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The
Los Alamos,
Sandia,
and
Livermore
Laboratories

Integration and Collaboration...
Solving Science and Technology Problems for the Nation

Livermore
(July 6, 1994)

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Preface

The Department of Energy national security laboratories have, for more than half a century, provided the science and technology to ensure that America's nuclear weapons meet the highest standards of performance and safety. The laboratories' multidisciplinary, multiprogram approach has been extremely successful at solving complex technical problems of national importance. Now, the future of these three laboratories—Los Alamos, Sandia, and Livermore—is being examined with a post-Cold War perspective.

To assist in that examination, I asked that a document providing important information about the laboratories' accomplishments and operating principles be prepared to help me in my responsibility for overseeing the work done at these laboratories and for ensuring the future health and vitality of their programs and facilities. This report concentrates on the integrated nature of the three laboratories and is a first step in planning their future. It does not tackle the broad policy questions of the U.S. government–national laboratory relation, which will be addressed in a subsequent report.

The nation's science and technology needs are many and wide ranging. The challenge facing us today is to determine how best to match the unique capabilities of Department of Energy national security laboratories to national needs.

National security will continue to be the primary mission of these laboratories. At this time, the nation is dramatically reducing its nuclear stockpile, and no new nuclear weapons are in development or production. As a result, the laboratories' expertise in nuclear science and technology is being applied to reducing the nuclear danger, principally through stockpile stewardship, stockpile and nuclear materials management, and nonproliferation and counterproliferation.

Other missions of national importance have also been proposed for Los Alamos, Sandia, and Livermore, including environmental remediation and pollution prevention, genetics and health care technologies, information management and infrastructure (e.g., the information superhighway), and energy (e.g., developing fusion energy for power production). These endeavors are highly interrelated and interdependent. They all require high-performance computing, new methods of information management, advanced materials, sophisticated sensors and instrumentation, and an in-depth understanding of fundamental science.

More than any one device or innovation, the real value of the three national security laboratories is their broad base of science and technology expertise. It is essential that this expertise be preserved and extended, that the laboratories continue their world leadership in science and technology. National security depends on the laboratories' expertise, facilities, and long-term commitment to tackle the high-risk, high-payoff projects that ensure that the nation's future science and technology problems will be solved.

Many people at the Los Alamos, Sandia, and Livermore laboratories contributed historical and technical information. Although they cannot be individually acknowledged, their efforts were essential to the preparation of this document.

I would like to extend to all readers an invitation to comment on any and all aspects of this report.

Victor H. Reis
Assistant Secretary for Defense Programs
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I. Overview

More than 40 years ago, three laboratories were established to take on scientific responsibility for the nation's nuclear weapons—Los Alamos, Sandia, and Livermore. This triad of laboratories has provided the state-of-the-art science and technology to create America's nuclear deterrent and to ensure that the weapons are safe, secure, and reliable. These national security laboratories carried out their responsibilities through intense efforts involving almost every field of science, engineering, and technology. Today, they are recognized as three of the world's premier research and development laboratories.

Throughout their history, Los Alamos, Sandia, and Livermore have worked together to produce integrated nuclear weapon systems, and the cooperation and collaboration that have been so effective in weapons work have carried over to the laboratories' civilian programs. The civilian programs have built upon and, in turn, have enriched the laboratories' core technical competencies.

Even with the end of the Cold War, it is clear that, for the foreseeable future, the U.S. will retain a nuclear stockpile, albeit much reduced from previous years. The safety and reliability of this stockpile must be ensured. Stewardship of the enduring stockpile will require that Los Alamos, Sandia, and Livermore retain the knowledge base and capabilities that are unique to nuclear weapons and vital for assessing nuclear weapons issues. In planning for these responsibilities, an important consideration is the peer review and technical critique that the laboratories provide one another—a crucial aspect of the quality assurance that is essential under the current moratorium on nuclear testing.

The U.S.–Soviet arms race may be over, but new nuclear dangers abound. Of gravest concern is the specter of nuclear proliferation and, indeed, the proliferation of all weapons of mass destruction. Recent events illustrate the extent of this threat—Iraq's secret nuclear weapons program, China's nuclear tests, North Korea's resistance to international inspections of its nuclear facilities. There are also grave concerns about the security of nuclear materials in Russia and other states of the former Soviet Union. Safeguarding, stabilizing, storing, and eventually disposing of these materials will require new technologies and unprecedented international cooperation. In addition, the nuclear weapons expertise of the three national security laboratories will be invaluable to U.S. efforts to discourage countries from developing weapons of mass destruction, to detect and evaluate the activities and capabilities of potential proliferants, and, if need be, to negate the efforts of a proliferant nation.

However, the end of the Cold War and the arms race does give the laboratories the opportunity to apply their scientific and technological expertise to other national needs. Innovative technologies, processes, and products are needed to enable the nation to compete successfully in the global marketplace. Recent legislation enhances the laboratories' abilities to assist U.S. industry and business—transferring laboratory-developed technologies, working together on mutually beneficial projects, collaborating on far-reaching research to achieve technological breakthroughs. The laboratories have entered into hundreds of technology-transfer agreements, many of which have already paid significant dividends and others that are in their early stages. Although we cannot forecast which efforts will make the greatest contributions, it is clear that all of these interactions greatly benefit all involved—U.S. industry, the three laboratories, and the nation.

Here we sketch the history of the laboratories and their evolution to an integrated three-laboratory system. We describe the characteristics that make them unique and highlight some of the major contributions they have made over the years. Our goal is that, with an understanding of the laboratories' heritage and their many achievements, policy-makers will be able to evaluate current and future opportunities for the three laboratories so they can continue to meet the science and technology needs of the nation.

II. A Brief History of the Laboratories

The Los Alamos laboratory was established for the Manhattan Project—the urgent World War II effort to develop atomic (fission) weapons before Hitler's scientists could. The Sandia laboratory was established in 1948 as a branch of the Los Alamos laboratory to integrate the nuclear explosive "packages" into deliverable weapon systems; a year later, Sandia was split off as a separate laboratory. The Livermore laboratory was created in 1952 to pursue weapon designs, in particular thermonuclear (fusion) weapons, different from those being developed at Los Alamos, and the Livermore branch of Sandia was established in 1956.

Through their nuclear weapons work—design, production, testing, surveillance, and the study of weapon effects—the laboratories have pushed the frontiers of virtually every area of science, from atomic and nuclear physics, to computing and numerical simulation, to advanced materials and precision fabrication, to remote sensors and miniaturized electronics, and even human genetics and environmental science.

Today, Los Alamos, Sandia, and Livermore operate as a system of multidisciplinary, multiprogram laboratories, carrying out their nuclear weapon responsibilities and conducting a wide variety of civilian programs. Taken together, the laboratories possess a collection of experimental facilities that is unequaled anywhere in the world. The combination of cutting-edge science and world-class facilities, applied to problems of national and even global importance, has allowed the laboratories to attract and retain an extraordinarily talented and innovative staff.

Competition, Cooperation, and Collaboration

The laboratories' interactions have evolved from competition—to secure new projects and facilities or to achieve scientific milestones—to cooperation—with the ready sharing of information, data, and facilities—to collaboration—where efforts are integrated from the outset to take advantage of each laboratory's areas of particular expertise and special facilities. In the early years, accomplishments often leapfrogged one over the other, with one laboratory's advances building on the achievements of another. As the technical issues to be investigated became increasingly complex and the necessary experimental facilities became more unique and more costly, competition gave way to cooperation and collaboration.

This combination of intellectual competition, cooperation, and collaboration in the highly specialized field of nuclear weapon science and technology has been central to the laboratories' success. Three principal benefits result from this three-laboratory complex:

• Peer review. The unique nature of nuclear weapons work precludes many of the peer review processes used in unclassified research. The two nuclear design laboratories—Los Alamos and Livermore—provide each other with peer review of weapons physics understanding, data interpretation, design concepts, and computational modeling. Similar review occurs between the Albuquerque and Livermore branches of Sandia. Weapon safety issues are the most critical subject for such peer review. Historically, when a problem has developed with a stockpile weapon designed by one laboratory, another laboratory often has the technology or insight for an effective solution. Today, with the moratorium on nuclear testing and the absence of new weapon systems in development or certification, such interlaboratory cross-checking remains as crucial as ever.

• Complementary work. Each laboratory has developed a distinct "culture" and unique areas of expertise. In many projects, the laboratories are able to pursue different but complementary paths. For other projects, one laboratory may be better equipped than the others. The integrated program for stockpile stewardship (in which the various responsibilities are assigned according to particular laboratory expertise; described in greater detail on pages 11 and 12) takes advantage of these differences among the three laboratories.

• Diverse facilities and capabilities. Many of the facilities available at the laboratories are one of a kind and world-class. The laboratories (as well as universities and other research institutions) share the use of these facilities, thereby avoiding unnecessary and costly duplication. The diversity of facilities available to the three laboratories is many times greater (at lower cost) than if each lab had to have "one of its own."

Innovative Management for the Laboratories

The original Manhattan Project management evolved into the Atomic Energy Commission (AEC). The AEC oversaw the three weapons laboratories from 1947 until it was dissolved in 1974. The Energy Research and Development Administration (ERDA) then took on responsibility for the laboratories. In 1977, ERDA was transformed into the Department of Energy.

An important factor in the excellence of the laboratories is the government-owned, contractor-operated (GOCO) management approach—a bold new concept when Los Alamos was created. The GOCO approach allows the government—the Department of Energy—to direct what work is to be done, while giving the contractors considerable leeway in managing the laboratories and allowing the laboratories to choose the best ways to do the work.

This management approach has been so successful that, among their recommendations, the Federal Advisory Commission on Consolidation and Conversion of Defense Research and Development Laboratories concluded that "Conversion of some or all of the [Defense Department] laboratories to government-owned, contractor-operated organizations could improve their effectiveness" (report of the Commission to the Secretary of Defense, September 1991, p. 27).

The University of California

In 1943, the University of California agreed to manage the Los Alamos laboratory and, in 1952, took on the same role for the Livermore laboratory. The Regents of the University accepted the responsibility as a service to the nation.

Affiliation of the Los Alamos and Livermore laboratories with the University of California, and in particular with E. O. Lawrence, has had profound effects on both institutions. Lawrence recognized the importance of combining scientists and engineers in integrated research teams to tackle large, complex projects. He used this approach with great success with his cyclotron projects at the University of California at Berkeley; the Livermore laboratory was set up along these lines from its inception.

Association with the University of California has:

• Created and fostered an academic-style environment of intellectual freedom and a dedication to scientific excellence.

• Set the highest standards for judging intellectual, scientific, and technological achievements.

• Facilitated the flow of ideas between the laboratories and the University of California campuses.

Today, in an era of increased scrutiny, by both the government and the public, and tight research budgets, association of the Los Alamos and Livermore laboratories with the University of California is more valuable than ever. The University's reputation for integrity and excellence enhances the laboratories, while the availability of laboratory experimental and computational facilities to outside researchers benefits the University.

AT&T and Martin Marietta

The selection of AT&T to manage Sandia was the result of an astute recognition that both industrial and scientific expertise would be required to turn nuclear device designs into militarily fieldable weapons. AT&T, with its parallel strengths in research and development and in manufacturing (as represented, respectively, by the Bell Telephone Laboratories and the Western Electric Company), was ideally qualified. Like the University of California, AT&T regarded management of Sandia as a service to the nation and received no compensation for this task.

AT&T brought its management structure, administrative procedures, and industrial practices to Sandia. The Director of Sandia usually came from Bell Laboratories, as did many other Sandia managers; similarly, senior Sandia personnel often did "tours of duty" at Bell Laboratories.

In 1991, AT&T determined that management of Sandia no longer fit with its long-range business plan, and the Department of Energy began the search for AT&T's successor. In 1993, Martin Marietta Corporation was selected as Sandia's new management contractor. (Martin Marietta and Lockheed recently announced their merger to form the Lockheed Martin Corporation, but this merger is not expected to affect the management and operation of Sandia.)

Martin Marietta brings to Sandia extensive experience in advancing and applying technology, from systems design and development, to manufacturing, testing, and operational integration. Martin Marietta is also widely respected for its cost-effective business practices and administrative systems. As it did with AT&T, Sandia will benefit from its association with Martin Marietta and its industrial expertise in turning ideas into products.

The Role of the Laboratories in the U.S. Nuclear Weapons Program

The Los Alamos, Sandia, and Livermore laboratories do much more for the nuclear weapons program than just research. The laboratories have end-to-end, concept-to-dismantlement responsibility for all U.S. nuclear weapon systems. These responsibilities include:

• The design and testing of nuclear weapons (although no new weapons are currently in design or production). In these efforts, the three laboratories worked closely with the Department of Defense and the military services to ensure that weapon designs met national security needs and with the Department of Energy's weapon production facilities to ensure that the weapon designs were fabricated into militarily useful hardware. The laboratories have been directed by the President to preserve the expertise and infrastructure for developing new weapons, should they be needed in the future. With the closure of a number of production facilities, the stockpile stewardship responsibilities of the laboratories are much more extensive now than they were in years past.

• Evaluating and ensuring the safety, security, and reliability of stockpiled weapons. Periodically, stockpile weapons (and stored weapon components) are disassembled, examined, and tested by the scientists and engineers who designed them. The purpose of these examinations is to identify age-related changes and to assess whether or not those changes affect the safety and performance of the weapon system. Stockpile surveillance will be a critical and continuing responsibility of the three laboratories for as long as the U.S. retains nuclear weapons.

• Assisting with the safe and secure dismantlement of nuclear weapons and the disposition and storage of weapon materials. In years past, the laboratories provided science and technology support for the weapons production complex. Today, weapon scientists and engineers oversee and assist in the dismantlement of the weapons they designed. Their intimate knowledge of how the weapons were designed and fabricated is invaluable, especially if something unexpected occurs. (Just such an incident happened in 1993, when a component of a Livermore-designed weapon cracked during dismantlement; the situation was readily contained. Livermore scientists determined the cause of the problem, and new procedures were developed to avert a future occurrence.) They help develop safe and secure procedures and techniques for disassembly and dismantlement and for the storage and disposal of weapon materials. Laboratory weapon scientists are also assisting with dismantlement and defense conversion efforts in the former Soviet Union. A collaborative program of nuclear materials protection, control, and accountability is being implemented to safeguard weapons materials from unauthorized access. Improved technologies for weapons transportation and dismantlement are also being implemented, and collaborative work on the design of storage facilities and methods for nuclear materials disposition is in progress.

The Los Alamos, Sandia, and Livermore laboratories also apply their nuclear weapons expertise to nonproliferation and counterproliferation efforts. In particular, they:

- Evaluate the nuclear weapon capabilities of other countries. During the Cold War years, the principal focus of this work was the Soviet Union. With the breakup of the Soviet Union and the reduction in U.S.–Soviet tensions, the laboratories have turned their attention to evaluating the activities and capabilities of potential proliferant states. They are also examining various technology options available to the U.S. for discouraging the proliferation of weapons of mass destruction, and for negating the efforts of a proliferant nation.

- Provide expertise and equipment to respond to nuclear emergencies worldwide. In their quest to ensure the safety and security of U.S. nuclear weapons, Los Alamos, Sandia, and Livermore have worked with the military services and other emergency response organizations to respond to accidents involving nuclear weapons. Various exercises have been staged to develop and test response procedures and equipment. Recently, the laboratories have become involved in providing accident-response equipment and training to Russia and the other nuclear-inheritor states of the former Soviet Union.

Partnerships with Industry

From the beginning of the nuclear era, Los Alamos, Sandia, and Livermore have worked directly with the production facilities that make the weapon materials and components and ultimately the weapons themselves. The AEC created a network of industrial contractors to manage the production facilities, where laboratory designs were turned into factory-produced components and weapon assemblies. Included in this network were giants of American industry and key contributors to the country's success in World War II—General Electric, DuPont, Union Carbide, Monsanto, and Bendix.

The laboratories and industrial contractors worked closely together to develop materials and components that met the stringent weapon requirements (e.g., extreme temperatures, accelerations, impacts). The laboratories had to ensure that the production plants could indeed produce their designs. Sometimes, designs required a level of precision (e.g., fit, finish) that was beyond current industry capabilities. In such cases, the laboratories developed new or improved manufacturing processes that were then transferred to the production facilities. The laboratories also worked directly with the manufacturers of the military delivery systems (e.g., missiles, aircraft, artillery shells) to ensure that the weapon would indeed be compatible with its intended delivery system.

As the laboratories' missions have expanded beyond nuclear weapons, they have continued to establish mutually beneficial working relationships with U.S. industry. In the past five years, Congress and the Department of Energy have specifically urged the laboratories to join with industry to commercialize existing laboratory-developed technologies and to invent new technologies that benefit both laboratory programs and industry. Recent legislation has been enacted to simplify and speed the establishment of cooperative research and development agreements (CRADAs), licensing agreements, memoranda of understanding, laboratory–industrial consortia, and other such collaborations. All told, the three laboratories have signed more than 400 of these agreements, spanning the spectrum of U.S. industry from small startup businesses to Fortune 500 companies.

Industry demand for partnerships with the laboratories currently outstrips laboratory resources available for the program. Clearly, industry recognizes the value of the laboratories' technologies and capabilities and the advantages that can be gained through collaboration.

Relations with Academia

The laboratories have long had extensive connections to academia. They sponsor programs to support faculty, post-doctoral, and student research, enhance the teaching of science and mathematics, and broaden the scientific and technical "literacy" of the general public. Los Alamos, Sandia, and Livermore host various summer workshops for faculty and students and numerous science-education activities for K–12 schools. In addition, laboratory staff frequently teach at nearby schools and universities.

The laboratories offer many research opportunities for university faculty and students, including joint university–laboratory projects, post-doctoral appointments, and Ph.D. thesis work. Post-doctoral appointments at Los Alamos, Sandia, and Livermore are eagerly sought by the most promising graduate students at U.S. universities: they are considered the "next step" for the best and the brightest. A number of joint university–laboratory institutes have been established. These institutes are tremendously valuable to the laboratories and the participating universities, providing the university researchers with access to world-class facilities and providing all participants with forums for the exchange of ideas and perspectives.

For decades, laboratory personnel have been involved, as individuals, in enhancing science and mathematics education at local schools. Many of these activities, often started as "traveling science shows," have been formalized and expanded. Programs for students have spun off workshops specifically for teachers, and many of those teachers have, with support from the laboratories, set up similar workshops in their own schools.

The laboratories work with school districts to develop customized curricula in science and technology—some districts have wanted to concentrate on biotechnology, others on environmental science, and still others on multimedia and information technology. The laboratories also participate in collaborations with other research institutions, universities, and high-tech industries and businesses. For example, Livermore and Sandia are participating in a regional collaboration to strengthen the science curricula of the Oakland public schools, while Los Alamos works with school systems in northern New Mexico.

A range of special-focus programs are available at the laboratories that assist hundreds of minority students each year. These programs provide valuable educational opportunities for promising students; they also help broaden the diversity of the future pool of qualified applicants for jobs in science, engineering, and mathematics.

Evolving Missions to Meet National Needs

In carrying out their national security mission, the Los Alamos, Sandia, and Livermore laboratories have created a pool of scientific and technical expertise that is truly outstanding. The laboratories' nuclear weapons work has spurred major inventions and technology breakthroughs that, in turn, have provided the basis for new areas of expertise and enabled the laboratories to address and solve important national problems. In their weapons work, the laboratories have vividly demonstrated the success of programmatic integration and interlaboratory collaboration, an approach that is proving equally successful in other areas of investigation. In the future, as in the past, the laboratories' expertise will continue to expand and evolve as their programs adjust to meet changing national needs.

III. A Half-Century of Meeting Defense Needs

For more than 50 years, the weapons laboratories have developed the technology that supports the nation's nuclear weapon stockpile. Over the years, they received Presidential authorization to design and develop more than 80 nuclear weapon systems (including major modifications to some designs). As the nation's defense strategies changed, so too did the military requirements for U.S. nuclear weapons. These requirements often entailed significant technical challenges; for example, reducing size and weight for a given yield, tailoring weapon output to produce specific effects, increasing safety and security, etc. The role of the Los Alamos, Sandia, and Livermore laboratories in the U.S. nuclear weapons program is described in Section II. Here we briefly describe the history of the weapons program and highlight significant accomplishments.

Genesis of the U.S. Nuclear Deterrent

The world's first nuclear explosion occurred with the Trinity test (July 16, 1945), designed and fielded for the Manhattan Project by the Los Alamos laboratory. This test confirmed the feasibility of producing a nuclear explosive using an implosion device to compress plutonium. The Manhattan Project also developed a gun-assembled device to produce a supercritical mass of enriched uranium. These two design approaches led to the first nuclear fission weapons (atomic bombs), Fat Man and Little Boy, that were used in August 1945 to end World War II.

In 1949, the Soviet Union startled the world with its first nuclear explosion. Tensions between the U.S. and the Soviet Union were high and rising still higher, and the nuclear arms race was on.

In 1951, Los Alamos demonstrated the first successful ignition of thermonuclear fuel, providing the physics basis for thermonuclear weapons (the hydrogen bombs). The first weapon-scale thermonuclear device was successfully tested in 1952. This test demonstrated the feasibility of using the fission process to drive the fusion process to attain very high yields. Measurements from this test provided key data for the subsequent development of thermonuclear weapons.

The Livermore laboratory was established in 1952 to pursue the development of thermonuclear weapons and to provide for intellectual competition. In response to military requirements (particularly for higher yield-to-weight ratios), Los Alamos and Livermore have built upon each other's discoveries and inventions, benefiting from each other's knowledge and data, spurring continued innovation, and pushing each other to ever higher levels of scientific and technical excellence.

For example, after testing the first implosion device in the Trinity event, Los Alamos continued to develop improved implosion systems and, in the course of that work, developed and demonstrated the boosting concepts that are now fundamental to all U.S. stockpile weapons. Shortly thereafter, Livermore demonstrated the feasibility of a more robust and reliable concept for the primary (or fission) stage that is now the design basis for all nuclear weapons in the U.S. stockpile. Los Alamos then designed and tested the first radiation-imploded secondary (or fusion) stage. A few years later, Livermore developed the design approach that forms the basis for all modern high yield-to-weight stockpile weapons. This leapfrog pattern of accomplishments became a hallmark of the Los Alamos and Livermore laboratories, as one built on the design successes of the other to solve increasingly complex problems to meet national needs.

Sandia was established, first as a branch of the Los Alamos laboratory, to develop the myriad nonnuclear components needed to integrate the Los Alamos and Livermore designs into militarily deliverable weapons. This weaponization process involves close interactions and teamwork with the design laboratories (Los Alamos or Livermore), the Department of Defense contractors, and the Department of Energy weapon production complex.

Sandia has developed many of the features that provide the high level of safety and security required for U.S. nuclear weapons. For example, Sandia devised a series of space- and weight-saving arming, fuzing, and firing systems for the warheads deployed on the Navy's Poseidon and Trident missiles. The culmination of this series of weapons is the W88, a highly integrated strategic system, that embodies the most modern safety and security features in a highly integrated and robust engineering design. Although such highly tuned designs allowed the U.S. to build much smaller delivery systems and greatly reduce the costs for our strategic systems, these designs do require a higher level of stewardship in order to ensure their reliable functioning.

Enhanced Safety and Security

The laboratories have made many ingenious advances to ensure the safety and security of U.S. nuclear weapons. Enhanced surety has been achieved through a combination of special design features of the nuclear package and sophisticated nonnuclear components.

Safety limits set in 1968 to ensure against accidental nuclear detonation specify that the probability of nuclear detonation must be no greater than one in a billion in normal environments and one in a million in accident situations. Extensive tests, modeling, and simulation of weapon materials and weapon components and their response to accident environments (e.g., high temperature, as in a fire, or impact, as from an airplane crash) were conducted to evaluate the weapons currently in the stockpile. The results of these tests identified the need for new design approaches to ensure safety.

The safety features that were developed (and are now standard in all modern nuclear weapons) include special packaging to exclude electrical energy from the explosive assembly, fail-safe critical components that become inoperable in a severe accident, and "strong link" safety switches that provide an accident-resistant, tamper-proof pathway for arming and firing. These safety features essentially eliminate the possibility of accidental nuclear detonation.

Despite the safety features to prevent nuclear yield, radioactive material could still be dispersed if a weapon's high explosive were to detonate accidentally. Therefore, the laboratories developed insensitive high explosives. These explosives, most of which are based on triaminotrinitrobenzene (TATB), are much less sensitive to sudden shocks and high temperatures than conventional high explosives and thus greatly reduce the likelihood of explosive detonation in an accident.

Another concern has been the dispersal of plutonium or uranium should a nuclear weapon be involved in a jet-fuel fire. Special fire-resistant components were designed to contain and prevent the dispersal of radioactive materials, even if the fire were to burn for hours.

The laboratories continue to devise new ways to enhance the safety and security of U.S. nuclear weapons. For example, an optical firing system is being developed as an alternative to electrical firing systems; such optical systems are insensitive to spurious electrical and optical pulses that could occur in an accident. This prototype system uses a compact, rugged laser and new methods for transmitting high-intensity light pulses through optical fibers to initiate an explosive detonator.

However, many of the weapon systems in the U.S. stockpile do not contain all of the modern safety and security features, having been designed and built before the various features were invented. As a result, in the end, the safety and security of U.S. nuclear weapons resides not in the weapons themselves but in the people responsible for their stewardship. Thus it is essential that the scientific and technical know-how unique to nuclear weapons—that is, the people expertise—be retained as long as the U.S. (and indeed the world) possesses nuclear weapons.

New Diagnostic Tools

In their quest to understand the fundamental physics of nuclear weapons, the laboratories have had to invent new diagnostic techniques and new experimental facilities so they could investigate previously unreachable phenomena under previously unattainable conditions. For example, to image the implosion of a nuclear device, Los Alamos and Livermore have become world leaders in the use of accelerators for dynamic radiography.

In 1963, Los Alamos began operation of the PHERMEX flash x-ray facility, which used rf accelerator technology to take radiographic snapshots of imploding primaries (in which nonnuclear material is substituted for the fissile material). In 1982, Livermore completed its Flash X-Ray (FXR) facility, which used linear accelerator technology; the FXR currently provides the greatest penetrating power of such radiography facilities in the world. In 1994, Los Alamos began construction of the Dual Axis Radiographic Hydro Test (DARHT) facility. DARHT will ultimately be able to provide a series of ultrahigh-resolution, three-dimensional images—essentially a CAT-scan-like movie—of an imploding device.

In the meantime, both Los Alamos and Livermore are upgrading their current radiographic facilities to provide double pulsing. With double pulsing, these facilities will be able to take two images of the implosion, which will provide much more information (e.g., surface velocity between the two times) that was possible previously.

The laboratories are also world-leaders in the use of high-power lasers and pulsed-power systems to create, in the laboratory, high-energy-density conditions relevant to nuclear weapons. Sandia's Particle Beam Fusion Accelerator II, a 50-TW, 12-MV ion accelerator, is the largest facility in the nation for generating pulsed ion beams. At Los Alamos, construction will begin in 1996 on a new 1- to 3-MJ pulsed-power machine, called Atlas, that will be used for implosion experiments relevant to nuclear weapons. Livermore has constructed a series of ever-larger glass lasers, culminating in the 10-beam, 40-TW Nova laser.

The National Ignition Facility is being designed to produce even higher temperatures, pressures, and material energies densities than are possible with Nova, conditions that closely approach those in nuclear weapons. This 192-beam, 600-TW laser facility also promises to establish the feasibility of inertial confinement fusion by achieving ignition of the deuterium-tritium fuel, an accomplishment that will open opportunities for the use of fusion for civilian energy production.

Sandia has designed and constructed several unique facilities to certify the robustness of weapons to external radiation. These include the Saturn facility (converted in 1987 from the Particle Beam Fusion Accelerator I) for cold and hot-x-ray testing and the Hermes III facility (completed in 1988) for gamma radiation testing. To complete its suite of aboveground weapons-effect test facilities, Sandia is in the process of designing the Jupiter facility for warm x-ray testing.

In addition, the Los Alamos Neutron Scattering Center (LANSCE) is being upgraded to provide an intense pulsed source of spallation neutrons for various stockpile stewardship tasks.

A Continuing Defense Mission

Meeting the defense needs of the nation remains a central mission for the Los Alamos, Sandia, and Livermore laboratories. Today, the U.S. is dramatically reducing its nuclear weapon stockpile, and no new nuclear weapons are currently in development or production. Thus, the primary focus of the laboratories' national security mission now is to reduce the nuclear danger, both in the U.S. and worldwide. This mission entails:

• Stockpile stewardship—providing the scientific and technical capabilities to ensure the safety and reliability of the U.S. nuclear weapon stockpile.

• Stockpile management—providing the technologies to maintain stockpile weapons, manufacture replacement weapons or weapon components, and dismantle weapons retired or removed from the stockpile.

• Nuclear materials management—providing the capabilities to ensure the continued availability of nuclear materials (including plutonium, enriched uranium, and tritium) and to manage their storage and disposition.

•Nonproliferation and counterproliferation—providing the expertise and technologies to detect, curb, and counter the proliferation of nuclear (and chemical and biological) weapons and weapon technologies.

Stockpile stewardship is particularly challenging. The laboratories must develop the science and technology base to maintain the stockpile at an affordable cost and without nuclear testing. They must also retain the technical know-how and infrastructure unique to nuclear weapons in order to respond to unforeseen (but inevitable) stockpile safety and reliability issues arising from age-related material degradation and changes in technology.

At the direction of the Department of Energy, the laboratories have developed an integrated Stockpile Stewardship Program to provide the scientific basis for confidence in the stockpile (outlined in the document *Stockpile Stewardship Program Strategy*, Department of Energy Office of Defense Programs, December 1994). Los Alamos, Sandia, and Livermore have identified the programmatic thrusts required to acquire a more complete and fundamental understanding of weapon physics and phenomena that will compensate, to the extent possible, for the absence of nuclear testing.

Four initiatives are central to science-based stockpile stewardship:

• The design, construction, and use of enhanced experimental facilities, particularly the National Ignition Facility, advanced hydrodynamic and pulsed-power facilities, and LANSCE.

• The dramatic improvement of computational simulation and predictive capabilities, through the Accelerated Strategic Computing Initiative. This initiative, involving the laboratories and industry, will significantly advance U.S. capabilities for developing and applying physical models, numerical algorithms, computer system software, and super computer hardware.

• The development of technologies for producing essential weapon materials, particularly accelerator production of tritium (such accelerators will also be used for studies of weapon material properties, as in LANSCE).

• Collaboration with industry to develop the "factory of the future" for low-volume, high-quality, intermittent manufacturing of weapon components. For the factory of the future concept, the laboratories are pioneering information-driven manufacturing, in which laboratory-designed parts can be analyzed and concurrently engineered in collaboration with industry suppliers through a secure distributed computer network.

The enhanced numerical simulations and innovative nonnuclear experiments required for reducing the nuclear danger will drive the development of new computational capabilities, diagnostic techniques, and test facilities. Thus, in fulfilling their national security mission, the laboratories will continue to extend the frontiers of science and technology in ways as unforeseeable today as supercomputers and lasers were just 50 years ago.

IV. Multiprogram Laboratories and Multilaboratory Programs

There is no single "weapon science." Nuclear weapons research and development is a demanding, specialized application of many scientific and engineering disciplines. To acquire the new knowledge needed for their weapons mission, the Los Alamos, Sandia, and Livermore laboratories have often found themselves advancing the state of an entire technical field.

Maintaining and increasing expertise at these laboratories has always required a scientific and technical staff equipped with the latest information and techniques. It has also required broad contacts with the worldwide scientific community. As an essential part of this process, the Department of Energy's Office of Defense Programs (and its predecessors) has made a point of supporting unclassified, publishable work relevant to the weapons program. These projects closely link the laboratories' direct weapons research with more fundamental work that has both military and civilian applications.

It is not only the skill of the laboratories' staff that has enabled such accomplishments. The Department of Energy and its predecessors also invested heavily in advanced technical facilities. These facilities, originally funded entirely by the weapons program and, more recently, by a wide range of sources, have helped attract a first-class technical staff and have enabled that staff to achieve breakthroughs in their professional fields.

Major inventions and breakthroughs have provided the basis for new competencies and new programs. For instance, lasers did not exist when the laboratories were founded; today, the laboratories are world leaders in many facets of laser technology. For another example, because of the unique nature of nuclear weapons, the laboratories have led in understanding the biological consequences of the production and, potentially, the use of such weapons. As a result, bioscience, including the ability to probe at the genetic level and understand the code of human DNA, has emerged as a new area of expertise, considerably different from the laboratories' core mission yet a logical outgrowth of it. In some cases, laboratory accomplishments have even reshaped technical landscapes, as when the invention of the laminar-flow clean room in the 1960s accelerated the establishment of the microelectronics industry.

One mark of the laboratories' accomplishments is their recognition from outside the Department of Energy. For example, since 1978, the laboratories have received more than 130 of the prestigious R&D 100 awards, given annually to mark the year's 100 most technologically significant products.

Another indication of the laboratories' influence is how often their work has been incorporated into national and international standards. This has happened, for instance, in areas as diverse as a high-performance computing interface specification, an international standard for aging tests on polymer materials, and a number of areas related to nuclear power and nuclear material safeguards.

A Multifaceted National Resource

Because the complex, multidisciplinary nature of weapons research and development produced a scientific and technical staff trained in a broad range of disciplines, the laboratories have proved to be a national resource for tackling other complex, long-range problems. Indeed, the laboratories fill an important niche in the U.S. science and technology system. They often address long-term scientific and technical problems that are beyond the scope of industry or university research. Thus the laboratories are ideally positioned to form mutually beneficial partnerships with both industry and academia.

As national issues have arisen—energy crises, shifts in conventional defense needs, environmental problems, even weaknesses in science and math education—the laboratories have directed their efforts to these areas. The sponsors of these programs, both inside and outside the Department of Energy, have found the expertise and special facilities of the laboratories essential to their needs. Los Alamos, Sandia, and Livermore have long been described as multiprogram laboratories; more and more, we can speak of multilaboratory programs.

Highlight Accomplishments and Collaborations

New competencies will evolve as laboratory missions continue to respond to national priorities. In addition to nuclear weapons, some of the areas in which the laboratories have made significant accomplishments include:

- Computers and information.
- Materials.
- Electronics.
- Sensors and instrumentation.
- Bioscience, biotechnology, and health care.
- Energy.
- Environment.
- Advanced manufacturing.
- Lasers and particle accelerators.
- Nonproliferation.
- Conventional defense.
- Basic science.

The following sampling of accomplishments and collaborations is representative of the depth and breadth of the national security laboratories' historical achievements and current efforts.

Computers and Information

Los Alamos, Sandia, and Livermore have pushed the frontiers of scientific computing ever since the days of the ENIAC and UNIVAC. The problems to be calculated or simulated demanded ever-faster and more powerful computers and ever-more sophisticated software, both for operating the computers and for modeling and analyzing the data. The laboratories worked closely with the computer industry—IBM, CDC, Cray, among others—in the development of each new generation of computers. For example, collaboration with the Cray Research team led to an operating system, software tools, and applications that helped Cray and the U.S. become the world's dominant force in supercomputing. Collaboration with Intel demonstrated a new model for parallel computing and led to thousandfold speedups in program execution. Computation techniques developed by the national security labs have had worldwide application: the Monte Carlo technique for radiation transport calculations, the DYNA3D code for predicting how materials behave under impact, automatic mesh-generation software that reduces a U.S. automaker's time to iterate engineering designs from 36 hours to 30 minutes, and the CTH code for events associated with explosions, impacts, or intense heat—recently used to model the impact of the Shoemaker-Levy comet on Jupiter.

The High Performance Parallel Interface (HIPPI) developed by the weapons laboratories has been adopted by the American National Standards Institute. HIPPI is now the primary standard for high-performance computer facilities throughout the world. A HIPPI-based link involving the laboratories recently set a world record for distance and speed of high-performance intercomputer communications. Another laboratory project was the first demonstration of using Asynchronous Transfer Mode switches for 45-Mb/s communication between two sites over the government's FTS2000 telecommunication system.

Expertise originally developed to track dispersal of radioactivity in case of accident or military use of a nuclear weapon has been used to evaluate nuclear reactor accidents, toxic chemical spills, and dispersion of smoke from oil well fires during the Persian Gulf War.

Among current collaborations, Los Alamos, Sandia, and Livermore are participating in testbed programs, such as the National Information Infrastructure Testbed, to advance the speed and interoperability of networks—a "real life" exploration of the possibilities of the "information superhighway." The Optical Network Technology Consortium is researching all-optical networks carrying ten to a thousand times as much data as is possible today. The National Storage Laboratory Consortium is developing new technologies for storing and retrieving massive amounts of data a hundred times faster than today. These collaborations also include U.S. industry, universities, and government agencies.

Materials Science and Technology

Early nuclear weapon research focused on building prototypes with minimal amounts of material. Now, the laboratories' accomplishments in materials science will be required to achieve the extended weapon lifetimes necessary for the enduring stockpile. These materials advances are also making new civilian technologies possible.

Fuel cell materials developed by the laboratories have led industry to invest in the commercial application of fuel cells. The laboratories have also contributed significantly to development of high-temperature superconductors for applications such as motors and fault-current limiters. New types of high explosives allow safer, more reliable munitions designs for harsh environments. Optically active ceramics, developed to protect pilots' eyesight in case of a nuclear blast, have led to such electronics applications as optical memories.

Work on plutonium–gallium alloys for nuclear warheads has led to an understanding of electronic structure that, in turn, laid the foundation for a better scientific interpretation of superconductivity. Other work on improved uranium alloys produced high-strength, high-toughness, armor-piercing rounds that proved highly effective in the Persian Gulf War.

Aerogels—materials of exceptionally low density—were initially developed for defense purposes. They have since found many civilian applications in areas such as insulation, aerocapacitors, integrated-circuit dielectrics, and catalysts. Research into the chemistry of polymer aging has been translated into national and international standards for aging tests of polymer materials.

An important collaboration is the Department of Energy's Center of Excellence for the Synthesis and Processing of Advanced Materials. Formed in 1992, the Center is currently focusing on seven coordinated projects: conventional and superplastic metal forming, materials joining, nanoscale materials for energy applications, tailored microstructures in hard magnets, microstructural engineering with polymers, processing for surface hardness, and mechanically reliable and corrosion-resistant coatings. An Industrial Advisory Board reviews the work and recommends programmatic direction for the collaboration.

Electronics

Strained-quantum-well compound semiconductor technology was pioneered by the laboratories in the early 1980s. This technology forms the basis for today's highest-performance microlectronic devices, including semiconductor lasers (such as those used for communication and compact disk players). Recent national-award-winning technology products developed by the laboratories include long-wavelength reflection optical modulators and vertical-cavity surface-emitting lasers.

The national security laboratories have also invented several major types of microelectronics. One example is radiation-hardened CMOS (complementary metal oxide semiconductor) for weapon and space systems. Another is nonvolatile memory SNOS (silicon nitride on silicon) integrated circuit technologies.

The laboratories have developed process technology and computer-aided tools for integrated circuit design and manufacturing, several of which have been adopted by industry and are now in commercial use. For example, the assembly test chip, a product designed to improve electronic package quality and reliability, is now used by more than 50 companies.

Theoretical work on the electronic band structure of semiconductor superlattices led to a structure that can detect very-long-wavelength infrared radiation, such as is emitted by objects at room temperature or below, including cold objects in space.

Collaborations currently include extreme ultraviolet projection lithography, potentially valuable to U.S. industry for producing microcircuit features 0.1 micron or smaller. This work could result in a 25-fold improvement in integrated circuit density by the end of the decade.

Sensors and Instrumentation

Nuclear weapons work led the national security laboratories to develop sensors and detectors with previously unattainable speed, sensitivity, resolution, miniaturization, autonomy, and robustness. Many of the instruments have been designed to function reliably after long periods under extreme conditions—launched into space, for instance, or buried underground in a nuclear test package. The need in nuclear testing to gather and record immense quantities of data in fractions of a second spawned devices that have broad application in nonproliferation of weapons of mass destruction, space science, environmental monitoring, and commercial ventures.

Sensors based on integrated-circuit microelectronic devices include a hydrogen sensor, developed for stockpile surveillance, that is now used to monitor hydrogen gas buildup in rocket motors, fossil and nuclear power plants, and batteries and automotive systems.

Sensors for unattended seismic monitoring and passive infrared imaging have been adopted for unattended intrusion-monitoring at locations such as border crossings and remote archaeological sites. A sensor system developed for ballistic missile defense was used on board the Clementine satellite to compile, in only two months, a spectral map and relief map of the entire lunar surface. The magnitude of this undertaking was such that it could not even be contemplated without these new sensor technologies.

Collaborations in sensors are among the laboratories' first partnerships outside nuclear weapon design. Beginning in the early 1960s, these collaborations resulted in a nuclear-explosion detection system for deployment on satellites. A series of sensors—optical, electromagnetic pulse, x-ray, gamma ray, neutron, charged-particle, and others—have been applied to later generations of surveillance satellite programs and to scientific purposes, such as NASA solar-wind missions and deep-space scientific probes like Galileo.

Bioscience, Biotechnology, and Health Care

An instrument developed in 1968 was the first to enable rapid analysis of single cells and chromosomes by flow cytometry. This laboratory-developed technology is now routinely used in medical centers and research labs around the world. Later developments in electronics and software that increased the speed of this type of analysis, together with an ultrasensitive technique for detecting single fluorescent molecules, are increasing the applications of this technology to basic research and medical practice.

Jointly developed technology has enabled the laboratories to isolate large amounts of human chromosomes and construct genetic libraries distributed to medical researchers at more than 4000 university and industry sites. In creating a detailed map of human chromosome 19, laboratory researchers have identified more than 100 new genes. They have also decoded the human telomere, the DNA sequence capping each end of each chromosome. The telomere has critical roles in aging and cancer. Recent identification of genes responsible for repairing damaged DNA is helping to explain the relationship between cancer and exposure to radiation or chemicals.

A noninvasive sensor for blood glucose uses technology originally designed to measure gases in high explosives of nuclear weapons. Directly applicable to monitoring glucose in diabetics, this technology is being extended to measure blood levels of substances critical in other medical conditions.

Other innovative technologies include new ways to interpret mammograms and magnetic resonance scans (reducing detection error rates), to image osteoporosis, and to remove blood clots with lasers.

A major collaboration is the international Human Genome Project, which includes the Department of Energy laboratories, national medical organizations, and research universities in this country and abroad. This multidisciplinary project (funded by the Department of Energy's Office of Health and Environmental Research) brings together disciplines such as biology, chemistry, physics, engineering, mathematics, and information science to develop innovative, cost-effective methods for sequencing and interpreting the human genome.

Energy

National security depends in large part on secure, abundant supplies of energy. Los Alamos, Sandia, and Livermore have been active for decades in research and development applicable to nuclear, fossil, and renewable energy sources. In fission reactor research, the laboratories have made fundamental contributions to reactor fuel development, medical isotope production, materials behavior studies, space nuclear power, and reactor safety. An experimental and theoretical program in probabilistic risk assessment provided a broad foundation for reactor safety analyses that can be applied, for example, to the present aging reactors in the U.S. Computer codes for analyzing reactor safety issues accurately calculated the reactor core damage after the Three Mile Island accident. A major piping reliability study led to cost-saving revision of federal design standards while maintaining safety.

In progress toward fusion energy, one of the weapons laboratories demonstrated for, the first time ever (in 1958), thermonuclear plasma in the laboratory. With this accomplishment, they accelerated the study of concepts for fusion power. Extensive studies of different confinement methods brought better scientific understanding of factors that affect economic fusion reactors. Other projects advanced capabilities in superconducting magnets and other critical fusion technologies. Stringent trials of a fusion test facility in the mid-1980s proved that all subsystems were able to work together at full capacity. Weapons program expertise in handling tritium (a radioactive isotope of hydrogen) has been vital to magnetic fusion efforts. The Los Alamos Tritium System Test Assembly (TSTA) has provided hands-on experience with the fuel loops required for magnetic fusion test facilities, and TSTA staff have trained magnetic fusion researchers in the safe handling of tritium, most recently participating in experiments on the Princeton Tokamak Fusion Test Reactor. The pursuit of fusion energy for civilian power production is immensely challenging—scientifically and technically—and costly. The laboratories are collaborating extensively with other U.S. and foreign research institutions, capitalizing on the synergy of scientific collaboration and spreading the costs and risks.

Other energy accomplishments include application of a patented hot-dry-rock concept for mining and using heat within the Earth, which has provided more fundamental and practical knowledge about the pressurized deformation of the deep Earth than any other experimental work in the world. Participation with industry has created a next-generation dish-Stirling system that uses a stretched-membrane solar concentrator and a free-piston Stirling engine for converting sunlight to electrical energy.

Los Alamos, Sandia, and Livermore are participants in the Natural Gas and Oil Technology Partnership, which aims at improved production of fossil energy. New technology from this partnership has reached the commercial market—for example, the development of a multilevel borehole receiver system.

Another collaboration, the Partnership for a New Generation of Vehicles, includes the three U.S. automobile companies and the U.S. Council for Automotive Research. This partnership is using the laboratories' expertise to develop technologies such as new catalysts, emissions control equipment, sensors and their associated digital control logic, manufacturing processes, and reliability assessments. This partnership follows a series of less-formal collaborations begun in the 1970s that successfully applied new laser-based diagnostic techniques, modeled the detailed chemical kinetics of combustion and emissions formation, and modeled on a large scale the engine's intake, fuel injection, combustion, and exhaust.

Environment

The national security laboratories have made major advances in monitoring atmospheric pollution with lasers and in producing inexpensive automated monitoring units for local use. The laboratories cooperated in assessing possible threats to global climate from oil fires in Kuwait before the fires were started. The Atmospheric Release Advisory Capability, a pioneering accomplishment in environmental simulation, can model the atmospheric release and dispersal of gaseous materials at hemispheric, regional, and local scales.

The RAPRENOx (RAPid Reduction of NOx) process for destroying nitrogen oxides (a major contributor to smog and acid rain) in combustion and exhaust streams has been transferred to the private sector. In environmental remediation, industry has adopted (through licensing) a method for a 50-fold improvement in extracting nonaqueous phase liquid contaminants from subsurface plumes.

The national security laboratories cooperated in developing some of the earliest computer codes to realistically simulate fluid flow in the earth for various waste-storage and oil-recovery techniques and environments, an area where they still lead. A collaboration with the National Oceanographic and Atmospheric Administration produced the most detailed global ocean current and eddy simulations ever done. A multisensor system allows characterization of heterogeneous high-level radioactive wastes stored underground, reducing the uncertainty in the hazard.

Together with NASA, other Department of Energy laboratories, industry, and universities, Los Alamos, Sandia, and Livermore are investigating climate change issues, applying their expertise in remote sensing developed originally for defense purposes. Measurements made from unmanned aerospace vehicles (UAVs) are focusing on the major uncertainty in greenhouse warming predictions—namely, the interaction of the earth's radiation with clouds. Although one of the newest formal collaborations, this program has already made the first-ever climate-relevant measurements from a UAV and has yielded a unique radiation-flux data set.

The weapon laboratories also collaborate in research and development for hazardous waste storage, including the proposed Yucca Mountain nuclear waste repository, the Waste Isolation Pilot Plant, and on-site storage. They develop products such as sensor systems, *in situ* thermal and biological remediation systems, waste treatment, separation, and minimization methods, and complex computer simulations. The Yucca Mountain Site Characterization Project involves extensive and close interactions, with individual laboratories responsible for studies of waste and containers, the geochemistry of rock formations, and performance assessments of the entire waste repository in the distant future. Each area of responsibility relies on teamwork from the others to credibly characterize the potential disposal site.

Advanced Manufacturing

Manufacturing technologies became part of the laboratories' responsibilities through the demands of producing high-reliability weapon components. Out of that need came, for instance, the laminar-flow clean room. This early 1960s invention accelerated the establishment of the modern microelectronics industry and has important uses in medicine as well. A more recent development, the hot-air solder leveler, saves manufacturers some $250 million a year. Still more recently, an automatically programmed robotic-cleaning process for integrated-circuit boards reduces human exposure to hazardous solvents, cuts waste, and improves quality, while reducing the process of programming the robot from days to seconds.

In other areas, the Fastcast process reduces the time for investment castings of complex parts by a factor of ten or more. The first U.S. millimeter-wave-beam processing facility for manufacturing applications transferred technology from the former Soviet Union and holds promise for sintering, joining, curing, annealing, and other manufacturing technology applications. The Precision Machining Commercialization project (in cooperation with the Department of Energy/Defense Programs' Oak Ridge Y-12 plant) transferred diamond-turning and precision-machining technologies to industry, with applications such as optics for weapon systems, computer memory disks, photocopier cylinders, contact lenses, and laser scanners for retail stores. The Large Optics Diamond Turning Machine (sponsored by the Defense Advanced Research Projects Agency and the Strategic Defense Initiative Organization) produced the most accurate large-diameter (greater than 1 meter) turning machine in existence. This machine makes possible the manufacture of optical systems that could not otherwise be fabricated. Research that leads to such achievements benefits industry while maintaining and advancing capabilities needed for the laboratories' nuclear weapon responsibilities.

Laboratory collaborations in advanced manufacturing intimately involve U.S. industry. The National Machine Tool Partnership, which also includes the National Institute of Standards and Technology, logged more than 1500 calls from U.S. companies in its first 18 months. This partnership makes available to companies, especially small and medium-sized businesses, expertise in areas where the laboratories have made fundamental advances—for example, diamond turning, specialized coatings, and the reduction of hazardous wastes during machining.

The National Center for Advanced Information Components Manufacturing, sponsored by the Advanced Research Projects Agency, focuses on manufacturing processes, materials, user facilities, and hardware and software tools. A major emphasis is large-area flat-panel displays, important to next-generation information processing for defense and civilian purposes alike.

Lasers and Particle Accelerators

In the 1960s, the "side-coupled" radiofrequency cavity made it possible to radically increase the output beam in particle accelerators; today, this laboratory invention permits the construction of compact, low-cost accelerators for physics research, medical purposes (such as cancer therapy), materials processing, and energy applications. A 1980s invention, a very-high-brightness accelerator electron source called a photoinjector, is now being installed in linear accelerator systems worldwide.

The fundamental principle of laser-beam relaying, which suppresses optical damage in lasers and permits cost-effective construction of ultrahigh-power laser systems, is a 1970s invention of the laboratories. Besides being applied in a series of large laser systems, relaying is also critical to the proposed National Ignition Facility for inertial confinement fusion.

A plant-scale laser system for the atomic vapor laser isotope separation process provides a new method for commercial enrichment of uranium. This method enriches fission-power reactor fuel at a several-fold lower cost than other commercial methods; the process has been adopted by the U.S. Enrichment Corporation as its future low-cost production method.

Other laser developments include several types of semiconductor lasers valuable for purposes ranging from optical interconnects and memories to commercial applications such as industrial scale precision manufacturing, metal and ceramic processing, and advanced medical therapeutics.

Development of very powerful pulsed accelerators has enabled production of the most intense proton, ion, electron, and x-ray beams available anywhere. These accelerators provide facilities for inertial confinement fusion research and for studies of radiation effects and material science.

Nonproliferation

As the centers of U.S. nuclear weapons expertise, the weapon laboratories have responsibility for providing technical advice about foreign nuclear programs and for aiding in controlling the spread of nuclear weapons. Laboratory-provided proliferation intelligence analyses have long helped guide U.S. nonproliferation policy.

Technical accomplishments include the sensors described in the "Sensors and Instrumentation" section, as well as a portal/perimeter monitoring system installed at the Votkinsk missile motor factory in Russia to verify provisions of the Intermediate-Range Nuclear Force (INF) treaty.

To help safeguard nuclear materials, the laboratories have provided accurate nuclear material measurement technology, including (in 1966) the first nondestructive assay method. Since then, they have developed near-real-time nuclear material assay and accountability methods and ways to track the growing stocks and flows of nuclear materials worldwide. Collaboration has marked the safeguards program, with the laboratories dividing responsibility for such areas as materials control and accountability (including training of international inspection teams), containment and surveillance, and physical protection of nuclear materials.

To expedite the development of efficient nonproliferation programs, the laboratories have established the Tri-Lab Nonproliferation Group. This group coordinates activities in such areas as nuclear test detection, proliferation detection technologies, arms-control negotiations support, interactions with counterpart laboratories in other countries, nuclear materials control and disposition, and definitions of future national security environments.

Laboratory weapon scientists are working with counterparts in the former Soviet Union to convert their nuclear weapons activities and facilities to peaceful scientific and industrial applications. The laboratories have funded various collaborative projects in which the advanced experimental and calculational capabilities developed for the Soviet nuclear weapons program are used for nonweapon purposes.

Conventional Defense

Expertise gained in nuclear weapons work has often proved valuable in other defense applications. Examples include miniaturized synthetic aperture radar (SAR) and automatic target recognition systems, enabling production of high-quality images from the air. This accomplishment has involved advances in SAR technology through new image-formation algorithms, high-speed digital signal processing, miniature microwave hybrids, precision motion compensation, high-accuracy compensation, and automatic focusing. SAR interferometry produces terrain elevation maps of unprecedented accuracy, useful for both military and civilian purposes.

Other nuclear weapons technologies are being exploited to develop instruments and methods for detecting and tracking chemical and biological warfare agents. This work also supports U.S. nonproliferation and counterproliferation objectives.

The application of free-form, shaped-charge technology to conventional weapon systems has provided high performance at greatly reduced weight and volume. Major contributions to the theory and modeling of materials performance have advanced the application of ceramic armor. A one-container, storage-stable sticky foam, originally intended for protecting nuclear weapons, creates a formidable barrier to personnel and is being evaluated as a nonlethal weapon for civilian and military use.

To enhance their work in conventional defense, the weapon laboratories are technical managers of a Department of Defense/Department of Energy program pursuing innovative warhead, explosive, and fuze technologies for nonnuclear munitions. This program draws on the laboratories' expertise in such areas as materials science, explosives technology, and computer simulation. Projects range from fundamental investigations of how explosives are initiated to improvements in the effectiveness of munitions against reinforced targets.

The Department of Defense drew extensively on the laboratories' expertise for the Strategic Defense Initiative. Although that initiative has since been reduced, important breakthroughs in free-electron lasers, high-intensity accelerators, and robust sensors and instrumentation were made, many of which are finding important applications in other areas (for example, accelerator production of tritium, sensors and mapping instruments for the Clementine satellite).

Basic Science

Laboratory activities span the spectrum from basic science through applied research and technology development. Through basic research, conducted in most cases to contribute to their national security mission, the laboratories ensure their connection to and participation in the international scientific community. The following examples illustrate the range of the laboratories' basic science accomplishments.

The international race to detect an elusive fundamental particle, the neutrino, was won by one of the national security laboratories in 1956.

Since then, the labs have contributed more to the understanding of this particle, most recently establishing an upper bound on its mass.

An advanced microscope is capable of measuring the forces of chemical bonds over atomic-level distances. Already demonstrated in problems involving the mechanical properties of nanoscale structures in metal films and biomaterials, as well as lubricating properties, this interfacial force microscope promises to have a large impact on the fundamental understanding of materials.

Evidence of massive compact halo objects, obtained in collaboration with researchers from other institutions, was recently discovered. These hypothesized dark stars and giant planets in the outer fringes of the galaxy could provide much of the answer to the question of the missing matter in the universe.

Experiments in neutron scattering led to the discovery that hydrogen molecules can bind to metal complexes. This finding, one of the most unexpected and significant developments in morganic chemistry made in the past 20 years, has dramatically altered the way scientists think about the interactions of hydrogen (and other molecules) with metal atoms and has important implications for large-scale industrial processes that are based on hydrogen reactions (for example, oil refining, fertilizer production).

Weapon-lab research using nuclear-treaty verification satellites disclosed a major class of objects in the universe that shine in short bursts of gamma radiation. Because the energy of gamma rays is so high, these are interpreted to be exotic objects of extremely high energy.

In the late 1970s, a mathematical relationship and solution approach was developed that applies to the chaotic behavior of nonlinear, deterministic systems. Because virtually every important system in the world—atmosphere, oceans, and many machines, for instance—exhibits such behavior, this understanding was a major breakthrough with worldwide impact.

Interdependence and Integration

The Los Alamos, Sandia, and Livermore laboratories have effectively integrated not only their resources and facilities but their programs and capabilities as well. Investments in any and all of the laboratories' programs help preserve their collective base of scientific and technological expertise. The increasing integration has enhanced and advanced the laboratories' technical fields. Scientific discoveries and technology breakthroughs in one area provide the basis for new competencies. Los Alamos, Sandia, and Livermore have been multiprogram laboratories for years; now, more and more of their work is being conducted as multilaboratory programs.

V. Meeting the Challenges of the Future

The Los Alamos, Sandia, and Livermore laboratories were forged in the conflict of World War II and tempered and honed in the tensions of the Cold War. Today, in yet another era of uncertainty, the U.S. faces no single, paramount adversary and national security involves much more than military strength. The three national security laboratories are poised to take on new responsibilities to, once again, meet the needs of the nation in a changing world.

The laboratories' world-renowned excellence in science and technology derives, in large part, from their nuclear weapons mission. The development of nuclear weapons, together with studies of their effects, has challenged and extended the frontiers of almost every field of science—physics, chemistry, materials, engineering, computers and computational simulation, biology, environmental science, and others. More so than any one device or innovation, the real value of the three-laboratory system is this broad base of science and technology expertise.

Today, the nation is dramatically reducing its nuclear weapon stockpile and no new nuclear weapons are in development or production. As a result, the laboratories' primary national security mission is now one of reducing the nuclear danger, both in the U.S. and worldwide. This mission entails science-based stockpile stewardship, stockpile and nuclear materials management, and nonproliferation and counterproliferation.

Stockpile stewardship—ensuring the safety and reliability of the nuclear stockpile—without nuclear testing requires a fundamental scientific and technological understanding of nuclear weapons.* Enhanced experimental facilities, dramatically improved computational capabilities, and new manufacturing and materials technologies will be needed to maintain and enhance the required science and technology capability.

The laboratories have unique expertise in handling and understanding the properties of nuclear materials, particularly plutonium. This expertise will be crucial to efforts to develop safer, environmentally acceptable methods for remanufacturing weapon components, dismantling retired weapons, and dealing with the legacy of 50 years of nuclear weapon production (for example, the Hanford Waste Storage tanks, the Rocky Flats Plant).

As custodians of U.S. nuclear weapons expertise, the laboratories are central to efforts to detect, curb, and counter the proliferation of weapons of mass destruction. Los Alamos, Sandia, and Livermore provide technical advice on foreign nuclear programs and have developed technical means for verifying compliance with arms-control and test-ban treaties. They apply their nuclear weapons expertise to detect and assess foreign activities related to the development of weapons of mass destruction. They are also developing technologies, should the need arise, for countering the efforts of a proliferant nation. These aspects of the laboratories' national security mission are perhaps more important now than ever before.

The technologies and expertise developed by the laboratories in fulfilling their national security mission can also help enhance U.S. economic competitiveness in the global marketplace, another urgent national need. Over and above the extensive industry collaborations essential for stockpile stewardship (particularly, creating the "factory of the future"), the laboratories are emphasizing industrial partnerships in most all of their research and development activities. Today, laboratory expertise in materials, processing, electronics, and computations, for example, is being combined with private-sector experience to produce new marketable products and services. The laboratories are working with small businesses, large corporations, and industrial consortia to transfer technologies, conduct joint research, collaborate on technology breakthroughs, and thereby make significant contributions to U.S. economic competitiveness.

The national security laboratories fill a vital niche in the U.S. science and technology enterprise. With their emphasis on applying science to solve complex technological problems, they are effective partners with both academia and industry. Los Alamos, Sandia, and Livermore embody decades of national investment in science and technology. Thus they have the expertise, the facilities, and the long-term commitment to tackle high-risk, high-payoff science and technology projects that solve important national (and global) problems.

These problems include energy resources and usage, environmental protection, and the effects of one upon the other. They also include cleaning up the environmental legacy of 50 years of nuclear weapon production as well as such areas, vital to economic and social vitality, as transportation and health care. These problems are highly interrelated and interdependent. They all require advanced computing and high-performance computers, new methods of data analysis and information management, advanced materials, sophisticated sensors and instrumentation, and an in-depth understanding of fundamental science.

Los Alamos, Sandia, and Livermore are widely regarded as some of the world's greatest laboratories. But what makes "great" laboratories great? Four features have been identified: (1) a compelling mission, (2) a high-quality needed product, (3) broad ties to the wider scientific community, and (4) highly qualified and dedicated people.

The laboratories were established to pursue a vital mission—ensuring national security through the development of nuclear weapons. In fulfilling this mission, they developed the high-quality products, the broad ties to the scientific community, and the world-class staff. Today, with the shift in national security needs, the laboratories' original mission is changing. However, this change in no way diminishes their greatness or their ability to make vital contributions to national security.

In summary, we ask again, "What mission or missions are appropriate, at this juncture, for this integrated system of national security laboratories?" The laboratories must be challenged with a mission that is as broad based and as scientifically and technically demanding as the development of nuclear weapons. Reducing the nuclear danger is such a mission. The technical challenges of science-based stewardship of the enduring U.S. stockpile, coupled with stockpile management (including dismantlement and remanufacturing), nuclear materials management (including cleanup of the environmental legacy of 50 years of the nuclear weapon production), and curbing and countering the proliferation of weapons of mass destruction, are considerable. For the long term, developing affordable, plentiful, and environmentally acceptable energy technologies, in partnership with U.S. industry, is a mission of vital importance to both national and global security, a mission that, again, will require scientific investigations, developments, and discoveries beyond our current ken.

America today is harvesting the fruits of a national security mission initiated 50 years ago. The laboratories retain all the vigor of those early days, enhanced by decades of scientific and technological advances. By making the right choices now, the nation will reap the benefits of this unsurpassed resource of science and technology expertise for years into the future.

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*The technical issues and required programmatic thrusts for science-based stockpile stewardship are outlined in *Stockpile Stewardship Program Strategy*, Department of Energy Office of Defense Programs (December 1994).