the committee about time-accounting restrictions that seem to limit their working on new ideas at home or on weekends. Some observe that excessive fractionation of their chargeable time among several tasks reduces productivity and efficiency. Inconsistent and unpredictable funding was also cited, along with conflicts between short-term project demands and sustained scientific progress.[13] Scientists in national security laboratories are isolated from the broader world of science due to classification and the nature of their work. Recently imposed restrictions on traveling to conferences, open or classified, adds to this isolation, limiting career development, access to the latest scientific advances, external collaborations, and the ability of scientists and engineers to bring the full range of relevant science to bear on their work at the laboratories.

Following the revelation in 2012 about spending by the General Services Administration for a conference in 2010, the Office of Management and Budget issued travel restrictions[14] that are hindering travel to scientific and engineering conferences by NNSA laboratory staff. Congress might consider requiring that such travel restrictions at NNSA national security laboratories be no more restrictive than those that apply to scientists and engineers funded by other agencies of the federal government.

Final integration of the advances and understanding in weapons simulation, analyses, design, and materials sciences and technology is a critical activity for the Stockpile Stewardship Program. The integration activities fall under the general areas of systems engineering. Systems engineering is also important in LEPs, for which the importance of training the next generation of scientists and engineers cannot be overemphasized. Special projects often help bring the established and the new systems

[12] NRC, *Managing for High-Quality Science and Engineering at the NNSA National Security Laboratories*, 2013, Chapters 4 and 5.

[13] This matter was also addressed in the phase 1 report—see, for example, NRC, *Managing for High-Quality Science and Engineering at the NNSA National Security Laboratories*, 2013, p. 17. That report noted that the four-agency agreement on national security laboratory governance was an important step in fixing this. In the past, task orders from agencies other than DOE were often designed to tap laboratory staff and infrastructure to obtain a specific product without investing in the development of staff or facilities.

[14] Memorandum to the Heads of Executive Departments and Agencies, Executive Office of the President, Office of Management and Budget, M-12-12, May 11, 2012.

engineering personnel together to assure the health and vitality of systems engineering expertise into the future.

In early 2012 (January to May), the three laboratories fulfilled a request from NNSA to conduct a 120-day study to evaluate alternatives for warheads to be deployed in multiple reentry vehicle systems and to inform NNSA on potential options for future LEPs. The "120-day study"[15]—which considered advanced options for the nuclear physics package and various approaches on how to configure the stockpile using existing components and systems with an emphasis on raising the levels of safety, reliability, and security—provided an example of how teams consisting of a few experienced designers, several mid-career designers, and a large number of near-entry level designers were given the opportunity to develop timely and workable design solutions within customer constraints. By bringing together scientists and engineers from these different career stages, it provided a mechanism for transmitting information and experience in a productive manner and helped develop useful practices. The 120-day study is an example of a best operational practice that demonstrates the high quality of the systems engineering capabilities within the complex.

Recommendation 3.4. NNSA should continue the approach used for the 120-day study as one means of developing and maintaining a new generation of well-trained weapons designers and the concomitant systems engineering capability.

[15] On January 10, 2012, NNSA officially requested that LANL, LLNL, and SNL perform a 120-day study to evaluate alternative warhead designs and to inform NNSA on potential options for future LEPs.

1

Introduction

STATEMENT OF TASK

In the FY2010 National Defense Authorization Act, P.L. 111-84, Congress directed DOE to request the National Academy of Sciences to review the quality of science and engineering (S&E) research at the three national security laboratories, Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and Sandia National Laboratories (SNL). Specifically, the Congress mandated that

> (a) IN GENERAL.—Not later than 60 days after the date of the enactment of this Act, the Secretary of Energy shall enter into an agreement with the National Academy of Sciences to conduct a study of the following laboratories:
> (1) The Lawrence Livermore National Laboratory, California.
> (2) The Los Alamos National Laboratory, New Mexico.
> (3) The Sandia National Laboratories, California and New Mexico.
> (b) ELEMENTS—The study required under subsection (a) shall include, with respect to each laboratory specified in such subsection, an evaluation of the following:
> (1) The quality of the scientific research being conducted at the laboratory, including research with respect to weapons science, nonproliferation, energy, and basic science.
> (2) The quality of the engineering being conducted at the laboratory.
> (3) The criteria used to assess the quality of scientific research and engineering being conducted at the laboratory.
> (4) The relationship between the quality of the science and engineering at the laboratory and the contract for managing and operating the laboratory.
> (5) The management of work conducted by the laboratory for entities other than the Department of Energy, including academic institutions and other Federal agencies, and interactions between the laboratory and such entities.

The principal motivation of Congress for this study is given in the conference report associated with this act:[1]

> There is a growing concern about the ability of the Department of Energy to maintain the overall quality of the scientific research and engineering capability at the three laboratories. This concern was most recently highlighted in the report of the Congressional Commission on the Strategic Posture of the United States. The conferees believe that an even handed, unbiased assessment of the quality of the scientific research and engineering at each of the three laboratories, with a clear understanding of the criteria used to measure quality and what factors influence quality would be useful in long-term planning for the operations of the laboratories.

The study was divided into two consecutive phases; in phase I, a committee examined management issues, and in phase II a second committee assessed the quality of the science and

[1] U.S. Congress, H. Report 111-288, 2010, p. 910.

engineering research.[2] The phase I report, released on February 15, 2012, addresses Tasks 4 and 5 and partially addresses Task 3; roughly speaking, how management at all levels affects the quality of the S&E at the three laboratories. The phase I study identified major management concerns that have the potential to impede the conduct of high-quality work at all of these laboratories. Phase II of the study, which evaluates the quality of S&E in key subject areas, was begun after the release of the 2012 report. This report presents the results of that second-phase effort.

The research and engineering programs of these three laboratories are very broad, as befits an enterprise whose total annual budget approaches $7 billion and which employs thousands of scientists and engineers. In addition to their diversified programs for the National Nuclear Security Administration (NNSA), they conduct significant work for other parts of the DOE, the Department of Defense, the Department of Homeland Security, and for the intelligence community, as well as many other sponsors and partners. Although each laboratory is a separately managed entity, the three form an integrated enterprise that performs a unique national security mission; inter-laboratory collaboration is an important pillar of their work, particularly in the nuclear weapons component of that mission. LANL and LLNL are the nation's sole centers for work on the "physics package," while SNL provides a unique function for engineering the non-nuclear components of warheads and integrating warheads into delivery systems. In a very general sense, LANL and LLNL are science laboratories that have (of necessity) vigorous advanced engineering capabilities, while SNL is an advanced systems engineering laboratory that maintains a vibrant science base.

The science base at all three institutions includes work in basic science, weapon science, nonproliferation, energy, and a long list of other mission areas and disciplines. One strength of these laboratories is the interconnections among work in various related areas. For example, materials science and engineering support the weapons program (including nonproliferation) as well as energy research and development and many other applications. Research related to the release of energy in nuclear reactions is directly relevant to weapons and nuclear power.

A complete, in-depth evaluation of all the work at the three laboratories is beyond what a single committee of individuals can do in a 1-year NRC study. Therefore, after obtaining agreement from the study sponsors at NNSA and relevant congressional staff, the committee's efforts were focused on those areas of research, development, and engineering that are most closely aligned with the laboratories' unique primary mission—that of maintaining the nuclear weapons deterrent. While the study committee examined how well some specific projects are executed,[3] it looked primarily at factors that could inhibit the quality of S&E. It concluded that the long-term S&E quality is driven by foundational capabilities: the technical caliber of the S&E staff, plus capabilities such as strategic planning and support; relevance of the work to the advancement of the S&E field and to the mission; integration with other work at the laboratory and connections with the larger technical community; adequacy of facilities, equipment, infrastructure, and other resources; and sustainability of the workforce. This decision was also discussed with and agreed to by the NNSA study sponsors and relevant congressional staff.

An evaluation of capabilities, however, requires—to some degree—an assessment of current work. That evaluation provides insight about the current state of many of the key capabilities, such as the state of facilities, planning and support, and the quality of the workforce. Because the capabilities listed above are foundational, their quality affects *all* of the laboratories' S&E work, including research on energy topics, basic research, and work for others, and, thus, this capabilities-focused evaluation also provides insight about the quality—or at least the upper limit that can be attained—in these other areas. Therefore, the analysis presented in this report with respect to the weapons mission should have some

[2] This division was largely motivated by security concerns. However, it facilitated appointing two different study committees, one focused on management and one on science and engineering.

[3] The projects were raised during discussions with the study committee and not selected in any systematic way prior to those meetings. The key areas of S&E in which these projects fell, however, were selected prior to the laboratory meetings, as discussed in the text below.

relevance for judging capabilities to perform quality work for the other responsibilities of the national security laboratories, including work for others.

To support this approach, the study committee organized itself into study teams focused on four broad areas: (1) science base for nuclear weapons; (2) nuclear weapons design; (3) modeling and simulation; and (4) systems engineering and system aging. The science base team focused on materials physics, chemistry, and engineering; condensed matter at extreme conditions; high-energy-density science; and radiation transport/hydrodynamics. Each study team employed an extensive sampling approach to its task. This included discussions with managers having broad responsibilities across major areas and numerous meetings with scientists and engineers conducting specific projects within those broad areas.

CONDUCT OF THE STUDY

To conduct this work, the NRC formed the Committee to Review the Quality of the Management and of the Science and Engineering Research at the Department of Energy's National Security Laboratories—Phase II, whose members were carefully chosen to provide broad and deep applicable expertise and experience in the four topic areas. To provide continuity with the first phase of the study, several members of the phase I study committee—including the two co-chairs—agreed to serve on the phase II committee. The phase II committee was assembled so its expertise spanned the four topic areas across relevant national and international communities, and its members had had various direct and indirect interactions with one or more of the NNSA laboratories.

The study committee began its work with an open-session meeting with staff from several NNSA offices to gain clarity about sponsor concerns. This was followed by a closed session at which it established a framework for how it would carry out its assessment. While the laboratories and NNSA regularly collect some quantitative metrics related to the quality of both projects and capabilities, given the resource and time limitations inherent in this study, the committee decided to rely primarily on qualitative data that it could receive and evaluate itself. The study committee, therefore, constructed the study's framework in a manner to impose as much rigor as possible.

First, to collect and assess its data, the study committee chose to meet with a broad and diverse selection of staff at the three laboratories in informal discussions with a format similar to that used in the phase I study. Laboratory staff made short presentations and then engaged in discussions with the appropriate study team. Much like the phase I study, questions raised by the study team were intended to elicit information that would be most useful to the study committee in its deliberations.

The study teams selected laboratory staff to meet with so as to examine major S&E areas critical to the weapons mission of the laboratories (e.g., materials science and engineering, advanced computing, high-energy-density science, and weapons-design codes). Each study team determined these key areas for its subject area based on the experience and expert judgment of its members and discussions with NNSA personnel at the first meeting. This information was given to the laboratories with a request to arrange sessions for a given study team with appropriate laboratory staff involved in these areas.

Second, in this context, the committee developed a set of criteria to its discussions with laboratory staff and its review and analysis of the results of these meetings.[4] These criteria were not applied as a checklist; rather, they constituted a set of considerations from which committee members drew, and to which they added, as appropriate, for a given area of work. The following criteria were used by the study teams:

[4] These criteria take into account standard processes, such as those recounted in National Research Council, *Best Practices in Assessment of Research and Development Organizations*, The National Academies Press, Washington, D.C., 2012.

1. Is scientific research and engineering in support of the missions well managed and well executed?
    a. Conduct of the work: Is the work executed well? Are the results of high quality compared to similar work elsewhere? Is this judgment supported by recognized objective measures? Is the work innovative, creative, insightful?
    b. What are the unique S&E accomplishments and impacts?
    c. Was the work well-planned and well-prepared? Is there a reasonable strategic plan, including planning for future funding?
    d. Are there alternative research and development (R&D) paths that are not being pursued, but which would better meet specific missions?
2. Is the work relevant to the advancement of the field, the advancement of the mission(s) (current and anticipated/emerging), and the advancement/continuation of this area of work at the lab?
3. Is the work effectively integrated with other work within the NNSA laboratories as appropriate?
4. Is this work a good use of laboratory resources?
    a. Could the needed information have been obtained by monitoring work elsewhere?
    b. Does it contribute to attracting new staff, sponsor interest, development of new laboratory capabilities?
5. Are the major facilities, equipment, and infrastructure necessary and sufficient for the missions? Is effective use being made of available facilities and equipment?
6. Is there an appropriate workplace culture, with evidence of enthusiasm, dedication, innovation, empowerment, flexibility and agility, leadership and mentoring, access to resources, and risk tolerance?
7 Is the workforce healthy, i.e. capable and sustainable?
8. Are scientists and engineers appropriately connected within the laboratory and with the broader S&E communities (national and international, both academic and industrial)?
9. General
    a. Are grand challenges and a vision for the future defined and appropriate for national laboratory missions?
    b. Do operations divisions appropriately support S&E?
    c. Is Laboratory Directed Research and Development effectively addressing and preparing for future missions?
    d. Is peer review appropriately used to evaluate S&E work?
    e. What are the values of, and trends in, traditional professional metrics: publications, citations, invited talks, awards, and patents (in both classified and unclassified domains)?

In addition to assisting the committee with its analysis, the criteria are offered in response to the third item of the committee's charge, as an indication of the multiple dimensions needed to assess the quality of an R&D laboratory and its S&E. Note that most of these questions must be addressed subjectively by peers who understand how to interpret the answers and who know which questions are most important at a given time. That is especially true when assessing the long-term capabilities and the risks that may affect a laboratory's quality, as is the case in this study.

Third, the committee agreed that its assessment of these data would rely primarily on the collective experience, technical knowledge, and expertise of its members, whose backgrounds were carefully matched to the technical areas within which the activities of the laboratories are conducted. Because state-of-the-art work is best evaluated by peer judgment rather than by quantitative metrics, the committee applied a largely qualitative approach to the assessment. In examining key areas of S&E—including examination of illustrative projects and programs—the committee's goal was to identify salient examples of accomplishments and opportunities for further improvement with respect to capabilities; evaluate the technical merit of these capabilities; assess their relevance to the laboratories' missions; and evaluate specific elements of the laboratories' resource infrastructure that is intended to support the capabilities and technical work.

During the meetings at the three laboratories, committee members met with laboratory directors and other senior management and with more than 300 mid-level managers, senior scientists and engineers, and early career scientists and engineers. These meetings included presentations, discussions, and poster sessions. Some of these discussions involved personnel from more than one laboratory so that inter-laboratory coordination could be assessed. Subsequent to the meetings, committee members asked for, and received, supporting materials. As envisioned in study's statement of task, the quality of a laboratory's S&E is intertwined with the quality of its management. Discussions, therefore, often included topics that had been raised in the phase I report, with particular emphasis on how these matters affect the ability of scientists and engineers to do high-quality work.

OUTLINE OF THE REPORT

Chapters 2-5 present the findings and recommendations in the four subject areas—nuclear weapons design; systems engineering and system aging; the science base for nuclear weapons; and modeling and simulation. Although each of these chapters addresses the same general matters, they are not organized identically. In each case, the chapter organization is driven by the specifics of the subject area. Each presents a snapshot assessment of quality of current work, as observed by the study team, and a broader assessment as described above. These chapters all address the major areas of concern that emerged across all discussions and data-gathering, as reflected in the summary: experimental science; facilities; work environment; and recruitment, retention, and continuation and continuity of knowledge and experience. In addition, each chapter raises issues of importance to individual subject matter areas.

Chapter 2 discusses the nuclear weapons design activities at the three national security laboratories, presents the study committee's assessment of the quality of the design work being conducted, and briefly discusses how that work draws from and is connected to the other major areas assessed in this report.

Chapter 3 addresses systems engineering and aging. Weapon design and systems engineering are the direct bases of "the product"—that is, the ability to certify the safety and reliability of the nuclear weapons stockpile now and in the future (and to understand nuclear activities outside the United States). Understanding aging is critical to stockpile stewardship. Like weapons design, engineering and aging work draws heavily from work conducted in the science base and the incorporation of the results of that work into computer codes.

Chapter 4 is the assessment of the science base. The study team for this subject area chose to focus on four areas that are most germane to the nuclear weapons mission: materials science, chemistry, and engineering; condensed matter/materials science at extreme conditions; high-energy-density science; and radiation hydrodynamics/transport.

Chapter 5 addresses the laboratories' capabilities in modeling and simulation.

Chapter 6 provides over-arching observations on S&E quality at the laboratories and summarizes concerns that were raised in connection with more than one of the subject areas covered in Chapters 2 through 5.

2

Nuclear Weapons Design

BACKGROUND

The nuclear testing moratorium has driven a fundamental shift in the process for maintaining the safety and reliability of the U.S. nuclear weapons stockpile. The science-based stockpile stewardship program has replaced the process of designing and testing that originated with the Manhattan project. This has affected many aspects of weapons design activities.

Because it is no longer allowable to conduct full weapon tests, the United States can no longer rely on new nuclear-test data to inform questions such as: (1) How, if at all, have the properties of a particular warhead design changed as it has aged? (2) What are the effects on weapon performance of changes such as replacement of aging components and upgrades to enhance factors such as safety, security, and reliability? (3) What are the effects of LEPs, upgrades, or new design approaches? and (4) How well are design codes able to predict the behavior of design elements? Accordingly, design code models that require calibration based on data from full nuclear tests are being upgraded with models that build on an improved understanding of the fundamental weapons' physics, and which therefore reduce the need for parameter fitting that attempts to link the codes to performance data from un-aged and subtly different systems.[1] Although the body of data from tests conducted prior to 1992 continues to be mined, the basis of generating new data has shifted from full weapons testing to above-ground experiments and subcritical tests.

The design codes used by the weapons design community in the past—largely developed and deployed at LANL and LLNL—have been extensively validated by a variety of physics experiments and by comparison with data obtained from actual weapons tests (both above and below ground). These codes relied on approximate phenomenological models to address physics that was not yet fully understood or too costly to model (either of which may still be the case). By calibrating these phenomenological models using test data, it proved possible to use these design codes in a predictive fashion, that is, for predicting the performance of devices for which the codes had not been calibrated.

Following the testing moratorium and signature of the comprehensive test ban treaty, the design community was faced with the conundrum of how modeling and simulation could continue to be used reliably as weapons continued to deviate from the precise form for which validation data from full-system tests are available. That deviation is inevitable because components age, weapons are refurbished using materials that differ from those originally used, and changes are made to improve device safety and reliability. There is no guarantee that the model calibrations derived from the original device designs are applicable to the aging stockpile, or to the refurbished portion of the stockpile. It, therefore, became urgent to find an alternative plan that would allow weapons scientists to continue the weapons

[1] The computer codes in question rely on phenomenological models that describe processes known to be important to weapons design but for which "first principles" models are not yet available. These phenomenological models contain parameters that must be adjusted so that the outputs of the simulations align with corresponding experimental data. This adjustment of model parameters is sometimes referred to as "tuning" or "calibration," and the parameters that are adjusted are often referred to as "knobs." For more detail, the reader is referred to National Research Council (NRC), *Evaluation of Quantification of Margins and Uncertainties Methodology for Assessing and Certifying the Reliability of the Nuclear Stockpile*, The National Academies Press, Washington, D.C., 2009.

certification process with the necessary confidence. Furthermore, the weapons design community has had the additional challenge of ensuring that the U.S. government understands the potential performance of novel nuclear weapons designs created abroad by established or aspiring nuclear weapons states or by non-state actors who have interests in designing "improvised" nuclear devices. Making such predictions requires a highly refined understanding of the capabilities and limitations of the models and experience derived from understanding the data from underground tests.

The science-based Stockpile Stewardship Program (SSP) was designed to support inferences about the performance of aging weapons and novel designs. In addition to weapon designers, the SSP requires systems engineers, the development of understanding of the effects of aging on existing weapons, a vibrant science base to provide the needed data, and the development of higher-fidelity design codes. The fundamental idea of the SSP was to systematically upgrade phenomenological models that required calibration from full nuclear tests, moving to higher-fidelity models based to an increasingly greater degree on improved understanding of the fundamental physics and which, therefore, do not depend as much (ideally, not at all) on the parameter adjustment characteristic of the phenomenologically oriented design codes. However, all codes require verification and validation (V&V); that is, they require tests that determine how accurately the codes solve the equations of the mathematical models (verification) and tests that determine the degree to which the models are accurate representations of reality (validation). Furthermore, it is not enough for a given science-based code to predict; it is also necessary to understand how well the code predicts, that is, to determine the uncertainties of the predictions (i.e., uncertainty quantification, usually referred to as UQ).[2] While the transition to higher-fidelity codes has made progress, it has not yet been possible to eliminate all of the phenomenologically based components of design codes, and in addition, the questions that must be answered continue to change with time. Thus, the codes will need to continue to evolve, and V&V and UQ are essential parts of that ongoing process of improvement.

The simulation codes for the future must be able to inform judgments about the performance and reliability of warheads that have changed due to aging and rebuilding without reliance on nuclear test data. Continued progress in the SSP requires the best science available, and, thus, requires a partnership among theory, experiment, and simulation and the leadership and participation of highly competent scientists and technologists. Stockpile stewardship relies on experts in modeling and simulation, design teams, systems engineers, ongoing experimentation, and a process that ensures continuation of these capabilities and passing of skills and knowledge to new generations of scientists and engineers.

EXPERIMENTAL FACILITIES

Experiments are essential for making discoveries, developing understanding of physical phenomena, and testing hypotheses. Experimental data are important for building confidence in designers' simulation codes—to compare code predictions with reality, thereby learning how well they do and do not match—and for strengthening the insight of those who rely on the codes. The ability to certify the stockpile depends on this coupling of simulation and data. Scientific experiments are used to obtain basic physics data, and also to provide integral data in limited parts of the nuclear weapon space.[3] High-quality design work requires experiments to compare with code predictions. The NNSA and the laboratories have long recognized the need for non-nuclear explosion experiments and have invested in some major experimental facilities. The principal facilities are the National Ignition Facility (NIF) at

[2] NRC, *Evaluation of Quantification of Margins and Uncertainties Methodology for Assessing and Certifying the Reliability of the Nuclear Stockpile,* 2009.

[3] Much of the complication of weapons design is related to it being "multi-physics" and multi-scale, specifically the fact that (for example) it deals with a combination of hydrodynamics, strength of materials, and radiation transport. Basic science activities typically focus on one of these disciplines. When investigating complex phenomena that extend across multiple disciplines, the only experimental venue is something like NIF (where one can "mix" hydro with rad transport), or DARHT (where one mixes hydro with materials).

LLNL, the Z Pulsed Power Facility (Z) at Sandia National Laboratories,[4] the Dual-Axis Radiographic Hydro-Test facility (DARHT) at LANL, and the underground hydrodynamic facility at the Nevada National Security Site.[5] These are very powerful facilities that address different parts of the nuclear weapon S&E space.

However, getting relevant experimental data is more difficult than it should be. Several weapons designers who met with the committee reported that the experiments they need are very costly and take an excessive amount of time. Their diagnosis is that increases in the formality of operations—the many steps and approvals that must be accomplished before an experiment may proceed[6]—has contributed to driving up the time and cost for conducting experiments, which has contributed to fewer experiments being done.[7]

This issue was discussed in some detail, with illustrating examples, by Siegfried Hecker, a former director of LANL, in testimony before the Strategic Forces Subcommittee of the House Armed Services Committee at a hearing on February 16, 2012.[8] In his statement, Dr. Hecker discussed specific examples from his long career at LANL, contrasting conditions he encountered when he arrived at the laboratory as a young man with more recent conditions and elaborating on the role of increasing oversight in driving up cost and time to conduct experimental work. What the study committee heard at meetings at all three laboratories is consistent with Dr. Hecker's testimony.

Two areas of particular concern are (1) experiments that use radioactive or otherwise hazardous materials and (2) high explosive-driven hydrodynamics experiments ("hydro shots"), a key part of the primary design and certification process.[9] The timescales involved in planning and executing a hydro shot can run from months to years, and the costs run into the millions of dollars. Dr. Hecker's testimony includes discussion of his experiences over the years with experiments that use plutonium. The high cost of experimental work is due in part to excessive formality of operations and duplicative oversight of environmental health and safety with essentially no risk-benefit analysis to create a balanced safety program.

From the committee's discussion with multiple weapons designers at both LANL and LLNL, a culture of risk avoidance has grown in the oversight levels of the laboratories to the point where there appears to be little distinction made among levels of risk. The following four organizations outside the

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[4] Also known as the "Z machine" and the "Z-pinch facility."

[5] Formerly the Nevada Test Site.

[6] As discussed in the phase 1 report, NRC, *Managing for High-Quality Science and Engineering at the NNSA National Security Laboratories*, The National Academies Press, Washington, D.C., 2013.

[7] Of course, simply counting the number of experiments provides only a coarse measure, as other factors can contribute to reductions in the numbers. For example, costs can increase because of a determination that a more complex measurement is required than was originally planned; and schedules can be delayed for reasons related to availability of equipment. Fewer experiments might be needed because of greater-than-anticipated success of the earlier experiments in a planned series. If a particularly type of experiment is conducted less and less often over time, that could indicate operational constraints, but it might also be indicative of funding problems, or it could indicate a successful program that has accomplished what it set out to do. For these reasons, the committee found the most compelling input to be the judgment expressed by many experts at the laboratories that the number is inadequate.

[8] See, for example, discussion and examples cited in testimony before the Strategic Forces Subcommittee of the House Armed Services Committee, Siegfried Hecker, February 16, 2012.

[9] NNSA online definition: "Hydrodynamic testing (hydrotesting) is the execution of high-explosive driven experiments to assess the performance and safety of nuclear weapons. Under test conditions the behavior of solid materials is similar to liquids, hence the term 'hydrodynamic.' These large scale hydrodynamic experiments utilize test assemblies that are representative of nuclear weapons but with the fissile material in an actual weapon altered or replaced with surrogates." The NNSA Quarterly SSP Experiment Summary-FY12-2Q (Final) further defines: "Subcritical Experiments: High explosive driven experiments to obtain information critical to certifying weapons performance in the absence of underground testing while still employing nuclear materials. No critical mass is formed due to the amount and quality of the nuclear material. As such, no self-sustaining nuclear chain reaction can occur in these nuclear experiments."

laboratories impose constraints on the conduct of operations: (1) the NNSA field office for each laboratory[10]; (2) NNSA Headquarters; (3) the DOE Office of Health, Safety and Security; and (4) the Defense Nuclear Facilities Safety Board (DNFSB). The DNFSB is an advisory body that does not directly impose regulations, although DOE and NNSA usually accept DNFSB recommendations. Moreover, the laboratories themselves sometimes contribute to increasing cost and decreasing throughput of experiments involving hazardous materials by imposing even more stringent regulations as pre-emptive defensive measures. The result is a layering of constraints that reportedly inhibits the experimentation needed for high-quality S&E.

Most of these restrictions appear to be based on an analysis of risks alone; the important benefits of executing experiments also need to be taken into account.

Finding 2.1. Experiments that support the nuclear weapons programs often involve hazardous materials or otherwise carry safety risks. Assessing and controlling those risks is necessary, and mechanisms have been put into place to do so. However, this process necessarily adds to the cost of conducting experiments and can slow or deter experimental work, particularly when the process involves multiple overseers (e.g., NNSA, NNSA field offices, the DNFSB, etc.) with overlapping safety responsibilities. Moreover, these assessments generally focus on the safety risks associated with particular experiments rather than weighing those risks against the benefits to be derived from the experiments and the risks to the nuclear weapons program from not conducting the experiments.

In addition to obtaining needed data, experiments provide exploitable experience to those who participate in them. Maintaining opportunities to participate in experiments, and comparing their outcomes with simulated data, contributes to building and maintaining a work environment that attracts new high-quality staff and encourages experienced staff to stay. Reducing the amount of experimental work, therefore, has multiple adverse consequences, all of which can have major impacts on the quality of S&E.

HUMAN RESOURCES AND NUCLEAR WEAPONS DESIGN CAPABILITIES

Current Design Capabilities

Nuclear weapon design capabilities at the NNSA national security laboratories extend beyond the expensive facilities and extensive S&E research base to include the people who maintain the ability to apply these impressive tools to national defense issues. This critical laboratory resource consists of trained, qualified, and experienced personnel. The staff members involved with weapons design who interacted with the committee certainly met all of these characteristics. The weapons design communities at both LANL and LLNL appear to be composed of high-quality people who are highly motivated and view their work as vital to the national interest. They have done high-quality work in the face of major obstacles, including complex layers of oversight, weakened funding, and impediments to experimental work.

The design program activities include monitoring and analysis of the current weapon stockpile, refurbishing selected portions of the stockpile through LEPs, and developing better understanding of (and computational models for) weapons design physics problems. The committee's discussions with the designers focused on weapon design physics issues, especially boosting. This work is very good—it is well thought out, and they have been making progress.

The laboratories' mission focus on nuclear stockpile stewardship is well in hand. However, the committee observed—and shares—concern that the intensive focus on the analysis of a static inventory of

[10] Los Alamos Field Office, Livermore Field Office, and Sandia Field Office.

nuclear weapon hardware may impede continuance of the design capabilities inevitably required to maintain the safety, security, and performance standards of an evolving stockpile. The lifetime extension programs do offer design challenges, but these may not be sufficient. The perpetual maintenance of a cadre of experienced nuclear weapon designers is no easy task, but is the central responsibility of nuclear weapons laboratory management.

One suggested approach to preserving high capability and competence for weapons design is to consider operational exercises to test nuclear weapon design capabilities in a process that mimics the phase 1 and phase 2 process used to develop the current stockpile.[11] Such an operational test—based on, for example, a design-and-experiment cycle for subcritical devices—could provide metrics of the status of design capabilities to include design and engineering. The metrics are important because they help build confidence in people and their judgments.

NIF could offer some opportunities of this kind for training weapon designers. The inertial confinement fusion (ICF) program utilizes a capsule implosion in an attempt to achieve fusion. While there are some differences from weapon design processes, there are also some similarities. The opportunity to design and conduct integral implosion experiments[12] at the NIF would be a great training tool for weapon designers and might even bring in some new ideas that would benefit the ICF program.[13]

Recommendation 2.1. In order to continue the laboratories' good work at recruiting, training, and retaining high-quality nuclear weapons design staff, the laboratories should include opportunities for them to conduct implosion experiments at the National Ignition Facility.

A positive observation about design laboratory personnel from LANL and LLNL is the quality of the early-career designers. The intelligence and enthusiasm of this group bodes well for the future of the nuclear design enterprise and is a clear indicator of the forward-looking capability development of the management of both laboratories.

International Issues (Nuclear Proliferation)

Serious international issues call for a highly competent domestic nuclear weapons design capability: it is essential to maintain high-quality expertise in weapons design not only to steward our own weapons, but also to understand thoroughly designs that are developed elsewhere. Many countries are embarked on nuclear energy programs. Some of these programs have already involved efforts to develop nuclear weapons, and some countries have demonstrated success by underground testing of nuclear devices. Not all countries will follow established paths in their nuclear weapons designs. The U.S. intelligence community works to find out as much as possible about efforts of other countries, but to understand the significance of such information, and to assist the intelligence efforts, having and involving a group of knowledgeable U.S. designers is crucial.[14] U.S. design teams are also important in assessing the significance of information concerning foreign groups' attempts to develop improvised

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[11] Appendix B of the "Nuclear Matters Handbook" (http://www.acq.osd.mil/ncbdp/nm/nm_book_5_11) describes the life cycle of U.S. nuclear weapons as consisting of seven phases. Phase 1 is a concept study; phase 2 is a feasibility study followed by phase 2A, which is a design-definition and cost study.

[12] That is, experimental designs that involve several different scientific disciplines. When combining codes that derive from different areas of physics, there is the huge problem that just because these codes, individually, passed verification and validation tests (these are the unit tests), it is not necessarily true that when one couples them that the resulting multi-physics code will give reliable results. So the only way to make sure that the coupled codes work is to carry out integral experiment—and in the case of the design codes, this obviously means proxy designs that exercise all of the physics components of a coupled design code.

[13] "National Nuclear Security Administration's Path Forward to Achieving Ignition in the Inertial Confinement Fusion Program," Report to Congress, United States Department of Energy, Dec, 2012.

[14] Examples exist where such has been shown to be important, but specific examples are classified.

nuclear devices. Understanding the gathered information requires substantial knowledge of weapons design.

Because such global nuclear security issues are of increasing importance, the laboratories are challenged to maintain or re-establish design capabilities from the past that may not be relevant to the modern U.S. nuclear stockpile. The overlap of design capabilities required for U.S. stockpile stewardship and those required for global security is extensive but not complete. The time urgency and precision required of the answers to questions that may come from our national leadership are quite different and may require different tools. The often abused notion of "expert judgment" plays a central role here, and this point again emphasizes the importance of maintaining the requisite human infrastructure—highly qualified and knowledgeable experts—in order to maintain mission capabilities.

3

Systems Engineering and Aging

Three critical engineering-based elements of the laboratories' efforts in support of their nuclear weapons mission are (1) systems engineering, especially as it applies to integration of efforts from multiple laboratories; (2) execution of nuclear weapons life-extension programs (LEPs); and (3) understanding aging effects, with an emphasis on aging effects on plutonium, but including aging in non-nuclear components for use in control, arming, fuzing, and firing.

The three national security laboratories, Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and Sandia National Laboratories (SNL), have a strong focus on systems engineering, which integrates advances in R&D, engineering, and component manufacturing. The systems engineering staff deal with some of the nation's most demanding and exacting high-technology systems, which must be extremely safe, secure, and highly reliable. These goals must be accomplished in the absence of the ability to fully test the system. The laboratories are also required to interface effectively with the NNSA production sites to ensure that the weapons they produce will perform as designed under all of the conditions specified by the military.

High-quality S&E expertise and performance are essential to modernizing both the stockpile and the nuclear weapons complex. A strong systems engineering function is the core integrating activity for the results of high-quality scientific research, development, engineering, and manufacturing. High-quality systems engineering underpins the success of the recent W-76 LEP and is essential to the B-61 LEP that is currently underway.

Within the nuclear weapons complex, SNL is generally regarded as the "engineering" laboratory with responsibility for entire weapons systems. However, both LANL and LLNL have significant engineering capabilities to turn designs into functioning physics packages. A strong foundational capability in systems engineering in a multidisciplinary team environment is, therefore, a requirement at each of the laboratories, and systems engineers at all of the laboratories constitute a significant percentage of the professional staff. The laboratories have a history of innovatively solving complex systems development and engineering challenges. In general, they have a unique base of people with the critical experience, skills, and integrated knowledge to rapidly design and engineer large, complex national security systems. This institutional experience base has been developed over decades, and stockpile stewardship at the nuclear weapons laboratories requires maintenance of the requisite skills.

HIGH-QUALITY SYSTEMS ENGINEERING

In general, the quality of systems engineering within the national security laboratories is very high. Based on its extensive discussions with staff working in systems engineering, the committee was impressed by the quality of the systems engineering capabilities. It is encouraging that early-career scientists and engineers expressed excitement at, and appreciation of, the opportunity to do exciting work on the nuclear weapons mission and, more generally, on key national security missions.

The laboratories have a unique base of people with critical experience, skills, and integrated knowledge to rapidly architect and engineer large, complex national security systems. However, in the absence of full-system testing, the opportunities to exercise the needed skill sets are decreasing and, frequently, are unavailable.

The laboratories currently have unique and critical high-quality expertise and capabilities in the areas of materials, including plutonium aging expertise, and device processing. They also maintain important specialized capabilities, such as for the production of certain nuclear weapons components (e.g., neutron generators), for plutonium processing and experimentation, and for producing radiation-hardened microelectronic, photonic, and related electronic components. In order to ensure that essential S&E capabilities are maintained by the laboratories, the NNSA should consider assigning them more scientific and programmatic development autonomy and responsibility. These topics are addressed later in this chapter.

The committee saw evidence supporting the observation in the phase I report that NNSA continues to direct not just the "what" of the laboratories' activities, but also the "how"—in spite of the fact that these laboratories were established to provide technical expertise that the government does not have. If the government goes beyond setting policy and imposes technical judgments on the laboratories, the basis of the federally funded research and development center model is called into question. An example is the set of rules that must be followed for all laboratory work that involves plutonium, which appear to make it very difficult for the laboratories to carry out their programmatic responsibilities. The imposition of these rules appears to have been done without adequately accounting for the fact that the laboratories have great expertise in working with plutonium.

WEAPONS SURVEILLANCE

Nuclear weapons surveillance is critical for measuring, evaluating, and understanding the aging of weapon components, not only for annual stockpile assessments but also for LEPs. Moves were begun in the 2007 timeframe to transform the weapons surveillance program by increasing emphasis on S&E through destructive and non-destructive non-nuclear testing and by decreasing the emphasis on flight testing of Joint Test Assemblies. The current surveillance program continues to identify potential S&E enhancements that would lead to an improved understanding of component aging effects, along with adding predictive capability, and retains the information traditionally gained from Joint Test Assembly flight tests. The envisioned transformed surveillance program assumes that the best approach to modern component aging assessment and management should be based on a sampling of components and materials; examination of a superset of that sample to determine the extent of age-related conditions and appropriate corrective actions; and eventual system recommendations, including a system de-rating if weapon reliability is partially compromised. Such an approach is necessary in order to maintain high quality.

PLUTONIUM AGING

Addressing the issue of plutonium aging is crucial for maintaining the reliability and safety of the stockpile. The laboratories have invested substantial resources to understand this important phenomenon. Although the stockpile is considered to have a sufficient margin to operate reliably in spite of the anticipated effects of aging, there are scientific unknowns. Experimental data is crucial for this field, and these data can often be extremely difficult to obtain. The laboratories are making progress toward understanding aging. Investments are being made in important areas, and the quality of the staff and facilities is high. However, progress is hindered by reduced budgets and a risk-averse culture that impedes the conduct of experiments involving plutonium and some other important materials used in weapons. It is necessary to compare the risk of not understanding plutonium aging versus the risk of performing experiments that may involve some (well-understood) risk to safety.

Construction of the CMRR (Chemical and Metallurgical Research Replacement) at LANL has been deferred.[1] Because of cost and siting requirements, there is a possibility that the CMRR will be deferred further, and perhaps never built. In addition to providing facilities for a range of research, the CMRR would support pit production in the plutonium facility (PF-4) in LANL's Technical Area 55. However, only a limited number of pits have been built there.

As pits continue to age, it is essential to maintain a vigorous surveillance program to ensure their integrity and predict if and when they must be replaced. For this, it will be necessary to continue to develop a fundamental understanding of the long-term behavior of plutonium. The Science and Engineering Campaigns and the Advanced Simulation and Computing program are also spurring attention to aging impacts in essential areas, including corrosion. Addressing this will involve an integrated program in experimentation, theory and modeling, and simulation.

To consider these issues, significant collaborative studies have been undertaken by LANL and LLNL on the topic of plutonium aging leading to the milestone 2007 plutonium aging report,[2] which was an effort to determine a minimum pit-lifetime estimate to support decisions on the need, timing, and capacity for pit-production capability. That study summarized the physics and materials issues surrounding aging of stabilized, delta-phase plutonium alloy based on data from naturally aged samples up to 46 years of age and through an accelerated aging experiment that extended the equivalent age to 65 years. The conclusion was that these plutonium pits could last at least 85 years.[3] As a result, additional studies that had been planned (such as examination of other alloys) were never undertaken, leaving unanswered some questions about plutonium aging. However, the conclusion that pits may be reliable for 85 years or more has renewed dialog on the possibility of pit reuse for extended timeframes for the dominant alloy, as well as for alloys for which there is only limited information. Since the 2007 study, some additional areas of concern have been identified, including surface reactions, phase stability and dimensional changes, additional self-irradiation effects not considered in the study, lattice damage, helium in-growth, and void swelling. Continued understanding of these effects requires experimentation.

Recommendation 3.1. In view of the constrained budgets, researchers should prioritize efforts that contribute to quantifying uncertainties in the information that led to the 2007 report and identify the key hallmarks of aging to ensure the long-term viability and performance of the stockpile.

SELECTED SUPPORTING DISCIPLINES

Materials Science and Engineering

Understanding irradiation effects and other materials issues, especially corrosion, is increasingly important in the aging stockpile, and several experts with whom the committee interacted expressed uneasiness, in particular, about the level of interest and support for materials science research to support understanding of plutonium aging. More generally, several presentations to the committee highlighted the reduction in the laboratories' work on materials science over the past several years. While the reduction in support in this area has been offset to some degree by related research done under work for others (WFO) and by the availability of non-nuclear materials scientists to support WFO, no single office at NNSA Headquarters has "ownership" of materials research. Possibly as a result of this situation, it does not appear that headquarters program managers regard materials research as a priority. Absent such a focus,

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[1] The September 2012 6-month Continuing Resolution for fiscal year 2013 appropriations contained no funding for the CMRR. This at least delays CMRR construction and possibly ends it.

[2] The MITRE Corporation, Pit Lifetime, JSR-06-335, McLean, Va., January 11, 2007.

[3] A more recent article (A. Heller, Plutonium at 150 years: Going strong and aging gracefully, *S&TR*, December 2012, LLNL, Livermore, Calif., available at https://str.llnl.gov/Dec12/pdfs/12.12.2.pdf) provides updated accelerated aging data that suggest no precipitous degradation at least until the alloy in question is 150 years old.

funds for materials research must be assembled piecemeal from other budget lines. The laboratories need the flexibility to continually develop the research and technology base to respond to future problems, especially in view of the aging of the stockpile. Chapter 4 contains some discussion about the quality of materials science and engineering research at the laboratories more generally.

Recommendation 3.2. NNSA, working with the laboratories, should support materials research at a level that adequately meets strategic materials research needs.

Nanodevices and Microsystems

SNL has established a focused "research foundation" program to advance its capabilities in nanodevices and microsystems. These capabilities play a strong role in SNL's mission and strategy for nuclear weapons, national defense, energy, and scientific excellence and are critical for nuclear weapons stockpile maintenance and LEPs. While advancing the scientific and engineering frontiers of nanodevices and microsystems and enabling advances in other research areas at SNL, the research foundation program for nanodevices and microsystems develops, designs, and produces tens of thousands of components while specifying and procuring a much larger number of components required for the nuclear weapons LEPs for the B61 and W88 weapons as well as for future LEPs. Because of the centrality of nanodevices, optoelectronics, microelectronics, and microsystems to SNL's mission and the nuclear weapons program, it is important that this research foundation be adequately supported by SNL's strategic recapitalization project and operating plans. Funding streams for recapitalization should not be interrupted, and budgets should be identified for future deliverables, from research to product.

Because of continuing rapid advances in technology in the microelectronics, photonics, sensors, and information technology areas, the research foundation program in this area needs to retain its current strong connections with the broader electronics R&D community so that it can continue to be well-informed about S&E advances in these fields. It also needs to develop strong partnerships with technical leaders from other organizations in that broader community.

Neutron Generators

The reliability of the neutron generators in weapons systems directly affects the reliability of the stockpile. SNL is responsible for all aspects of the neutron generators, including design, manufacturing, and testing, and for addressing any issues that arise from surveillance and inspection. As with many components in the stockpile, it is difficult, if not impossible, to build neutron generators identical to those that are being replaced, whose performance is reflected in weapons test data. This is due to unavailability of certain materials, the inability to replicate many manufacturing processes because of, say, changes in allowable practices, and the loss of expertise as the workforce ages. To address this issue, SNL is engaged in a major effort to put the design and manufacture of neutron generators on a stronger S&E basis. This transition is key for assessing the reliability of neutron generators when missions change or there are changes to the extreme environments that are faced. SNL has been applying an impressive, disciplined approach to understanding the S&E of neutron generators in which every aspect of the neutron generator design and operation is modeled and subjected to testing to validate the models.

TRANSITIONING TECHNOLOGY FOR ENGINEERING: LDRD AND TECHNOLOGY READINESS LEVELS

The Laboratory Directed Research and Development (LDRD) program[4] is critical for the laboratories to maintain their needed S&E edge. It is a major source of cutting-edge S&E and appears to be a robust program. For example, at SNL approximately half of the intellectual property generated by the laboratories, as measured by patent disclosures and copyrights generated, comes from LDRD projects. The process by which LDRD projects related to systems engineering, aging, and LEPs are reviewed, modified as necessary, and eventually selected is impressive. Proposed LDRD projects are categorized by potential application and by funding level. Among projects with smaller funding requirements, a substantial number are focused on advancing S&E capabilities that are important to systems engineering, aging, and LEP work in support of the primary mission. Other LDRD funding is allocated to such areas as grand challenges (projects that have the potential to address major issues that could be mission-transforming), early-career projects aimed at nurturing the next generation of scientists and engineers, and capability sustainment and enhancement.

Technology developed under LDRD funding often has direct and sometimes immediate application to current or near-future programs related to systems engineering, aging, and LEPs (for example, in creating a new option of potential value to an LEP for an existing weapon system). However, LDRD is explicitly designated for generating new scientific and engineering understanding and concepts that have the potential for major advances in S&E for future use; LDRD funds may not be used to augment existing programs. LDRD funding is often—but not always—limited to maturing a new technology option only to a technology readiness level (TRL) of 2 or 3—that is essentially a laboratory or bench-top demonstration—well short of TRL 5 or 6 (or higher) that would generally be needed by mission program managers. Transforming LDRD results to appropriate technology maturation levels that can be incorporated into the stockpile stewardship program is a continuing challenge. SNL staff told the committee that this gap can occasionally be bridged during the engineering phase of a new project, but such attempts tend to fall short and leave project managers with no choice but to opt for an existing design solution, rather than a more advanced solution deriving from LDRD results that are assessed to have the potential to offer substantial improvements.

Lack of technology maturation investment results in an inability to use some innovations that would be more responsive and more efficient than existing technologies. Some potential mitigating efforts have been suggested (e.g., establishment of a continuous 6.3 program[5]) in which funds are allocated specifically for maturation of new technology based on discoveries or inventions from the LDRD program. In 2011, NNSA launched a Component Maturation Framework "to serve as a long-term planning tool [that] includes the maturation plans for development and production of stockpile sustainment components."[6] These steps indicate that this issue is recognized and appreciated by all three laboratories and by NNSA management, but there is no apparent process addressing it systematically.

[4] LDRD annual reports for all three national security laboratories can be found at http://tri-lab.lanl.gov/.

[5] NNSA manages life extension efforts using a multipart nuclear weapon refurbishment process, referred to as the 6.X Process, which separates the life extension process into phases. The first three phases—6.1 Concept Assessment; 6.2 Feasibility Study and Option Down-Select; and 6.2A Design Definition and Cost Study—are primarily R&D activities and studies that determine what changes are needed to ensure that a weapon system remains a safe and reliable part of the nation's nuclear stockpile. The next three phases—6.3 Development Engineering; 6.4 Production Engineering; and 6.5 First Production—convert the R&D designs into final designs and manufacturing processes in order to produce refurbished weapons that meet the military requirements set by the Department of Defense (DOD). The last phase—6.6 Full-Scale Production—manufactures and installs the components needed to refurbish the weapons undergoing life extension and returns refurbished weapons to the stockpile. See GAO-02-889R.

[6] U.S. Department of Energy, "FY 2012 Stockpile Stewardship and Management Plan: Report to Congress," April 15, 2011, p. 26, available at http://www.fas.org/programs/ssp/nukes/nuclearweapons/SSMP-FY2012.pdf.

Recommendation 3.3. The laboratories and NNSA management should take steps to ensure that the gap between the low technology readiness level (TRL) achieved by Laboratory Directed Research and Development projects and the higher TRL required by program managers can be bridged, as necessary, to exploit improved technologies.

A more strategic approach, which recognizes the 5- to 10-year timeframe often needed to bring new technologies to readiness levels required to support the mission, would be very positive. Some efforts have been made in this regard through the Advanced and Exploratory Program and the Stockpile Transformation Program.[7] However, the potential of these programs to develop new technologies is limited. With regard to systems engineering, the committee was told that, in a recent year, 60 proposals for new technologies were suggested at SNL, all of which were determined to be valuable for inclusion into one or more LEPs. The list of 60 new technologies with good potential had to be pared down to seven candidates, and only three of those could be pursued. The committee does not know the appropriate fraction of promising technologies that should be matured, but such a large-scale paring down should not be done based on available budget alone but approached more strategically.

WORK ENVIRONMENT AND STAFFING

The three NNSA national security laboratories appear to have taken aggressive approaches to replace retiring S&E personnel high-quality hires, as gauged by standard metrics such as prior academic performance and class standing. These aggressive approaches have no doubt been aided by the economic downturn, which has created a talent-buyers' market since 2009. All three laboratories indicated that no significant problems have been encountered in hiring outstanding systems engineering personnel over the past five years. SNL has implemented strategies at an early stage to anticipate impending demand by hiring and training on a more accelerated schedule. However, continuing budgetary uncertainties are causing uneasiness at the laboratories about the continued prospects for the aggressive hiring, with SNL perhaps less uneasy than the other two laboratories because of its larger diversity of funding sources and WFO.

WFO activities have come to play increasingly important roles in the intellectual development at the laboratories. At SNL, for example, it was reported that the laboratory could not sustain its systems engineering talent without the infusion of funds and programs from WFO activities. In the past, the laboratories had sufficient flexibility in their core mission funding to pursue new technology directions. For example, SNL embarked years ago on pioneering work in the area of microelectronics, which not only stimulated a major new technological field for the laboratory, but also became of fundamental importance in modernizing the nuclear stockpile and for the LEPs.

While the laboratories are able to take advantage of robust postdoctoral programs to bring in new science researchers, on the engineering side postdoctoral training is less common and new hires tend to enter the laboratories more directly. The national security laboratories also hire many staff at the master's degree level. In many cases, the laboratories are able to take advantage of strong ties with universities, and especially with professors working in fields related to the laboratories' activities, to attract well-qualified new hires.

Nonetheless, the laboratories are facing continuing workforce challenges. LANL, for example, has gone through two voluntary separation programs in the last 4 years. And the laboratories' ability to access the expertise of retirees is constrained by limitations on contracts with individuals who have left

[7] See, for example, (1) SNL publication "Sandia's Nuclear Weapons Mission" (http://www.sandia.gov/news/publications/fact_sheets/_assets/documents/NW_mission_2012_FNL.pdf); (2) SNL webpage for "materials aging and surveillance" (http://www.sandia.gov/materials/science/people/corrosion.html) [Technical Basis for Stockpile Transformation Planning (TBSTP)]; and (3) LLNL FY13 25 year site plan, September 2012, UCLR-AR-143313-12.

the laboratories. Conversely, SNL has been hiring in anticipation of the B-61 LEP. Timing of the funding for the program will be critical to providing work for the staff that has been brought into the lab. In general, the laboratories continue to invest in the staffing pipeline, but sustaining the human infrastructure for S&E excellence is continually challenging.

Without new weapons to design and build, there is less full-systems work through which early-career systems engineers can learn the full range of skills required to design and develop a nuclear weapons system, including inserting products from R&D into new weapons systems.

The pipeline of personnel possessing capabilities (possibly new) needed for the next generation of systems is extremely important. Candidates within some disciplines that are critical to weapons systems, such as metallurgy, are becoming increasingly scarce and difficult to recruit because these disciplines have declined as fields of study at universities. These challenges, which are recognized by the laboratories, along with uncertainty in federal funding and program direction, could negatively impact the laboratories' ability to continue to attract and retain talent, especially as the economy recovers and the laboratories face increasing competition from other sectors to hire new graduates.

The situation is exacerbated by an aging workforce, a significant fraction of which is now eligible for retirement. Knowledge preservation and knowledge transfer—succession planning—are important issues. A deliberate strategy is needed to maintain sufficient systems engineering core capabilities for future missions. The "120-day study" discussed in the next section is a good example of an activity designed to help facilitate the passage of experience and knowledge from older staff to early- and mid-career engineers and scientists.

THE 120-DAY STUDY

The three laboratories recently worked together to carry out a novel "120-day study" as a means of exposing early-career engineers and scientists to the challenges of weapons design.[8] This study did not design new nuclear weapons, but it did consider advanced options for the nuclear physics package and various approaches on how to configure the stockpile using existing components and systems with an emphasis on raising the levels of safety, security, and reliability. The study ranged from basic concepts to engineering and examined the type of experimental capabilities needed to support the future stockpile. It also exercised the systems engineering skills needed to integrate the design into the intended delivery system. The study teams took appropriate considerations of re-use, refurbishment, and replacement established by the surrogate customer for a particular LEP. The staff assembled to address these considerations consisted of a few experienced designers, several mid-career designers, and a relatively large number of near-entry-level designers who were given an opportunity to work together within the customer constraints to develop timely and workable solutions. The S&E skill sets represented in this "design-subject-to-constraints" study were impressive. The study provided a clear demonstration that the quality of the S&E expertise available at the three laboratories continues to be extremely high and able to do excellent work within customer constraints.

Recommendation 3.4. NNSA should continue the approach used for the 120-day study as one means of developing and maintaining a new generation of well-trained weapons designers and the concomitant systems engineering capability.

[8] On January 10, 2012, NNSA officially requested that LANL, LLNL, and SNL perform a 120-day study to evaluate alternative warhead designs and to inform NNSA on potential options for future LEPs.

4

The Science Base

INTRODUCTION

The three NNSA laboratories have a broad science and engineering (S&E) base that supports the nuclear weapons mission. The S&E research activities at the laboratories are an integral element of their unique mission to ensure a safe, secure, and reliable U.S. nuclear deterrent well into the future. Building on decades of S&E advances and infrastructure developments in support of the weapons mission, each of the laboratories has broadened its S&E activities to address, in addition to other areas such as basic science and energy, a wide array of national security challenges—global security, including cyber security issues; intelligence community issues; energy and climate security; the Department of Defense's non-nuclear needs; and countering future threats, including weapons of mass destruction and bioterrorism. The fundamental and applied S&E research activities supported by the nuclear weapons (NW) programs at the laboratories have proven to be essential to the success of their broader national security missions, and they are expected to continue to be so. Although the evaluation contained in this chapter is focused on the NW mission, the findings are likely relevant to many laboratory programs beyond the nuclear weapons mission.

Finding 4.1. The overall quality of science base activities is excellent at all three laboratories. The NNSA laboratories successfully integrate fundamental science, advanced technology, and engineering activities to address important national security challenges in a timely manner, including important multidisciplinary science and technology (S&T) problems of national interest. Their achievements and advances in a broad range of science base research are impressive.

Despite these well-deserved accolades, each of the NNSA laboratories will need to successfully address important challenges pertaining to the workforce and the work environment if they are to continue their legacy of impact to the national security mission well into the future. These overarching issues are discussed below, following the discussion of each of the four technical thrust areas.

MATERIALS SCIENCE, CHEMISTRY, AND ENGINEERING

Materials science, chemistry, and engineering are of critical importance to the nuclear weapons mission at each of the NNSA laboratories, and more generally to their broader national security missions. Virtually every aspect of stockpile maintenance depends critically on the laboratories' ability to synthesize, formulate, integrate, and evaluate materials into systems that eventually result in a functional weapon. An in-depth understanding of materials, including the effects of aging on their characteristics, is central to all aspects of the nuclear missions. In addition to age-related changes in materials within existing weapons, replacement materials (when needed) may not be identical because of changes in raw feedstock or industrial processes. Thus, some components of weapons in the stockpile will be challenging to replicate exactly. To help address these challenges, the laboratories are developing new approaches, including first-principles computations, to understand and control materials properties at the nano-scale level to improve materials performance. In addition, new electronic and photonic materials are being developed and evaluated to continue to decrease feature sizes and to improve device and component reliability.

At LANL, the 5-year plan of strategic goals and S&E needs related in that laboratory's fiscal year 2011 LDRD Annual Report identifies eight necessary pillars of science, technology, and engineering, of which "materials on demand" is most germane to the current discussion. The materials strategy at LANL focuses on the development of materials with controlled functionality to provide solutions that enable LANL's mission. Within this pillar, effort is concentrated on three crosscutting themes: defects and interfaces, extreme environments, and emergent phenomena. Materials are at the heart of the LANL weapons program because they are central to stockpile assessments, life extensions, and manufacturing as well as to weapons physics, weapons engineering, and stockpile manufacturing.

The quality of materials science and engineering activities at the laboratories appears to be high, although the committee has some concerns about quality over the long term because the materials expertise across the laboratories, and thus the commitment to supporting this pillar, is dispersed across the organizations. Based on data supplied by the laboratories on publications in peer-reviewed, top-ranked journals, each of the laboratories has a demonstrated track record of excellence.[1] LLNL publications in chemistry and materials over the past decade have received more citations than average for papers in these fields.[2] LANL's intellectual output as measured by materials publications has been relatively constant over the past 5 years. Just comparing DOE laboratories, LANL ranks second in number only to Oak Ridge National Laboratory (ORNL) among five DOE laboratories (LANL, ORNL, Argonne National Laboratory, LLNL, SNL). In chemistry, depending on which journals are considered, LANL publication numbers range from second to fourth out of seven DOE laboratories, including Lawrence Berkeley National Laboratory and Pacific Northwest National Laboratory.[3] The degree to which collaborations and formation of cross-disciplinary teams to attack problems are an integral part of the culture of each laboratory is impressive. Among the material scientists at all of the laboratories, there is a healthy environment that fosters and encourages the formation of research teams to tackle problems that are of high priority to the mission of the laboratory. All three laboratories are able to sustain research collaborations with top-quality academic researchers in the United States (and, as appropriate, abroad), and they are able to hire high-quality postdoctoral researchers.

Despite its importance for the laboratories' broader national security missions, however, materials science may be at risk in the future due to inadequate planning and coordination across the NNSA complex. While the LANL materials science and chemistry effort is perhaps the best defined and supported, there is an overall lack of coordination in materials science and chemistry programs across the NNSA laboratories. Materials science was described as being a "quiet capability" at LLNL. LLNL staff pointed out that processes are underway to develop a vision for the capability that would define core expertise in materials-oriented divisions (including expertise in high-performance computing). These efforts, however, appear to be more aspirational than concrete.

SNL leadership is taking steps to strengthen its materials work, including a set-aside of additional resources for fundamental science projects through augmentation of the LDRD and a request to customers for resources for materials science. Leadership at LANL also appears to have a heightened awareness of what the committee was told are reduced funding streams in support of basic materials science[4] and of the important role that materials science plays in the laboratories' mission.

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[1] D. Teter, LANL Materials Science and Technology Division Leader, Publication statistics in materials science, chemistry, and engineering at all three laboratories, presented to committee August 14, 2012.

[2] The "average" is that measured by ISI for all papers published in a given field (here, materials science and chemistry) from all institutions worldwide. Data were provided by LLNL in the handout "Executive Summary of Scientific and Technical Metrics at LLNL, Summer 2012," p. 1.

[3] D. Teter, Publication statistics, 2012.

[4] D. Teter, Publication statistics, 2012.

Finding 4.2. Failure to adequately nurture the materials science capability could put it at risk and jeopardize meeting the needs of the nuclear weapons mission in the future.

Recommendation 4.1. The laboratories, in conjunction with NNSA, should define, plan for, and support an integrated program in materials science necessary to sustain the laboratories' nuclear weapons mission.

An additional challenge for preserving the quality of the S&E enterprise in materials science and chemistry is the declining state of facilities and the physical infrastructure. For example, some LLNL laboratory facilities for materials research (particularly chemistry) are widely recognized to be of poor quality.[5,6] Senior management recognizes the seriousness of this issue and is taking steps to address high-priority needs, but the scope of the problem greatly exceeds the limited budget available for this purpose. The declining quality of laboratory space at LANL represents a significant long-term threat to the quality of the S&E base and fulfillment of the nuclear weapons mission. LANL staff commented frequently about the poor condition of many buildings and facilities that house expensive and advanced experimental equipment. Staff members stated that basic necessities for the workplace are in some cases disappearing or delayed, and there have been occasions when researchers found it necessary to bring their own basic, daily housekeeping supplies to work. In contrast, at SNL, the committee found materials researchers to be quite pleased with the excellent facilities.

Recommendation 4.2. LANL and LLNL management, in conjunction with NNSA, need to address infrastructure issues to sustain excellence in materials science and chemistry.

CONDENSED MATTER/MATERIALS SCIENCE AT EXTREME CONDITIONS

An in-depth understanding of how materials behave under extreme dynamic loading (very large compressions, high temperatures, large deformations, and short timescales) is at the core of the S&E base for the weapons program and is important for related national security missions at the laboratories. The intellectual vitality and excellence of the S&E that provides this understanding is essential to the health of the Stockpile Stewardship Program (SSP), non-proliferation and threat reduction, and applications related to conventional munitions. Although dynamic loading is of primary interest to the SSP, static high-pressure/high-temperature studies add considerable value to broader scientific and programmatic objectives. Within the umbrella of dynamic compression science, the focus is on condensed matter at extreme conditions (CMEC). Broadly speaking, CMEC involves thermo-mechanical loading of a material that is initially in a condensed-matter state. Depending on the specifics of the thermo-mechanical loading, the end state can be either a condensed-matter state, warm dense matter, or a dense non-ideal plasma. This section is focused only on those loading conditions where the resulting final state is also a condensed-matter state.

All three laboratories are engaged in CMEC activities, but there are significant variations in the levels of effort and the scientific emphasis at each. In a large measure, the majority of the scientific activities at each laboratory reflect the favored experimental platform of that laboratory to produce dynamic compression in materials: lasers at LLNL, explosives and high-velocity impacts at LANL, and

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[5] "More generally, however, LLNL has not been able to keep pace with the needs for reinvestment in an aging infrastructure." This statement refers to LLNL facilities in general, including but not limited to materials science, chemistry, and engineering facilities (U UCRL-AR-143313-10, FY11 ten year site plan, LLNL, March 2010; R-143313-12, FY13 twenty-five year site plan, LLNL, September 2012).

[6] Regarding office buildings at LLNL: "However, most of the permanent facilities are reaching their end-of-life-cycle, requiring refurbishment, modernization, or replacement . . . backlog in deferred maintenance." Regarding these aging facilities: "From FY08 through FY09, over 850K gsf have been vacated, and an additional 750K gsf are targeted to be shut down." See UCRL-AR-143313-10, FY11 ten year site plan, LLNL, March 2010.

pulsed power at SNL. Although each experimental platform creates significant benefits (and unique attributes) for CMEC efforts, each platform also has associated limitations. However, the coordination and prioritization of CMEC activities across the different platforms was not clearly defined.

Some noteworthy CMEC achievements in recent years are shockless (or ramp) compression at hundreds of gigapascals (using pulsed power and laser platforms) to produce thermodynamic states that were previously inaccessible; significant advances in multiscale-theory and computations to examine a broad range of condensed matter phenomena; effects of pulse shape and loading path on dynamic fracture; and advances in static pressure research through synchrotron measurements. Each of these achievements, scientifically noteworthy, also provides significant benefits for NW programmatic objectives.

Looking first at LLNL, the committee observed that scientific achievements in multiscale-theory and computations for a wide range of materials, including high explosives, are impressive and represent a longstanding strength at LLNL—that is, the lab's ability to integrate theoretical advances at different length scales with continuing advances in hardware and software to benefit both scientific and programmatic activities. Lasers achieve shockless compression of materials to peak stresses of several terapascals, achieving condensed-matter states previously unattainable. This development opens up a new field—cold dense matter science. The static high-pressure, high-temperature research activities at LLNL are likely the strongest among the NNSA laboratories, and synchrotron measurements have been used very effectively for both scientific and programmatic needs. The combination of static pressure and laser-shock capabilities has been creatively used to study light elements and their mixtures. Overall, the scientific productivity, as measured by publications and professional recognition, is excellent, and the transition of scientific results to mission needs is commendable.

CMEC experimental activities at LLNL have relied primarily on laser platforms; the scientific publications and staff member comments supported this observation. Since no experimental platform can cover all S&E needs (which span a wide range of length and timescales and stress magnitudes), a better balance among laser-experiments, gas-gun experiments, and static pressure experiments would be desirable.

The quality of the published results from LANL indicate that experimental CMEC activities, including high-explosive (HE) studies, are strong there. Although more traditional drivers (HE and high-velocity impacts) have been used primarily in CMEC activities, significant advances have been made with other drivers. Studies of solid-solid phase transition kinetics and the relationship to material defects and microstructure are addressing long-standing scientific challenges that are programmatically relevant.

The integration of expertise in materials science and in dynamic experiments is an important feature of LANL activities. Two scientifically important and programmatically relevant advances stemming from this integration are particularly noteworthy: (1) LANL researchers have unequivocally demonstrated the importance of stress pulse shape (and not just amplitude and duration) on tensile damage; and (2) a clever set of experiments has demonstrated the role of loading path on tensile damage in metals.

In addition, static pressure research is growing at LANL. The HE effort is aimed at gaining better insight into the response under dynamic loading of insensitive high explosives, an important element of the modern stockpile. LANL researchers are to be commended for using the Z facility at SNL for CMEC activities.

Some concerns and challenges regarding the future quality of the S&E base conveyed by many LANL staff members who met with the committee included the following: the large number of projects assigned to some individual staff members; the costs per full-time equivalent; uncertainty in budgets; and competition between short-term program demands and longer-term scientific investments. The committee is concerned that these matters could pose a risk to long-term S&E research quality.

Since the 1960s CMEC activities at SNL have been strong. SNL's CMEC activities are currently centered mainly around experiments at the Z facility and a variety of multiscale theory and computations efforts. Over the past decade, on the other hand, the use of gas-gun and static pressure research has declined. Within the scope of CMEC activities at SNL, the quality of the research activities utilizing the Z facility is first rate and has produced noteworthy and significant achievements, examples of which are described below. Pioneering developments at SNL demonstrated the use of pulsed-power capability (the Z facility) to carry out shock-wave experiments with unprecedented accuracy and at stresses previously unattainable in laboratory studies. The integration of theory and computations with experiments associated with this work is impressive and can serve as a model for similar work. SNL deserves credit for pioneering the development of shockless compression experiments at high stresses. Shockless experiments at the Z facility (and subsequently at Omega and NIF) represent game-changing developments both on the scientific front and for addressing programmatic needs. Although the origins of the Z facility are in the ICF program, its use for understanding the dynamic response of materials at extreme conditions has been both unique and impressive. In addition to the quality of the work, collaborative efforts at the Z facility among the three laboratories appear to be quite productive. However, as stated by several staff members during the meeting with committee members, excessive Environmental Safety and Health (ES&H) bureaucracy and internal constraints have limited the experimental productivity for dynamic materials research at the Z facility. This is an important issue for SNL management.

HIGH-ENERGY-DENSITY SCIENCE

High-energy-density science (HEDS) addresses dense plasmas and matter at conditions of high pressures and temperatures well beyond the thermodynamic states considered in the previous section, "Condensed Matter/Materials Science at Extreme Conditions." HEDS is one of the fundamental underpinnings of science-based stockpile stewardship. In particular, thermonuclear fusion can take place in this regime under the appropriate conditions. The health of HEDS is essential to various elements of the NW program.

Methodical studies of this challenging regime have become accessible in the past 20 years due to technological advances in high-powered laboratory facilities and computer simulations. With the absence of nuclear-explosion testing, the development of tools and techniques to help certify weapons and assess changes in the stockpile through other experiments has become critical. Accordingly, the NNSA laboratories have played a major role in the development of the requisite experimental and computational capabilities for HEDS.

Because HEDS is so integrated and complex, the design and execution of relevant experiments are challenging—for example, experiments to measure quantum mechanical and relativistic effects and experiments to benchmark simulations and codes that are important to the stockpile. While all three laboratories articulate the importance of the core weapons mission, they have difficulty describing an overall plan of how to allocate resources to different aspects of HEDS work that underpins weapons physics. Nevertheless, good progress has been made in determining many of the complex phenomena relevant to weapons physics. For example, equations of state, shock physics, hydrodynamics, and opacities are requisite S&E-base competencies that are sustained in the NNSA laboratories. However, the laboratories presented differing priorities, and it is not clear how well those priorities are coordinated.

At LLNL, the NIF dominates the HEDS program. NIF is a unique facility with multiple important missions that include stockpile stewardship as well as attempts to demonstrate ICF. Until recently, much of the NIF program focused on ICF. For the HEDS activity, the combination of terawatt power, megajoule energies, and precision-pulse shaping, together with a flexible target chamber and target-manufacturing capability and an ever increasing suite of diagnostics, makes NIF the finest scientific facility of its type in the world. The tri-laboratory HEDS scientists associated with NIF excel at integrating theory and modeling programs into the experimental design and post-shot data analysis. LLNL, in particular, has spearheaded many critical experiments that have resulted in innovative measurements of material equation of states, capsule ablation and symmetry, and hohlraum plasma conditions.

NIF has attracted outstanding talent internationally to work on critical components of the facility, including the laser, targets, diagnostics, and the experimental campaigns associated with NIF. The promise of this unique platform, the push of NIF's technical capabilities to the frontiers, and the desire to contribute to multiple missions have led to considerable resources being devoted to NIF, in terms of federal funding, internal laboratory resources including LDRD, and a major fraction of the nation's talent in HEDS.

LANL has developed a world-leading capability in particle beam generation through intense laser-matter interaction. Significant understanding of ultra-intense laser/matter interaction is being developed through strong interaction of theory and experimental groups at the important and unique Trident laser facility at LANL. Kinetic plasma modeling is an example of leading research at LANL, in which foundational theoretical and experimental capabilities are applied to astrophysics, including magnetic flux in terrestrial and solar environments, as well as to applied, mission-oriented problems. A LANL-led campaign also fielded important diagnostics at NIF, and laser/plasma interaction experiments and modeling have led to mitigation of instability effects relevant to fusion targets. LANL's publication output in HEDS is impressive, with key publications including particle beam generation from intense laser/matter interaction and important work on NIF drive and compressions, as well as experiments at the OMEGA laser.

At SNL, HEDS is centered on the capabilities of the unique Z facility, a pulsed power machine capable of delivering both high peak power and energy. Z-pinches have been studied for nearly 50 years at SNL. A recent refurbishment of the Z machine, completed in 2009, is performing well, and seminal, world-leading SNL experiments have yielded data on the performance of materials, including plutonium, as well as on opacities found in solar atmospheres or capsule implosions. The work is important for stockpile stewardship as well as for the fundamental science base.

There are clear pockets of HEDS excellence in each laboratory, with all three having personnel who have been recognized by Defense Programs Award of Excellence and DOE Early Career Investigator Awards.

The largest recent HEDS effort within NNSA has been the execution of the tri-laboratory National Ignition Campaign (NIC). Recently, DOE acknowledged that efforts to achieve ignition on NIF had not succeeded.[7] While many of the design parameters were met or exceeded, model predictions were too optimistic. To move forward on ignition requires a renewed emphasis on a scientific approach that acquires and applies knowledge, over an empirical approach that simply tunes parameters to achieve optimal conditions. Furthermore, the best minds must be recruited and meaningfully engaged. For instance, the NIC has struggled with embracing inclusiveness and accordingly has not fully benefited from the expertise of HEDS researchers at other laboratories (within NNSA and more broadly), and also in other relevant fields, such as those in the weapons physics community. To overcome these challenges, relevant experiments must be undertaken, open debates of scientific merits must be valued, and resources must be distributed throughout the community.

NIF serves to highlight another challenge NNSA laboratories face. Despite the intense focus on ignition, NIF was not built for a singular program. Such a large versatile facility is too expensive to serve only a single mission area of research, and its existence is precarious if monopolized by a single goal. While NIF will continue to explore the physics of ignition in concert with a stepped-up modeling effort, a portion of NIF's experiments will be devoted to enhancing the stockpile stewardship program's science base, including HEDS. Accordingly, NIF will be a keystone in the federation of U.S experimental facilities—such as the Z facility at SNL, Trident at LANL, OMEGA at the University of Rochester's Laboratory for Laser Energetics, and Nike at the Naval Research Laboratory—that are available for a broad range of research in plasma physics, atomic physics, and hydrodynamics that encompass stockpile stewardship HEDS, but also more widely for the collection of HEDS thrust areas that include laboratory

[7] U.S. Department of Energy, *National Nuclear Security Administration's Path Forward to Achieving Ignition in the Inertial Confinement Fusion Program,* Report to Congress, December 2012.

astrophysics, beam-induced high-energy-density conditions, and the investigation of ultrafast, ultra-intense laser science.

Even during periods of tight funding, the judicious partitioning of limited resources is necessary to support a balanced scientific portfolio and to ensure optimal utilization of large signature facilities.

Finding 4.3. The existence of a loosely defined collection of HEDS research, including opportunistic research as well as focused programmatic NIC studies, substantiates a broader concern that the NNSA complex has not yet established a national plan for HEDS, including definition of national facilities and corresponding research programs.[8]

Recommendation 4.3. The laboratories, in conjunction with NNSA, should identify core high-energy-density science experimental and computational capabilities and implement a coherent national program for sustaining those capabilities.

RADIATION HYDRODYNAMICS AND TRANSPORT

Radiation hydrodynamics, crucial to both laser-based and Z-pinch inertial confinement fusion (and to many other areas that rely on HEDS), is a scientifically challenging area that depends significantly on computer simulations. When executed well, radiation transport research provides a compelling demonstration of the integration of experiments, theory, and simulation to achieve the desired progress. Even the fastest computers and most efficient algorithms are forced to incorporate major approximations for this research, however, due to the complexity of the scientific issues.

A signature accomplishment in this area is resolution of a problem that has long interested the nuclear weapons designers. That a combination of simulations and experiments—including experiments performed at NIF—resolved the underlying physics of a longstanding problem is a tribute to the laboratories' capabilities and to the effectiveness of their stockpile stewardship.

Recent radiation transport work at LLNL addressed an important issue for the stockpile, gaining significant traction from its experimental grounding. The development of a radiation-driven laboratory platform for experiments was crucial for validating related simulations and for gaining acceptance for the resulting model. LLNL's cohesive emphasis on radiation transport is reflected in the fact that the organizational chart explicitly recognizes the Secondary Division from the Primary Division within the Weapons Complex Integration Directorate.

In contrast, at LANL there does not appear to be a clearly delineated radiation transport program. There have been, nevertheless, relevant and high-impact efforts at LANL that stretch back over decades. LANL staff cited successful topical efforts, including astrophysics jets, crossed-beam energy transfer, and validation of kinetic effects in laboratory implosions. In these areas, accurate representation of radiation effects is unambiguously necessary for fidelity.

At SNL, there is a high-quality radiation transport effort in the area of developing a Z-pinch source that is powerful enough to perform radiation and x-ray effects experiments. SNL has the tools in place and is advancing the field. Research at the Z facility appears to be approaching an important tipping point. Z-facility research, for example, might be on the verge of making contributions to the field of radiation transport S&T that could be profound. However, the facility does not appear to have adequate funding to build on recent achievements. This work should be encouraged by both the laboratory and NNSA.

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[8] Lack of a HEDS strategic plan was noted in the report accompanying the Senate Energy and Water Appropriations Bill for fiscal year 2013: "The Committee directs NNSA to establish an independent advisory committee as soon as possible to help set a strategic direction for inertial confinement fusion and high-energy density physics research and determine how best to use current facilities to advance this scientific field." The language in this Senate report also mandated the NIF report referenced above.

Analogous with the situation for HEDS work, none of the three laboratories have described an overall plan of how to allocate resources to different aspects of radiation transport as a scientific underpinning of weapons physics. Scientific priorities are unclear, and there are significant open questions and challenges.

Finding 4.4. The NNSA laboratories are at a critical juncture with their large experimental and computational facilities for radiation hydrodynamics and transport, yet sustainability presents a significant challenge.

Recommendation 4.4. The NNSA laboratories should define a tri-laboratory strategy for retaining the science base essential to their nuclear weapons mission, clearly identifying priorities for facilities and programs to achieve and maintain sustainability of the requisite capabilities.

WORKFORCE DEVELOPMENT AND THE WORK ENVIRONMENT

Based on extensive discussions with laboratory staff members, it is clear that they place a significant emphasis on the quality of their S&E activities. They are strongly committed to the overall national security missions of their respective laboratories, and they want their activities to have meaningful scientific and programmatic impacts well into the future. In short, staff members at the NNSA laboratories are dedicated professionals who take pride in their work.

The NNSA laboratories are recruiting excellent early-career staff. Postdoctoral fellows and early-career permanent staff displayed strong enthusiasm and intellectual engagement regarding their projects. The quality of the work displayed during a poster session with these staff members was uniformly high. Access to state-of-the-art research capabilities, the potential to address nationally important issues, and the opportunity to work with outstanding researchers were cited as the primary reasons by them for joining the NNSA laboratories.

A large fraction of technical staff members (80 percent at LLNL) are hired from the ranks of postdoctoral researchers. The recruitment process is from a reasonably deep pool with appropriate selectivity (about 30-40 percent of the postdoctoral researchers are converted to regular staff). At LANL, 1,800 postdoctoral fellows were hosted from 2003 through the present, with approximately 27 percent converted to staff. Applications to the postdoctoral program appear to be numerous, and the quality of applicants remains high.[9] The postdoctoral program is the primary pipeline for new talent at both LANL and LLNL, and a dedicated effort has been made to maintain or increase its size and quality. Workforce recruitment at SNL relies more on offering staff positions to new Ph.D.s.[10]

The effectiveness of the mentoring program for postdoctoral and early-career staff ranges from outstanding to minimal. A clear career path in stockpile stewardship discipline areas at the laboratories was not apparent in spite of the staff's keen, expressed awareness of their national security missions. If there is no clear career path in this area, it may become increasingly difficult to attract and retain the best and the brightest to the NNSA research missions. In particular, how do new generations obtain hands-on experience with matter at very extreme conditions of pressure and temperature?

Within the areas of S&E covered by this chapter, mid-career staff demonstrated in-depth S&E expertise, important scientific and programmatic accomplishments, and a strong commitment to

[9] LA-UR-12-23908, Alan Bishop presentation to committee August 13, 2012, shows postdoctoral candidates at LANL by quarter FY06-FY12. The number was about 350 per quarter through the end of FY09, when it began to climb, reaching about 450 by the beginning of FY11, where it has remained. In FY12, the postdoctoral population of LANL was about 450. Analogous figures from the other laboratories were not readily available.

[10] Compared with the other two laboratories, SNL has more engineers and fewer scientists. In general (i.e., not just at these three laboratories) postdoctoral positions are used much less within engineering than within science. However, the postdoctoral population at SNL and LLNL are roughly equal (~210) and less than half the 450 at LANL.

addressing the needs of the national security mission. However, the following concerns were cited by staff members: micromanaging of research activities by program managers within and outside the laboratory; fragmentation of a researcher's time over as many as 5 to 7 projects per staff member in some cases; and increasing costs associated with research activities, particularly for experiments. Because mid-career scientists represent the experts who play a key role in achieving S&E advances to address the mission needs, decline in their productivity and/or their loss, due to the factors cited, can have significant, negative impacts on the future quality of the science base programs.

Finding 4.5. While good staff members are recruited and often retained through early- to mid-career, an effective path for developing the next generation of scientific leadership—particularly for the stockpile stewardship program—is not clear.

Two other issues also affect the morale of staff members and possibly the quality of S&E activities. Budget uncertainties affect the planning and continuity of research activities. And restrictions on participation in S&E meetings and conferences limit necessary professional interactions. Conferences and professional meetings offer a necessary means for laboratory researchers to demonstrate excellence relative to their peers internationally; because the United States no longer tests nuclear weapons, the credibility of U.S. deterrence rests on the credibility of our laboratory scientists and engineers in the outside world. Participation in conferences is crucial for sustaining the quality of S&E at the NNSA laboratories, particularly through professional growth of early-career staff.

All three laboratories stated a strong interest in recruiting women and minority staff members. There appears to be growing participation by women in S&E in all sectors of industry and academia, resulting in increased competition in recruiting women at all career levels, including entry to management. To compete, the NNSA laboratories need to carefully monitor recruitment, retention, and career advancement of a diverse workforce to ensure continued excellence.

Because a large fraction of S&E graduates are not U.S. citizens,[11] the NNSA laboratories face challenges in recruiting staff members into areas that require security clearances. Moreover, U.S. citizens who are outstanding graduates in S&E are in strong demand. The landscape is not uniform: there are shortages of qualified applicants in some disciplines and (more than) adequate numbers in others. For example, HEDS staff at LLNL reported a rich choice of applicants. Exciting and challenging scientific research remains a major attraction for new graduates. As such, the scientific enterprise at the NNSA laboratories needs to remain strong to ensure recruitment of the best talent.

With the resources available to them and the programmatic guidance developed in conjunction with NNSA, all three laboratories have processes in place to integrate the different stockpile stewardship disciplines together on selected topics. They all actively assess and make decisions and, as needed, compromise to prioritize support for in-house and shared large-scale facilities that are required to perform stockpile research.

At LLNL and LANL, a significant fraction of postdoctoral scholars and junior employees are supported in some manner through LDRD funding. Given that the majority of this funding is directed toward projects aligned with lab, DOE, and NNSA strategic plans, this support mechanism provides potential future technical staff with exposure to mission-relevant research.

Finding 4.6. The LDRD programs appear to be well managed at all three laboratories, and these programs are the primary means of supporting new and creative ideas, training new staff, and fostering meaningful collaborations with academic institutions. The novel and innovative approaches supported by LDRD are essential to the nuclear weapons mission.

Funding to sustain scientific research, however, is not stable, which can compromise quality. The impact of this instability on the facilities is evidenced by inconsistencies in support among the various

[11] National Center for Science and Engineering Statistics, NSF 12-317, May 2012.

areas, such as weapons physics versus ignition physics. For instance, the fledgling user program at NIF, at its current funding level, does not have enough flexibility to support users across a breadth of experimental areas.[12]

At all three laboratories, staff expressed concerns about conditions that erode the experimental environment and make it difficult for staff to be creative and innovative. Staff claimed that intellectual inquiry is often impeded by micromanagement through excessive reporting requirements and without an adequate cost/benefit analysis related to ES&H processes. A recurring theme at all three laboratories appeared to be a lack of shared vision or purpose between the ES&H staff and the S&E staff to achieve a proper balance between process and productivity.[13] ES&H staff at the laboratories see their reporting responsibilities to the health, safety, and security staff at DOE HQ (via the laboratory director) and do not have responsibility to the programs themselves. DOE has resisted external regulation in the ES&H area (say, via the Occupational Safety & Health Administration). Furthermore, within DOE in general, the ES&H and programs are not well coordinated. This is an example of DOE telling the laboratories how to do things, not just what to do, as discussed in the 1995 "Galvin Report" and elsewhere.

Finding 4.7. The staff's expression of concern about the costs and process burdens (e.g., excessive operational formality and lack of shared purpose between ES&H staff and S&E staff) associated with relevant experiments is a significant issue because experiments are needed for addressing stockpile stewardship issues, training and code validation, and to ensure ongoing stockpile stewardship productivity.

Because this concern was reported in multiple discussions with laboratory staff, it is discussed further in Chapter 6, leading to Recommendation 6.1.

More generally, a supportive and nurturing work environment that encourages highly creative scientists and engineers across all S&E disciplines is essential across the three laboratories. Such an environment fosters the ability of scientists and engineers to do their work while encouraging the retention of senior staff and the recruitment of early-career staff. The work environment at the laboratories is deteriorating and is at risk of further deterioration. Early-career staff at the laboratories complained to the committee about time-accounting restrictions that seem to limit their working on new ideas at home or on weekends. Similar restrictions impede their ability to discuss task-related problems with other laboratory staff (who would have to be authorized to charge time). Some observe that their chargeable time is often too fractionated among several tasks, reducing productivity and efficiency. Inconsistent and unpredictable funding profiles were also cited, along with conflicts between short-term project demands and sustained scientific progress.[14] These restrictions arise from a lack of trust by

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[12] One of the study committee members, who has also been a member of the review committee for NIF for the past 3 years, commented that the fundamental problem has been a lack of agreement between LLNL and NNSA about the user program. In particular, during the period of the NIC, diverting shot resources to the user program at a level that was originally advertised when the user program was established simply did not occur. This was not a funding issue, but a priority issue. NIF does not have a formal program of supporting scientists, but rather has an informal process of assigning staff to user efforts. This informal process breaks down when programmatic needs become urgent (as they did during NIC). The fact that NIF is pursuing experimental campaigns that look amazingly like NIC without being called NIC means that this issue has not been resolved. As far as the user program is concerned, what is really needed is a formal agreement between LLNL and NNSA that establishes the user program as understood within the DOE Office of Science. Otherwise, there is really no de facto user program at NIF, only good intentions.

[13] See the phase I report, National Research Council (NRC), *Managing for High-Quality Science and Engineering and at the NNSA National Security Laboratories,* The National Academies Press, Washington, D.C., 2013.

[14] This matter was also addressed in the phase 1 report—see, for example, NRC, *Managing for High-Quality Science and Engineering and at the NNSA National Security Laboratories,* 2013, p. 17. That report noted that the four-agency agreement on national security laboratory governance was an important step in fixing this. In the past,

laboratory and NNSA management, resulting in excessive operational formality embedded in the implementation of statutes, rules, regulations, and policies that are put into place to solve specific problems, sometimes across a broader set of institutions than these three laboratories. Impeding the laboratories' S&E is clearly an unintended consequence.

Another major problem is the restriction on attendance at professional meetings and unclassified scientific conferences and on funding for associated travel. These restrictions are the result of actions taken by the Office of Management and Budget and by DOE following the revelation in 2012 about spending by the General Services Administration for a conference in 2010.[15] Scientists in national security laboratories are already isolated from the broader world of science due to classification and the nature of the work. To further isolate the laboratories' scientists and engineers by restricting access to unclassified scientific conferences will limit their career development, their knowledge of the latest scientific advances, external collaborations, and their ability to bring the full range of relevant science to bear on their work at the laboratories. To ease the effect of these travel restrictions, Congress might consider requiring that travel restrictions to scientific conferences by scientists and engineers at NNSA national security laboratories be no more restrictive than those that apply to scientists and engineers funded by other agencies of the federal government.

SCIENTIFIC FACILITIES

Major Facilities and Infrastructure

The quality of infrastructure that supports the science base is uneven, ranging from world-leading to unsatisfactory. At one extreme, the NIF at LLNL is a world-leading facility of impressive design and engineering. At the other extreme, at the same laboratory (and at the others as well) there are facilities that the committee understands to be in poor condition (particularly because of their age), including some at which scientists and engineers report having to perform basic housekeeping functions in order to be able to conduct their work. Funding difficulties resulting from federal budget contraction make it very difficult to address this issue. Nevertheless, continued careful monitoring and planning by NNSA and laboratory management is essential in order to set appropriate priorities for facility improvement.

Balance Between Major Experimental Facilities and Smaller Ones

The laboratories maintain and operate world-leading major facilities for the science base—such as DARHT,[16] NIF,[17] Z,[18] and petascale[19] computing centers. These major facilities are vital to the execution of the laboratories' missions. Smaller facilities are also crucial for research in the science base, and they are an important component of the work environment that attracts new talent and retains experienced staff. As discussed in Chapter 6, the rising costs of building and operating large signature facilities can threaten the continued support of vital smaller facilities, particularly in periods of greatly constrained budgets. Moreover, because signature facilities have greater public and political visibility and can be seen as being inextricably bound up with a laboratory's fate, there can be understandable pressure on management to sacrifice other capabilities in order to ensure the continuing support of major facilities.

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task orders from agencies other than DOE were often designed to tap laboratory staff and infrastructure to obtain a specific product without investing in the development of staff or facilities.

[15] See http://www.aps.org/publications/capitolhillquarterly/201306/travelrestrict.cfm.

[16] The Dual-Axis Radiographic Hydro-Test facility at LANL.

[17] The National Ignition Facility at LLNL.

[18] Z Pulsed Power Facility at SNL, also known as the Z machine or the Z-pinch facility.

[19] Computing facilities capable of performance in excess of one petaflop, that is, 1 quadrillion floating point operations per second.

5

Modeling and Simulation

BACKGROUND

The NNSA laboratories have an extensive set of activities in modeling and simulation (M&S) that are essential to maintenance of the nuclear weapons stockpile given the complexity of the weapon systems and the absence of testing. The laboratories also use computational modeling to answer fundamental scientific questions and to aid in engineering analysis and design, sometimes in collaboration with university researchers, other laboratories, or U.S. industry. In aggregate, the scope of the M&S program is very broad, from focused science codes that address a particular physical phenomenon, to integrated modeling codes (IMCs) that provide physical models involving the interactions between multiple physical processes. The IMCs used by LANL and LLNL are geared toward development and evaluation of the nuclear explosives packages of nuclear weapons. They are some of the most complex numerical simulations used anywhere, with millions of lines of software written over decades to capture the behaviors of and interactions between materials, plasmas, fluids, and radiation. SNL also uses IMCs, primarily in the engineering design/analysis space but also in support of complex experimental facilities such as the Z-pinch machine.

Compared to the IMCs, the science codes are typically smaller and involve fewer interacting physical models. That is not to say they are less sophisticated, because some of them represent the limits of our understanding of underlying physics and push the frontiers of mathematical algorithms, the methods for quantifying uncertainties, and the computer systems on which they run. None of these codes are entirely static, as they are regularly adapted to incorporate refinements in the models, new algorithmic techniques that improve accuracy or performance, and changes in the underlying computer architectures.

A successful program in this sort of advanced M&S requires deep expertise in applied mathematics, computer science, and a range of physical science disciplines relevant to the mission, plus access to experimental data to validate the simulation models and to quantify uncertainties. It also needs a sophisticated set of software engineering activities for the design, development, and maintenance of codes. The work must cover, in a balanced way, both support for production software used in weapons design and certification and innovations needed to develop new models, algorithms, and computer systems. Successful M&S programs capable of addressing these requirements and challenges are built around large, interdisciplinary team-based science and engineering (S&E) projects, which are a hallmark of the NNSA national security laboratories.

A strength of the M&S programs at the laboratories is the quality of the senior scientific staff, including those in management roles. Several of them have strong backgrounds in theoretical or experimental research, only later moving into M&S. They demonstrated to the committee an appreciation of the importance of a strong interface between modeling and basic science.

QUALITY OF MODELS AND NUMERICAL METHODS

When DOE began the Accelerated Strategic Computing Initiative (which later transitioned into today's Advanced Simulation and Computing program), the IMCs were seen primarily as tools for nuclear weapons design, particularly for stockpile stewardship in the absence of underground nuclear tests. But they have also proved valuable in a range of other applications, including designing inertial confinement fusion capsules at LLNL, exploring high-energy-density physics and other basic science topics, enabling studies to underpin the LEPs, and providing simulations in support of counter-proliferation.

While the codes have had an important impact on laboratory science and technology decisions, the code developers acknowledge that they do not yet have a robust predictive capability for a number of key phenomena, such as energy flows and boost, except through the use of problem-dependent calibration from experiments. The predictive capability of a numerical simulation depends on several factors, including the following:

- The validity of the physical models encoded in the simulation;
- The fidelity of the numerical methods used, including whether the discretization accurately captures the essential features;
- The quality of the algorithms—for example, the choice of preconditioner used in solving linear systems and the numerical accuracy of the algorithms in the face of roundoff errors; and
- The quality of the software implementation of the algorithms.

The predictive capability that has been achieved is assessed by validating the simulation code against experimental data, assessing parametric uncertainties, estimating numerical errors, estimating the impacts of uncertainties in initial and boundary conditions, and so on, all for the range of applications of interest.

Although all of these factors must be attended to, it is essential to ensure that the equations attempting to describe the phenomena under study are properly captured and are sufficiently accurate in the parameter range being explored. If that condition is not clearly met, then ancillary experiments should be undertaken, as possible, to decrease the uncertainties. That step might have been incomplete in the case of the ignition experiments at NIF.

HYDRODYNAMICS AND MATERIALS

Hydrodynamics and mixing at material interfaces are critical processes related to stockpile stewardship, and M&S is a primary means of exploring these phenomena. While the work the committee examined is in general well executed, and the staff involved are working at the state of the art, the committee has concerns about one strategic issue in connection with this work. Those concerns are addressed in the classified Annex to this report.

TRANSPORT AND PLASMAS

Transport involves the modeling of the flow of neutrons and other particles and of x rays and other radiation, as determined from their couplings to electrons and ions, which is essential for describing the dynamics of nuclear weapons and related components. The modeling of radiation and neutron transport accounts for the bulk of the computational time in a typical weapon simulation. Accordingly, there is a premium placed on efficient and accurate modeling of radiation and neutron transport (denoted "particle transport") phenomena at the NNSA laboratories. There are also unclassified applications of particle transport, including nuclear reactors, medical diagnostics and treatments, astrophysics, nuclear fusion, high-power lasers, and some industrial processes.

The NNSA laboratories were the pioneers in developing particle transport methods and continue to be leaders in the field. The computational methods for transport include discretization of the partial differential equation that describes the transport process (denoted "deterministic" transport methods) or stochastic modeling of the underlying radiation or particles ("Monte Carlo" methods). All three NNSA laboratories are actively involved in the development of deterministic and Monte Carlo codes for transport simulation.

Two notable examples of high-quality efforts in computational transport for general science at the NNSA laboratories are the groups that develop the deterministic transport capabilities in the code KULL at LLNL and the Monte Carlo radiation-transport code MCNP6 at LANL. The KULL code has an unprecedented capability for modeling radiation transport. For example, a recent simulation of the Searchlight experiment with KULL, which modeled the flow of x-ray energy through an evolving density gradient to validate modeling of stellar atmospheres, was one of the largest radiation transport problems ever run at the NNSA laboratories. This calculation included more than 275 million unknowns and ran for 30,000 time steps (to simulate 12 nanoseconds of experiment time!). Perhaps just as significant, the same radiation transport code was used to help plan an optimal signal-collection strategy for a related experiment. There are other examples of successful deterministic transport codes at the NNSA laboratories, but the development of KULL is particularly noteworthy.

The MCNP series of Monte Carlo codes at LANL is recognized as the international "gold standard" for Monte Carlo particle transport, with more than 10,000 users around the globe. There is a rigorous verification and validation process for MCNP revisions, and the MCNP team is internationally respected for its expertise and achievements in Monte Carlo development. The development of MCNP and the support provided to the large user community is an indirect peer review of the Monte Carlo methods development at the laboratories, and the community's acclaim for these codes couples with the MCNP team's strong record of journal publications and conference proceedings to illustrate the high quality of MCNP development and applications.

SNL has long been a leader in developing electron transport and neutron transport methods for determining the radiation dose to electronic components and other devices. This input can then be used by materials scientists to predict the effect of the radiation on device performance. By necessity, this effort requires experimental data to validate the models. The Sandia Pulsed Reactor (SPR) was the source of much of this data, but this facility was decommissioned in November 2006. The QASPR (Qualification Alternatives to Sandia Pulsed Reactor) initiative is an outstanding example of the systematic approach taken by SNL in validating its engineering models for predicting radiation dose, materials damage, and impacts on device performance. Data from SPR experiments have been collected, stored, and treated as new data that complements data from existing experimental facilities.

ENGINEERING

Within the nuclear weapons design mission, there is a division of labor between LANL/LLNL and SNL. LANL and LLNL are responsible for designing the "physics package," i.e., the components of the weapon that are directly responsible for the nuclear explosion, and its response to the external environment. SNL is responsible for the design of the non-nuclear components and for integration of the weapon into the delivery system. In contrast to the IMCs used to design the physics package, SNL's mission requires M&S tools that are more closely aligned with those in other more general engineering applications.

To carry out its mission, SNL has developed a broad range of simulation capabilities in areas such as fluid dynamics and heat transfer, solid mechanics, radiation effects, and electromagnetics. The groups developing these packages have strong software engineering practices, including a layered design that factors different capabilities into reusable components, and a documented software design process. The IMC development at SNL is closely coupled to basic research activities that are funded by the DOE Office of Science to build capabilities for numerical partial differential equations, linear and nonlinear solvers, and grid generation.

Nonetheless, SNL is subject to the same pressures as the other two laboratories in its weapons mission: expansion of the mission, particularly due to the demands of the LEPs, without corresponding increases in resources. In addition, over the past 15 years, SNL has deliberately expanded its sponsor base to the point where 50 percent of its funding comes from sources other than NNSA and DOE. While laboratory management has attempted to cultivate a long-term institutional relationship with these non-DOE stakeholders, in practice, many of the projects have been short term, sometimes as little as a year, placing enormous pressure on the scientific personnel due to the difficulties of staffing such short-term projects and delivering on such short timescales and the fragmentation of individual staff members' time. The phase I report from this study[1] endorsed this movement of the laboratories into broader "national security" laboratories, but short-term and fragmented work imposes risks to the S&E quality over the long term.

QUALITY OF SCIENTIFIC COMPUTING PRACTICE

Verification, Validation, and Uncertainty Quantification

Laboratory staff presented an analysis of a particular code's sensitivity to three choices that are made in all M&S, looking particularly at how these choices affected the code's ability to represent an implosion. The sensitivities examined were (1) parameter variation for a given model, (2) choice of model, e.g., a change in the choice of equation of state (EOS) used, and (3) choices of numerical methods, such as the mesh resolution. The striking result was that all three of these factors were significant—i.e., the code's output was clearly sensitive to all of them. The presentation noted, though, that parameter variation, while non-negligible for the particular case treated, was less important than either of the other two factors. It also explained that some loss of precision due to choices of numerical methods can be mitigated via higher resolution calculations, albeit at the cost of longer runs. The outcome of this analysis is to highlight the substantial importance of model choice.[2]

The committee was later informed that a switch from an older EOS to a more modern version had resulted in less accurate results. This outcome prompted staff to reconsider the EOS in question in the light of very recent results, and the result is that a code improvement is very likely. The committee found this discussion to be a very positive illustration of the scientific method at work, causing the weapons community to revise its views. In more detail, it also shows that the original development of uncertainty quantification (UQ) that emphasized parameter variation needs to be updated to accommodate the less tractable uncertainty of model choice (as part of epistemic uncertainty). This technical exchange between and within the laboratories is a compelling example of the importance of inter-laboratory peer review.

Effective Use of High-Performance Computing Technology

Overall, the laboratories' work in M&S related to the core weapons mission is quite impressive. The interplay among basic physics, numerical techniques, and computer science is robust and energetic. Roughly 15 years ago, the laboratories led the transition of M&S codes from vector supercomputers to massively parallel machines. Today, the production codes run on large-scale parallel clusters, while laboratory developers have been able to modify the science codes and associated algorithms to make use of the Blue Gene systems at LLNL and, in some cases, the heterogeneous Roadrunner architecture that arrived at LANL a few years ago. For example, production codes routinely run on parallel clusters using 5,000-10,000 processors and some occasionally run with up to 100,000 processors. However, significant challenges loom ahead, starting with underlying computing technology.

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[1] National Research Council, *Managing for High-Quality Science and Engineering at the NNSA National Security Laboratories,* The National Academies Press, Washington, D.C., 2013.

[2] M. Henrion and B. Fischhoff, Assessing uncertainty in physical constants. *American Journal of Physics*, 54:791-798, reprinted in *Judgment Under Uncertainty II: Extensions and Applications* (T. Gilovich, D. Griffin, and D. Kahneman, eds.), Cambridge University Press, New York, N.Y., 1986.

Well-known technology challenges limit the growth of high-performance computing performance: power density is constraining the clock speed of individual processors; the cost of data movement in time and energy continues to grow relative to the costs of computation; failure rates may increase due both to device-level physics and to the multiplicity of components; and total system power places practical restrictions on the design and operation of large systems.[3] These considerations have led to plans for new computer architectures that will require the development of new algorithms and programming techniques at enormous software costs, costs that will escalate if the software is not well organized and documented. The BlueGene and Roadrunner architectures, which represent very energy-efficient processor designs, have provided early examples of the kinds of transitions, analogous to those required for migrating to parallel computers in the 1990s, that will be necessary if production workloads are to keep pace with hardware advances.

In the past, the NNSA laboratories have been leaders in co-developing hardware with vendors and in transitioning applications to these systems. Individuals at the laboratories are well aware of the changes ahead, have support to work on specific software development, and are active participants in the discussion of "exascale" challenges occurring across the DOE community. The goal of building an exascale system capable of performing 10^{18} floating point operations per second reflects a broader interest in improving energy efficiency and making sure the systems are balanced, programmable, and generally useful for science. However, in contrast to the way the high-performance computing community within the national laboratories contributed to major architecture transitions in the past, the committee heard concerns about the present lack of a coordinated plan from DOE to support laboratory engagement with the computer industry in developing future generations of systems and in transitioning codes to these platforms. The committee also heard that budget trends are likely to set up a competition between hardware and software.

Software Engineering Practices

Software engineering is important for delivering reliable results and for adapting code to new mathematical or programming techniques. The committee has some doubts about the quality of the software engineering methodology used in the IMCs. When questioned about how software developers at the laboratories use documentation of the model (including its discretization and algorithms) as part of their design process, the response was that the codes under development are too changeable for such an approach to be practical. This answer was provided across the board with respect to code-design projects dating from the mid-1990s to today.

To give a sense of scale of the IMCs, a typical integrated code at LLNL has 750,000 to 1 million lines of code, in addition to shared libraries that are on the order of 3 million lines of code. There are some positives in the software practices at LLNL, including systematic regression testing, revision control, release processes, and some documentation, such as user manuals and, in at least one case, a developer's manual. However, the codes at both LLNL and LANL lack systematic documentation of the physics, algorithms, and software design and, rely instead on developers themselves to be the repositories of such information. LLNL recognizes this as a serious defect, and it has begun to repair the problem, but to date progress has been limited. This is a potentially unstable situation, given that the expected disruptive change in computer architectures will almost certainly require a reconsideration of all design decisions for the IMCs, a process that will be extremely difficult without documentation of the current designs.

[3] P. Kogge, K. Bergman, S. Borkar, D. Campbell, W. Carlson, W. Dally, M. Denneau, P. Franzon, W. Harrod, K. Hill, J. Hiller, S. Karp, et al., ExaScale Computing Study: Technology Challenges in Achieving Exascale Systems, DARPA, Arlington, Va., 2008, available at http://users.ece.gatech.edu/mrichard/ExascaleComputingStudyReports/exascale_final_report_100208.pdf.

SNL has notably practiced modularization of their software packages, with an emphasis on dual use and open-source publication of lower level modules, e.g., Trilinos. In this respect the overall approach of SNL appears to be superior to that of LLNL or LANL. Certain of the SNL codes have become de facto standards (e.g., LAMMPS for molecular dynamics simulations in materials science).

One contrasting point at LANL was an effort to develop protocols for producing new code in a 4-year period, which is substantially shorter than the typical 10-15 year timeframe. Although the concept is laudable, the committee could not establish that industry-standard software engineering methods were being applied (beyond basic steps such as version control). In contrast, SNL presented evidence that they are indeed applying such methods. While it is a challenge to find staff with the appropriate training, SNL's M&S staff is committed to the discipline and believes that the overall greater degree of acceptance of their software (e.g., LAMMPS) outside the nuclear weapons complex can be partly attributed to their adherence to good software engineering practices. SNL staff deserve credit for making effective use of good software engineering practices, which are very important.

STAFFING AND SUCCESSION PLANNING

The impressions gleaned by the committee suggest that all three laboratories have long been seriously committed to staff recruiting, retention, and succession planning. The committee met with energetic and promising groups of postdoctoral researchers, many of whom were drawn to the laboratories' mission and the opportunity to work with the senior staff. With respect to diversity, the M&S staff at the three laboratories mirrors the general technical population, which means that the fraction of women, for example, is quite low.

Despite these efforts, the committee has concerns about some areas, one being "core" computer science activities, such as computer architecture, systems software, programming models, tools, and the algorithms used in these systems. While there are some outstanding individuals in these areas within the laboratories, there were also signs of difficulty in recruiting and retention. These researchers are mobile because they can easily find challenging and lucrative employment in industry, and while their work is necessary to the NNSA mission, they have other good options. The committee was told that researchers and engineers in these areas are more likely to leave mid-career than are people in other disciplines. This does not seem to be an issue for other specialists who are key to the laboratories' M&S, such as physical scientists, applied mathematicians, computational modeling experts, or even computer scientists in selected areas like scientific visualization—probably because the laboratories offer unusual intellectual challenges for these specialties.

The committee also has a general concern about the dilution of resources devoted to at least some aspects of M&S. Until the mid-2000s, the code teams at LLNL contained some 25 full-time equivalent (FTEs) for each IMC. Since that time, the staffing has decreased to approximately 17 FTEs for each IMC, while the mission demands have expanded. Given the range of activities that are required to meet the M&S challenges identified earlier in this chapter, this appears to be a woeful understaffing. Furthermore, the funding for collaboration with organizations such as the Center for Applied Scientific Computing at LLNL, which have better connections to the science communities, has been shrinking. While the laboratories have continued to invest in cutting-edge computing platforms, they must also invest appropriately in all aspects of software development for stockpile stewardship.

FINDINGS AND RECOMMENDATIONS

The laboratory scientists and facilities involved in M&S represent a unique national asset, with both depth of expertise in particular technical areas and the experience to integrate across areas to solve critical and challenging problems. LANL, LLNL, and SNL have developed a spectrum of capabilities in M&S that have solved critical problems in national security. The scope of the M&S activities has grown substantially in recent years, as the laboratories have become more reliant on predictive modeling of an aging weapons stockpile in this era of no testing. At the same time, many of the computational groups are smaller than they were a decade ago.

The committee also observed that funding pressures—budgets that are lower than laboratory staff feels are necessary, fluctuations from year to year, and uncertainties associated with those fluctuations—appear to have had a noticeable impact on the morale of the laboratories' M&S scientists. The contract changes at LANL and LLNL raised costs and, therefore, contributed to this pressure, along with overall decreases in funding, growing scope, and general increases in the cost of doing business. If planned LEPs divert funding away from M&S research, the situation could worsen.

Finding 5.1. The next decade is expected to bring disruptive advances in computer architectures, with profound consequences for laboratory M&S capabilities. While there is awareness of the issues, DOE and NNSA have not developed a comprehensive plan to respond to the challenges. The issues are not being addressed with the kind of coordinated effort that has characterized prior major DOE initiatives in scientific computing.

Finding 5.2. Changes in materials properties due to weapons aging and component replacement, or due to refurbishment of materials or the use of materials fabricated with processes that differ from those used for the weapons that produced test data, are an increasing source of uncertainty in weapons systems. The laboratories' staff recognize that new physics-based models capable of addressing these uncertainties must be developed to replace key current models whose reliability is dependent on their calibration to old nuclear test data.

Finding 5.3. The development of predictive codes based on physics modeling requires data for validation and uncertainty quantification, plus close connection between modeling and experiment. The committee shares the concerns of laboratory M&S staff that the increasing difficulty in fielding experiments is undercutting this process. This difficulty is most evident for small-scale experiments, as discussed elsewhere in this report.

Finding 5.4. The quality of the NNSA laboratory scientific and technical workforce is the most important factor determining how well the laboratories respond to computer architecture changes, to the challenge of new physics-based models, and to the need for ancillary experiments for code and physics validation. Maintaining staff quality is a major challenge in the face of budget uncertainties, competition in computer science from other employers, and a perception among some that the scientific environment of the laboratories has eroded.

Finding 5.5. There are substantial needs for higher model fidelity and numerical accuracy in the IMCs. In particular, there are no robustly predictive simulation capabilities (i.e., ones that do not require calibration from UGT data) for multiple key physical phenomena. The staffing levels of the M&S effort are inadequate to meet the needs of retooling the IMC codes to meet the simultaneous challenges of developing higher-fidelity simulation capabilities, meeting expanded mission requirements, and changing the algorithms and software architecture of the codes to respond to the disruptive changes in computer architecture expected to occur over the next decade.

Recommendation 5.1. The laboratories should ensure that they have an environment that nurtures broad scientific inquiry to aid in recruiting and retaining a cadre of first-rate, creative, energetic scientists with expertise in all aspects of M&S, ranging from deep understanding of the underlying physics and mathematics to the most advanced ideas in computer architectures, algorithms, and programming methods. They also should track staffing and prioritize activities so as to deal with the growing demands on M&S and related technical challenges.

Recommendation 5.2. Given the increasingly important role that the IMCs will play in certification of the stockpile in the absence of testing, the NNSA should undertake a detailed assessment of the needs for simulation and modeling over the next decade and implement an adequately funded execution plan to meet the challenges outlined in Finding 5.5.

6

Cross-Cutting Themes

Chapters 2-5 focused on evaluating the quality of S&E in connection with four different core capabilities of the NNSA laboratories. This chapter identifies and discusses major themes that cut across those capabilities.

OVERALL QUALITY OF S&E

As explained in Chapter 1, the focus of the committee was to assess the quality of the S&E foundations—the staff, facilities, planning, recruitment and retention of staff, and the work environment—capabilities that suggest whether the laboratories are poised for long-term success. Specific work was evaluated to assist the committee in that evaluation, and in the process it did observe an impressive range of excellent ongoing work at the three laboratories, giving it a very favorable impression of the current state of their S&E. In the judgment of the committee, no S&E quality issues were found that would prevent certification of the stockpile. Another important aspect of the quality of S&E within the context of the nuclear weapons mission—because of its complexity and the need for it to bridge successfully between state-of-the-art research and complex and reliable engineered systems—is the degree to which the work is appropriately connected and relevant. The committee found ample examples of productive communication, cooperation, and coordination across disciplines; between research and development and other programmatic activities; and within and among laboratories. Scientists, engineers, and managers with whom the committee interacted displayed a strong recognition that their work is interdependent and that cooperation across disciplines is essential to the nuclear weapons missions at the laboratories. Strong cooperative attitudes were seen across disciplines within laboratories and across laboratories. Such open interaction is generally essential to high-quality S&E in support of science-based stockpile stewardship and global security (nonproliferation).

The current favorable state of quality is, however, facing several stresses. Most of the findings and recommendations in this report, accordingly, deal more with forward-looking issues that might affect the future quality of S&E. Many of these forward-looking issues are similar or inter-related. For example, three of the findings (2.1, 4.7, and 5.3) concern the difficulty in operating and performing experiments. The remainder of this chapter summarizes those concerns that cut across multiple areas of the laboratories and which might be "leading indicators" of a decline in quality or a threat against maintaining quality. In order to preserve today's highly productive situation, each of the laboratories and NNSA will need to successfully address the following cross-cutting challenges.

EXPERIMENTATION

Compared to the years when nuclear testing was being conducted, science-based stockpile stewardship has necessitated important changes in the focus of work in all four of the areas examined by this study—weapons design, systems engineering, the science and engineering base, and modeling and simulation. That is because, although data collected during the testing years are still being exploited, there is now an increased reliance on fundamental scientific understanding and computer simulations as replacements for the empirical information obtained from full-scale testing. Experimentation at less-than-full scale is still critical, maybe even more so, because it is essential for validating computer simulations and estimating their uncertainties. The coupling of simulation and data is necessary to the ability to certify the stockpile.

However, several of the committee's teams heard laboratory staff express concern about the difficulty in obtaining relevant experimental data because of the excessive formality of operations, with no real benefits, which in at least some cases leads to multiple approval steps before an experiment can be run. These processes in turn lead to delays and extra costs; this is especially true for experiments that use radioactive or otherwise hazardous materials, which are often the key materials in nuclear warheads. There is a strong concern among S&E staff at all three laboratories that the amount of experimental work has declined and continues to decline.

Factors driving experimental costs and delays include a lack of trust, excessive duplicative oversight, formality of operations, and a culture of audit and risk avoidance with inadequate attention to the consequent risks to the S&E program. All experimental activities have inherent risk, which must be balanced against the benefits that derive from conducting the experiments if reasonable decisions are to be made. It is in the nation's best interest to stabilize the conditions for safe, secure, cost-effective mission success. The risks inherent in doing an experiment need to be weighed against the benefits of doing the experiment and the associated risks to S&E capabilities if the experiment is not carried out.

Recommendation 6.1. DOE or NNSA, in conjunction with laboratory management, should review the overall system for assessing and mitigating safety risks and identify opportunities for savings and efficiencies, for example, from reducing redundant responsibilities. They should develop a methodology to assess both risks and benefits and should employ that methodology in ensuring safe and productive experimental work at the national security laboratories.

The recommended risk/benefit analysis process should be able to: (1) review and revise the determination of conditions under which proposed experiments are permitted to proceed (i.e., the current catalog of safety and other rules and requirements that need to be met); (2) guide individual decisions to conduct specific experiments; and (3) evaluate any and all new or proposed significant requirements placed upon experimental work in the future. The process should explicitly include the benefits of conducting an experiment and the mission risk associated with not conducting the experiment.

Congress might consider requesting annual updates on progress in implementing this recommendation, until such time as the methodology is sound and the implementation process is functional.

FACILITIES AND INFRASTRUCTURE

As noted in Chapter 4's discussion of scientific facilities, the quality of infrastructure at the laboratories is uneven, ranging from world-leading to unsatisfactory. This concern pertains to more than just the science base. The deterioration of facilities reduces the productivity of scientists and engineers because their work can be interrupted or impeded by mundane tasks or repairs, and it will also have negative impacts on morale and the ability to recruit the best people. In extreme cases it can of course also lead to safety problems, damage of expensive equipment, or problems with the work quality.

The committee is also concerned about the possibility that major laboratory facilities can undercut the amount of attention and resources devoted to smaller-scale, less visible facilities. While the three laboratories maintain and operate world-leading major facilities such as DARHT, NIF, Z and petascale computing facilities, smaller facilities are also crucial for executing the mission, and they are an important component of the work environment that attracts new talent and retains experienced staff. Examples of smaller facilities include certain specialized capabilities for production of components of nuclear weapons such as neutron generators, for plutonium processing and experimentation, for radiation hardened microelectronics and photonic related components, for beryllium parts fabrication, and many other facilities required for research in the physical sciences and engineering. (Specialized facilities for other disciplines are also required for the laboratories to execute their other missions.) The rising costs of building and operating large signature facilities could threaten the continued support of vital smaller facilities, particularly in periods of greatly constrained budgets.

Finding 6.1. World-leading signature experimental facilities are essential to fulfilling the nuclear weapons mission of the national security laboratories, but smaller experimental facilities are also essential to the ability of the laboratories to conduct their work and to attract, develop, and retain staff.

Recommendation 6.2. The laboratory directors, working with NNSA, should ensure a balance between small scientific facilities and the larger signature facilities at the laboratories appropriate for sustaining the nation's nuclear deterrent and addressing related national security threats within a tight budget profile.

In general, the sort of strategic planning called for in this recommendation is not always apparent across the three laboratories. The committee noted that strategic planning could be improved for high-energy density science and radiation transport. The committee also noted that uncertainty and unpredictability in resources (especially funding, due in large part to forces beyond the control of the laboratories or NNSA) is a factor that impedes high-quality work.

WORKFORCE RECRUITMENT AND RETENTION; WORK ENVIRONMENT AND CULTURE

All three laboratories maintain highly qualified, productive workforces. All three laboratories indicated that no significant problems have been encountered in hiring outstanding personnel over the past five years. Attrition rates are low—about 4 percent per year—and relatively steady.[1] Those with whom the committee met are enthusiastic and apparently pleased with being at the laboratories.

However, the committee has some reasons for concern. It heard numerous, and widespread, complaints about deteriorating conditions at the laboratories. As in the first phase of this study, these focused primarily on infrastructure and a perceived increasing burden of rules, regulations, operational formality, constraints and restrictions, and administrative burdens. While this has not yet resulted in notable declines in recruitment and retention, the negative forces might have been offset by the state of the economy since 2008. Thus, an improving economy may produce better opportunities outside the laboratories and lead to more competition for workers and more departures.

The three laboratories appear to have taken aggressive approaches to replace retiring S&E personnel with high-quality hires, based on standard metrics such as prior academic performance and class standing. Sandia National Laboratories (SNL) has implemented strategies to anticipate impending demand by hiring and training on a more accelerated schedule. However, continuing budgetary uncertainties seem to be causing uneasiness at the laboratories about the prospects for continued aggressive hiring.

The laboratories are able to take advantage of robust postdoctoral programs to bring in new researchers with science backgrounds. On the engineering side, in which postdoctoral training is less common, new hires tend to enter the laboratories more directly. SNL also hires many staff at the masters level. In many cases, the laboratories are able to take advantage of strong ties with universities, and

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[1] National Research Council, *Managing for High-Quality Science and Engineering at the NNSA National Security Laboratories*, The National Academies Press, 2013, p. 13.

especially with professors working in fields related to the laboratories' activities, to attract well-qualified new hires.

Nonetheless, the laboratories are facing continuing workforce challenges. LANL, for example, has gone through two voluntary separation programs in the last four years. And the laboratories' ability to access the expertise of retirees is constrained by limitations on contracts with individuals who have left the laboratories. In general the laboratories continue to invest in the staffing pipeline, but sustaining the human infrastructure for S&E excellence is continually challenging.

The committee notes some worrisome statistics in specific disciplines. As explained in Chapter 5, there is particular concern in core computer science areas, such as computer architecture, systems software, programming models, tools and the algorithms used in these systems. While there are some outstanding individuals in these areas within the laboratories, there were also signs of difficulty in recruiting and retention. Among laboratory scientists and engineers, these researchers are the most mobile, because they can easily find challenging and lucrative employment in industry—while their work is necessary to the NNSA mission, they have other good options. These researchers and engineers appear less likely to come to the laboratories and more likely to leave mid-career than other disciplines.

Appendixes

A

Acronyms

CMEC	condensed matter at extreme conditions
CMMR	Chemical and Metallurgical Research Replacement
DARHT	Dual-Axis Radiographic Hydro-Test Facility
DNFSB	Defense Nuclear Facilities Safety Board
DOD	Department of Defense
DOE	Department of Energy
EOS	equation of state
ES&H	Environmental Health and Safety
FFRDC	federally funded research and development center
FTE	full-time equivalent
FY	fiscal year
HE	high explosive
HEDS	high-energy-density science
ICF	inertial confinement fusion
IMC	integrated modeling codes
LANL	Los Alamos National Laboratory
LDRD	Laboratory Directed Research and Development
LEP	Life Extension Program
LLNL	Lawrence Livermore National Laboratory
M&S	modeling and simulation
NIC	National Ignition Campaign
NIF	National Ignition Facility
NNSA	National Nuclear Security Administration
NRC	National Research Council
NW	nuclear weapons
ORNL	Oak Ridge National Laboratory
PF-4	LANL plutonium facility
R&D	research and development

S&E	science and engineering
S&T	science and technology
SNL	Sandia National Laboratories
SPR	Sandia Pulsed Reactor
SSP	Stockpile Stewardship Program
TRL	technology readiness level
UGT	underground test data
UQ	uncertainty quantification
V&V	verification and validation
WFO	work for others
Z	Z Pulsed Power Facility

B

People with Whom the Committee Held Discussions

SENIOR MANAGEMENT

National Nuclear Security Administration

Dimitri Kusnezov, Chief Scientist and Director of the Office of Science and Policy (NA-1.1)
Donald Cook, Deputy Administrator for Defense Programs (NA-10)
Rhys Williams, Assistant Deputy Administrator for Nonproliferation Research & Development (NA-22)
Steven Aoki, Associate Administrator and Deputy Under Secretary for Counterterrorism (NA-80)
Jay Tilden, Director, Office of Nuclear Threat Science (NA-82)
Kathleen Alexander, Director, Interagency Work Programs (NA-10.1)

Los Alamos National Laboratory

Charles F. (Charlie) McMillan, Director
Brett Knapp, Principal Associate Director for Weapons Programs
Alan Bishop, Principal Associate Director for Science, Technology and Engineering

Sandia National Laboratories

Paul Hommert, President and Laboratories Director
Jerry L. McDowell, Deputy Laboratories Director and Executive Vice President for National Security Programs
Stephen Rottler, Chief Technology Officer, Vice President of Science and Technology
Bruce C. Walker, Vice President, Weapons Engineering and Product Realization, Chief Engineer for Nuclear Weapons

Lawrence Livermore National Laboratory

Penrose "Parney" C. Albright, Director
Bruce Goodwin, Principal Associate Director for Weapons and Complex Integration
Bill Goldstein, Deputy Director for Science and Technology
Dona Crawford, Associate Director for Computation

LABORATORY SCIENTISTS AND ENGINEERS

Carol Adkins (SNL)
Hans Aichlmayr (LLNL)
Robert Aikin (LANL)
Brian Albright (LANL)
Patrick Allen (LLNL)
Andrew Allerman (SNL)
Mark Anderson (LANL)
Athanasios “Tom” Arsenlis (LLNL)
Teresa Bailey (LLNL)
Bryan Balazs (LLNL)
William Ballard (SNL)
Charles Barbour (SNL)
Edward Barnat (SNL)
Nathan Barton (LANL)
Eric Bauer (LANL)
Joseph Bauer (LLNL)
Jonathan Belof (LLNL)
John Benner (LANL)
Michael Bernardin (LANL)
Irene Beyerlein (LANL)
Stephen Birdsell (LANL)
Brad Boyce (SNL)
Patrick Brantley (LLNL)
Todd Bredeweg (LANL)
Thomas Brunner (LLNL)
Kimberly Budil (LLNL)
Debra Callahan (LLNL)
Geoffrey Campbell (LLNL)
Robert Canaan (LLNL)
Bruce Carlsten (LANL)
John Castor (LLNL)
Robert Cauble (LLNL)
Ellen Cerreta (LANL)
Mark Chadwick (LANL)
Becky Chamberlain (LANL)
Ricky Chau (LLNL)
David Chavez (LANL)
Wendy Cieslak (SNL)
David L. Clark (LANL)
Mathew Cleveland (LLNL)
Patrick Colestock (LANL)
Gilbert Collins (LLNL)
Jeffrey Connors (LLNL)
Andrew Cook (LLNL)
Christine Coverdale (SNL)
William Craig (LLNL)
Mary Crawford (SNL)
Patricia Crossno (SNL)
Paul Demange (LLNL)
Darcie Dennis-Koller (LANL)
John Densmore (LLNL)
Michael Desjarlais (SNL)
Bronis de Supinski (LLNL)
Lori Diachin (LLNL)
Shawn Dirk (SNL)
Paul Dodd (SNL)
Paul Dotson (LANL)
Erik Draeger (LLNL)
Michael Dunning (LLNL)
Michael Edwards (LLNL)
Matt Eichenfield (SNL)
Robert Falgout (LLNL)
Juan Fernandez (LANL)
Timothy Flanagan (SNL)
Dawn Flicker (SNL)
Michael Fluss (LLNL)
Franz Freibert (LANL)
Chris Freyer (LANL)
Laurence Fried (LLNL)
David Funk (LANL)
Gil Gallegos (LLNL)
G. Todd Gamblin (LLNL)
Vladimir Georgevich (LLNL)
Timothy Germann (LANL)
Robert Gilbertson (LANL)
Libby Glascoe (LLNL)
S. Gail Glendinning (LLNL)
Nir Goldman (LLNL)
Robert Gore (LANL)
Julie Marisa Gostic (LLNL)
Dana Goto (LLNL)
Frank Graziani (LLNL)
George “Rusty” Gray (LANL)
Jeffrey Greathouse (SNL)
Katrina Groth (SNL)
Daniel Guildenbecher (SNL)
Richard Gustavsen (LANL)
Joyce Guzik (LANL)
James Hammer (LLNL)
Alex Hamza (LLNL)
Stephanie Hansen (SNL)
Eric Harding (SNL)
David Harris (LANL)
Robert Heeter (LLNL)
Gilbert Herrera (SNL)
Hans Herrmann(LANL)
Denise Hinkel (LLNL)
Jeffrey Hittinger (LLNL)

Robert Hoekstra (SNL)
Nelson Hoffman(LANL)
Michael Holmes (SNL)
Daniel Hooks (LANL)
Kevin Horn (SNL)
Richard Hornung (LLNL)
Juliana Hsu (LLNL)
Yalin Hu (SNL)
Aimee Hungerford (LANL)
Omar Hurricane (LLNL)
Carlos Iglesias (LLNL)
David Jablonski (LANL)
Quanxi Jia (LANL)
Justine Johannes (SNL)
Bryan Johnson (LLNL)
Paul Johnson (LANL)
Byung-Il Jun (LLNL)
Ian Karlin (LLNL)
Rick Kellogg (SNL)
Jacqueline Kenneally (LLNL)
Robert Kirkwood (LLNL)
John Kline (LANL)
Marcus Knudson (SNL)
Barbara Kornblum (LLNL)
Andrea Kritcher (LLNL)
Mukul Kumar (LLNL)
Adam Kunen (LLNL)
I-Feng W. Kuo (LLNL)
George Kyrala (LANL)
Matthew Lane (SNL)
Brian Lansrud-Lopez (LANL)
Stephen Lee (LANL)
Robert Leland (SNL)
Sen-ben Liao (LLNL)
Stephen Libby (LLNL)
Robert (Bob) Little (LANL)
Leonard Lorence (SNL)
Robert Lowrie (LANL)
Thomas Luu (LLNL)
Stephan MacLaren (LLNL)
Scott Manwaring (SNL)
Michael Marinak (LLNL)
Richard Martin (LANL)
Ann Mattsson (SNL)
Keith Matzen (SNL)
Thomas McAbee (LLNL)
Rose McCallen (LLNL)
Michel McCoy (LLNL)
Steven McCready (LANL)
William McLean, II (LLNL)
Dennis McNabb (LLNL)
Douglas Medlin (SNL)
Nathan Meezan (LLNL)
James Mercer-Smith (LANL)
Brad Meyer (LANL)
Charles Mielke (LANL)
Aaron Miles (LLNL)
Dennis Miller (SNL)
Paul Miller (LLNL)
Russ Miller (SNL)
Kyran (Kim) Mish (SNL)
Kathryn Mohror (LLNL)
Lisa Mondy (SNL)
David Montgomery (LANL)
Christopher Morris (LANL)
Michael Murillo (LANL)
Charles Nakhleh (SNL)
J. Rob Neely (LLNL)
Albert Nichols (LLNL)
Cynthia Nitta (LLNL)
Paul Nowak (LLNL)
K. Henry O'Brien (LLNL)
Daniel Orlikowski (LLNL)
Ivan Otero (LLNL)
James Owen (LANL)
Hye-Sook Park (LLNL)
J. "Reed" Patterson (LLNL)
Robert Paulsen (SNL)
Luc Peterson (LLNL)
Julie Phillips (SNL)
Desmond Pilkington (LLNL)
Jesse Pino (LLNL)
Christopher Plechaty (LLNL)
Dean Preston (LANL)
William Priedhorsky (LANL)
Brian Pudliner (LLNL)
Peter Raboin (LLNL)
Kumar Raman (LLNL)
Peter Rambo (LLNL)
Rekha Rao (SNL)
James Rathkopf (LANL)
Jonathan Rau (LANL)
Bryan Reed (LLNL)
Bruce Remington (LLNL)
William Rider (SNL)
Robert Rieben (LLNL)
Paulo Rigg (LANL)
Allen Roach (SNL)
Christine Roberts (SNL)
Don Roberts (LLNL)
Reina Romo (LLNL)
Robert Rudd (LLNL)

Brian Ryujin (LLNL)
Gary Sanders (SNL)
Joe Satcher (LLNL)
Didier Saumon (LANL)
Kurt Schoenberg (LANL)
Jacob Schroder (LLNL)
P. Randall Schunk (SNL)
Adam Schwartz (LLNL)
Eric Schwegler (LLNL)
Joseph Sefcik (LLNL)
Brandon Seilhan (LLNL)
Clifford Shang (LLNL)
Dawn Shaughnessy (LLNL)
Daniel Sinars (SNL)
Lucas Snyder (LLNL)
Christopher Spadaccini (LLNL)
Krista Stalsberg-Zarling (LANL)
Liam Stanton (LLNL)
Stephen Sterbenz (LANL)
Philip Sterne (LLNL)
Linda Stuart (LLNL)
Ganapathi Subramania (SNL)
Kyle Sullivan (LLNL)
Fritz Swenson (LLNL)
David Teter (LANL)
Heidi Thornquist (SNL)
D. Ray Tolar (LLNL)
Mark Ulitsky (LLNL)
Angel Urbina (SNL)
Nenad Valisavljevic (LANL)
Charles Verdon (LLNL)
Gary Dean Wall (LANL)
Bradley Wallin (LLNL)
William Wampler (SNL)
Alan Szu-hsin Wan (LLNL)
David Ward (LLNL)
Steve Weber (LLNL)
Robert Webster (LANL)
Christopher Weinberger (SNL)
Heather Whitley (LLNL)
Gregory Wickstrom (SNL)
Larry Wiley (LLNL)
Brian Wilson (LLNL)
Michael Wong (SNL)
Jonathan Workman (LANL)
Matthew Wraith (LLNL)
Frederick Wysocki (LANL)
Nancy Yang (SNL)
Lin Yin (LANL)
Michael Zika (LLNL)

C

Topics Discussed at Laboratory Meetings

TOPICS DISCUSSED AT LOS ALAMOS NATIONAL LABORATORY

- Materials at extreme conditions
  - — Condensed matter
  - — Materials activities
- Radiation transport
- High energy density science
  - — Warm dense matter
  - — Dense plasmas
- Materials physics and chemistry and engineering issues
- Computation, computer science, modeling and simulation
  - — Current codes
    - ▪ Current physics and algorithms
  - — Verification and validation approaches and results
  - — Career issues
    - ▪ Early career and post-docs
    - ▪ Students
  - — New physics under development for production
  - — New algorithms under development for production
  - — Computing requirements and out year plans

TOPICS DISCUSSED AT SANDIA NATIONAL LABORATORIES

- Radiation effects and high energy density science
- Materials science, and nanodevices and microsystems
- Engineering sciences, and computer and information science
- Major facilities for nuclear weapons research
- MESA, Z-Pinch and environmental test facilities
- Weapons engineering and product realization
- Systems engineering and stockpile modernization overview
- Plutonium aging
- Weapons aging – annual assessment
- Advanced systems and the 120 day study
- LDRD program overview: LDRD impact on NW mission
- Weapons engineering and product realization
- Computation, computer science, modeling and simulation
  - — Impact of advanced computing at Sandia on national security
  - — Sandia's vision and strategy for computing science

— Production software and computer science research
— Verification, validation and uncertainty quantification
— Early career staff and post-docs
— Computer and information sciences/materials sciences, engineering science
— Physical models for research to impact

- Poster session topics
  — Exploring formal verification methodology for FPGA-based digital systems
  — New coatings for MEMS-based sensors for enhanced surveillance
  — Nonresonant broadband funneling of light via ultrasubwavelength channels
  — Use of limited data to construct Bayesian networks for probabilistic risk assessment
  — Richtymer-Meshkov instabilities in cylindrical and planar geometries on Z
  — Using magnetic fields to create and control high energy density matter
  — Development of ab initio techniques critical for science-based explosives research and development

TOPICS DISCUSSED AT LAWRENCE LIVERMORE NATIONAL LABORATORY

- Materials physics and chemistry, and engineering issues
- Materials at extreme conditions
  — Condensed matter
  — Materials activities
- High energy density science
  — Warm dense matter
  — Dense plasmas
- Radiation hydrodynamics
- Weapon design topics
  — Life extension programs
  — Improvised nuclear devices assessment
  — Nuclear weapons leadership
  — Internal metrics and quality
  — Connections to basic science
  — PMP, PVS, Safety Suite, and Advanced Simulation and Computing
  — National Boost Initiative
  — Workforce issues
    - Special topics for junior designers
- Computation, computer science, modeling and simulation
  — Mod/sim overview
  — Design codes
  — Science codes
  — Verification and validation
  — Requirements/plans
  — Design codes
    - Verification and validation
  — Science codes
  — Advanced algorithms, advanced architectures
  — Post-docs and early career S&Es
- Poster session topics
  — Optical temperature diagnostics for flames and detonation events
  — A new approach in dynamic compression equation of state

— Measurements utilizing transparent crystals
— Small-scale experiments for predicting and validating thermal explosion phenomena
— Development of a many-body semi-empirical local basis set approach for materials under extreme conditions
— How shocks change the hydrodynamic mixing of inertial confinement fusion capsules
— HYDRA simulations of recent collisionless shock
— Experiments performed on OMEGA
— Measuring the $^{239}Pu(n,f)/^{235}U(n,f)$ cross section ratio with the NIFFTE time projection chamber
— Measuring the alpha to spontaneous fission decay
— Branching ration of ^{252}Cf with a time projection chamber
— Direct numerical simulations of structure and transport in dense plasmas

D

Summary of the Phase I Report of this Study

The three national security laboratories—Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), and Lawrence Livermore National Laboratory (LLNL)—are managed by private sector entities under contract to the National Nuclear Security Administration (NNSA). The fiscal year (FY) 2010 Defense Authorization Act mandated that NNSA task the National Research Council (NRC) to study the quality and management of science and engineering (S&E) at these laboratories. Specifically, NRC was tasked to address for each laboratory:

1. The quality of the scientific research being conducted at the laboratory, including research with respect to weapons science, nonproliferation, energy, and basic science.
2. The quality of the engineering being conducted at the laboratory.
3. The criteria used to assess the quality of scientific research and engineering being conducted at the laboratory.
4. The relationship between the quality of the science and engineering at the laboratory and the contract for managing and operating the laboratory.
5. The management of work conducted by the laboratory for entities other than the Department of Energy, including academic institutions and other federal agencies, and interactions between the laboratory and such entities.

This study is being conducted in two phases. This report covers the first phase, which addresses tasks (4) and (5) and partially addresses task (3): roughly speaking, how management at all levels affects the quality of the science and engineering (S&E) at the three laboratories. The study's second phase will evaluate the actual quality of S&E in key subject areas.

"Quality of S&E" measures the expertise and accomplishments in those areas of science and engineering that are necessary to accomplish the laboratories' missions. "Quality of the management of S&E" measures management's capability to build, maintain and nurture S&E expertise for current and future mission needs. The S&E performed by any laboratory can only be as good as the people employed. Thus, ensuring that high-quality people are attracted to the NNSA national security laboratories, and that they are retained, is a necessary condition for the laboratories to carry out high-quality S&E. Assuming that foundation is available, high-quality S&E then requires good facilities and adequate resources, and operating processes that do not impede the ability of those scientists and engineers to perform at their highest levels. Management controls these conditions, and this report evaluates the quality of the laboratories' management, at all levels, by its success in providing these prerequisites for high-quality S&E. Management includes government (primarily NNSA and its three site offices), the management and operations (M&O) contractors, and on-site laboratory management.

Because of this high-level view of management's role with respect to the quality of S&E, the study committee saw no distinction between management of the laboratories' work for NNSA (roughly, Task 4) and their work for other entities (Task 5). Therefore, the discussion and recommendations in this report generally apply to the laboratories' S&E work across the board.

NOTE: Summary reprinted from National Research Council, *Managing for High-Quality Science and Engineering at the NNSA National Security Laboratories,* The National Academies Press, Washington, D.C., 2013, pp. 1-5.

Each of these laboratories is a federally funded research and development center (FFRDC) operated for NNSA under a government-owned/contractor-operated (GOCO) relationship. This contracting mechanism allows the government access to the capabilities and knowledge of industry and universities to manage these technically complex institutions. Contracting relationships for some FFRDCs—in particular LLNL and LANL—have endured for many decades. In 2004, Congress mandated that the long-standing contracts with the University of California to manage LLNL and LANL be re-competed.[2] As a result, these two M&O contracts were awarded to two independent LLCs that both include Bechtel Corporation and the University of California.[3] Subsequently, a number of current and former employees of these laboratories have expressed concerns about deterioration of morale at the laboratories along with ongoing or potential declines in the quality of science and engineering. Many of those employees attributed those inferred trends to the new M&O contracts and contractors.

To carry out this study, the study committee met with congressional staffers, senior leadership of NNSA and the Department of Energy, staff from the NNSA site offices that serve as a vital link between NNSA and day-to-day laboratory management, and a wide variety of former and current employees of the three laboratories. It held site visits at each of the laboratories, organized around panel discussions with a large number of employees at different levels, from bench scientists to senior management. The study committee controlled the agendas for all of its meetings and had final say on the list of speakers. At LANL and LLNL, the study committee also held well-advertised public sessions at which anyone was invited to speak and management was voluntarily absent. The study committee also examined past reports on the laboratories and the language of the current contracts. Details of the study processes are included in Chapter 1 of this report.

While the new contracts at LANL and LLNL clearly produced a noticeable level of staff frustration, staff members with whom the study committee interacted continued to show a strong commitment to their work. Those who testified to the study committee about morale problems spoke primarily of the situation as it existed at the time of the contract transitions, or of the subsequent layoffs at LLNL. When the study committee examined the M&O contracts, it found very little that prescribes the management of S&E. Many of the bureaucratic frustrations raised at all levels appear to be either within the power of the laboratories to address or driven by governance strategies above the laboratory level: they are not traceable to the M&O contractor or the contracts themselves. It is indeed true that all three laboratories have been under cost and funding pressure. In the case of LANL and LLNL that pressure is connected with the contract change; the costs of their re-competed contracts are significantly greater than the previous contracting arrangements. But this is due to the combined effect of increased contractor fees, pension obligations, and, in the case of LANL, a need to now pay New Mexico state taxes. Accounts that attribute the increased cost simply to award fees are not accurate. Some employees and stakeholders have been concerned that M&O contractors pursuing a fee might not act in the public interest, and this is an important issue. Therefore, the study committee discussed incentives with the three laboratory directors and was convinced that their primary objective remains to manage the laboratories in the public interest.

An evolution of the laboratory missions to "national security laboratories" is well underway. The absence of nuclear testing means that experimental validation of much of the S&E performed by the laboratories is not possible, and thereby lessening the intellectual attractiveness of the work for at least some prospective employees. The expansion of the laboratories' mission into new non-nuclear areas offers the prospect of increasing the laboratories' appeal to top-quality scientists and engineers while also serving important national security missions. Thus, the quality of S&E, being preconditioned on attracting high-quality people, depends in the long run on successfully making this transition to national security laboratories. It is for this reason that the study committee was pleased to see that, a governance charter has been established among the Departments of Energy,

[2] U.S. Congress, H. Rpt. 108-292, Division C-Energy and Water Appropriations Act, 2005, Sec. 301, p. 151, November 2004. The new M&O contractor for LANL took over in 2006, and the new contractor for LLNL began work in 2007.

[3] The parent organizations of Los Alamos National Security (LANS) are the University of California, Bechtel, Babcock and Wilcox, and URS. For Lawrence Livermore National Security (LLNS), the parent organizations consist of the same four plus Battelle.

Homeland Security, and Defense, plus the Office of the Director of National Intelligence.[4] Many of the challenges facing these agencies are synergistic with the capabilities of these NNSA laboratories, and they can, and do, benefit from the large investments that NNSA and its predecessors have made in S&E capabilities. In a time of constrained budgets, broadening the mandate to a national security mission helps preserve S&E expertise by providing opportunities to work on problems posed by partner agencies. However, while such Work for Others (WFO) is very important for the future of S&E at the laboratories, all three of the laboratory directors were very clear that maintenance of the nuclear weapons stockpile remains the core mission of the laboratories.

Recommendation 3.1.[5] The study committee recommends that Congress recognize that maintenance of the stockpile remains the core mission of the laboratories, and in that context consider endorsing and supporting in some way the evolution of the NNSA laboratories to national security laboratories as described in the July 2010 four-agency Governance Charter for an Interagency Council on the Strategic Capability of DOE national laboratories.

A crucial part of the laboratories' ability to conduct their missions is derived from Laboratory Directed Research and Development (LDRD), the primary source for internally directed R&D funding. Among its other benefits, LDRD provides a major resource for supporting and training staff at each laboratory.

Recommendation 3.2. The study committee recommends that Congress and NNSA maintain strong support of the LDRD program as it is an essential component of enabling the long-term viability of the laboratories.

Historically, laboratories had another source of discretionary research spending. The weapons program (at each laboratory) had the flexibility to use part of its budget to fund a robust research program, in support of the core weapons mission. Currently, the weapons program budget is subdivided into so many categories with so many restrictions that this important flexibility is effectively lost. This loss in funding flexibility has significantly reduced the amount of core program research being performed at the laboratories. This lessens the appeal of the laboratories when recruiting scientists and engineers.

Recommendation 3.3. The study committee recommends that Congress reduce the number of restrictive budget reporting categories in the Nuclear Weapons Program and permit the use of such funds to support a robust core weapons research program and further develop necessary S&E capability.

In the view of this committee, the relationship between NNSA and its national security laboratories is broken to an extent that very seriously affects the laboratories' capability to manage for quality S&E. There has been a breakdown of trust and an erosion of the partnering between the laboratories and NNSA to solve complex S&E problems; there is conflict and confusion over management roles and responsibilities of organizations and individuals. For example, the study committee heard reports of mid-level issues being elevated to the laboratory director level because there was no clarity about how to resolve disputes between a laboratory and an NNSA Site Office. Another example was a recent instance in which NNSA HQ tried to overrule a laboratory's best scientific judgment about how to carry out a scientific task. Subsequently, language appeared in a congressional report opposing that NNSA order. A better mechanism could be established for resolving technical disputes, without elevating them to top NNSA management and congressional levels. A technical advisory committee, established at the NNSA level, would be a helpful mechanism for filling this gap in S&E management. More generally, such an advisory committee could monitor progress on other aspects of roles and responsibilities, as described next.

Erosion of trust on both sides of the relationship shapes the oversight and operation of the laboratories, resulting in excessive bureaucracy governing laboratory activities at a deep level of detail, including the conduct of S&E. The study committee observed widespread perception among laboratory S&E staff and some managers that NNSA oversight activities were inconsistent with statements by NNSA that oversight

[4] See Appendix A.
[5] The first number refers to the chapter of the report in which the recommendation appears.

is accomplished without being intrusive; i.e., "eyes on, hands off." The study committee was repeatedly told that oversight officials frequently blur the line between oversight and evaluation and insert themselves in an operational role. This problem was reported to occur in many aspects of laboratory activities.

This erosion of the trust relationship is prominent with respect to LANL, where past failures in safety, security, and business practices attracted much national attention and public criticism. But it has also spilled over to LLNL and SNL. The loss of trust in the ability of the laboratories to maintain operational goals such as safety, security, environmental responsibility and fiscal integrity has produced detailed scrutiny by NNSA HQ and site offices and increased aversion to risk. A major byproduct of this has been to create a bias against experimental work, because of the onerous processes sometimes required before running an experiment. The bias is problematic because experimental science is at the very heart of the scientific method.

The FFRDC relationship is based on a partnership between the Federal government and a laboratory in which the government decides what problems need to be addressed and the contractor determines how best to address those problems. There is a perception among S&E staff and managers at the three laboratories that NNSA has moved from partnering with the laboratories to solve scientific and engineering problems, to assigning tasks and specific S&E solutions with detailed implementation instructions. This approach precludes taking full advantage of the intellectual and management skills that taxpayer dollars have purchased. The study committee found similar issues in transactional oversight of safety, business, security and operations. Science and engineering quality is at risk when laboratory scientists and engineers are not encouraged to bring forth their creative ideas in partnership with NNSA to solve problems vital to our national security.

Recommendation 4.1. The study committee recommends that NNSA and each of the laboratories commit to the goal of rebalancing the managerial and governance relationship to build in a higher level of trust in program execution and laboratory operations in general.

Recommendation 4.2. The study committee recommends that NNSA and the laboratories agree on a set of principles that clearly lay out the boundaries and roles of each management structure, and also that program managers at headquarters, the Site Offices, and in the laboratories be directed to abide by these principles.

For example, the site manager and the director and/or deputy director of each laboratory could establish, in consultation with other laboratory staff, a process to identify and agree on eliminating certain oversight procedures that are not necessary or related to the overall goals of the laboratory. Similarly, some mechanism could be established to filter program taskings at both the headquarters level and at the laboratory senior management level to assure that each tasking is necessary and consistent with the agreed management principles.

Recommendation 4.3. The study committee recommends that the goal of rebalancing the relationship and the set of principles laying out the boundaries and roles of each management structure be memorialized in memoranda of understanding between NNSA and its laboratories. NNSA should assess performance against these understandings on an annual basis over a five-year period and report these assessments to Congress.[6]

A key to ongoing laboratory success has been a strong focus on the long term and on maintaining deep technical capability. Under the new management structure of the laboratories, industrial and other private sector partners can help assure that this long-term focus is maintained.

Recommendation 5.1. The study committee recommends that the NNSA, Congress, and top management of the laboratories recognize that safety and security systems at the laboratories have been strengthened to the point where they no longer need special attention. NNSA and laboratory

[6] The committee observes that it is important to design this approach to be self-correcting and to avoid problems such as: (1) adding to a check-list approach to management; (2) enforcing measures that annual assessment shows to be unworkable; and (3) requiring congressional intervention when not needed.

management should explore ways by which the administrative, safety, and security costs can be reduced, so that they not impose an excessive burden on essential S&E activities.

Recommendation 5.2. The study committee recommends that NNSA reduce reporting and administrative burdens on the laboratory directors, and purposely free directors to establish strategic science and engineering direction at the laboratories.

Among other benefits, this may encourage laboratory directors to serve longer terms with the organization.