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Multiple Programs Essential to the Scientific Vitality of the DOE Defense Program Laboratories

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Preface

The future of the Department of Energy's Defense Program (DP) laboratories—Los Alamos, Livermore, and Sandia—has been extensively debated and examined over the past several years. To assist in this process, I have asked that a set of documents be prepared, which, when taken together, present a comprehensive picture of the three laboratories.

This document describes the multiprogram nature of the DP laboratories and the value of their involvement in non-DP work as it relates to the nuclear weapons program. The other two documents, *Integration and Collaboration...Solving Science and Technology Problems for the Nation* (DOE/DP-96009797) and *Roles and Responsibilities of the Department of Energy Nuclear Weapons Laboratories in the Stockpile Stewardship and Management Program* (DOE/DP-97000280), describe respectively the integrated nature of the DP laboratories and the roles of the laboratories as they meet their individual and collective responsibilities of ensuring the safety and reliabilities of the U.S. nuclear weapons stockpile.

The scientific and technical challenges inherent in the DP laboratories' national security responsibilities today are as complex as those during the Manhattan Project and the Cold War years. Science-based stockpile stewardship and management require in-depth understanding of the full spectrum of nuclear weapons science and technology—physics, chemistry, materials, manufacturing, computational modeling, engineering, and electronics, to name a few—as well as a combination of capabilities and facilities unavailable anywhere else in the country.

In addition to stockpile stewardship and management, many other nationally important issues involve science and technology—for example, nuclear nonproliferation, energy security, and environmental protection and remediation. Over the years, the DP laboratories have applied expertise and technologies developed in their nuclear weapons work to these other issues, focusing on those areas where they can make unique and valuable contributions.

The nation has invested substantially in the three DP laboratories, creating an unmatched resource of scientific and engineering expertise, facilities, and capabilities. In this era of tight budgets, it is important that the laboratories extract maximum leverage from this investment and fulfill their nuclear weapons responsibilities as cost-effectively as possible.

The multiprogram nature of the DP laboratories has been key to their success in achieving the outstanding level of scientific and technical excellence that has become their hallmark and in carrying out their national security mission. The multiprogram work of the laboratories also provides an extremely effective way of leveraging the nation's investment in science and technology. It makes sense for the DP laboratories to apply their expertise to non-nuclear-weapons programs of national importance. It also makes sense for the DP laboratories to collaborate with other government laboratories, universities, and industry to apply the unique expertise, facilities, and capabilities of these institutions to national security challenges.

This report briefly reviews the challenges faced by the DP laboratories in fulfilling their stockpile stewardship and management responsibilities. It then discusses the benefits of the synergy and the accelerated pace of scientific achievement that arise from the laboratories' multiple programs. A representative selection of accomplishments is presented that illustrates the importance of the contributions made to the laboratories' national security mission by their non-nuclear-weapons projects and their connections with the wider scientific community.

The laboratories' history of accomplishments attests to the success of their multidisciplinary, multiprogram approach to technical problem solving. Now and in the future, the institutional vitality required for the DP laboratories' national security mission depends on their integrated, multidisciplinary and multiprogram nature. Indeed, the multiprogram nature of the laboratories is essential for their continued ability to carry out their primary mission.

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I. Introduction

In carrying out their national security mission, the three DOE Defense Program laboratories—Los Alamos, Livermore, and Sandia—have extended the frontiers of many areas of science and technology. Today, these laboratories are recognized as world leaders in atomic, nuclear, and plasma physics as well as in computing and numerical simulation, lasers and electro-optics, materials science and precision fabrication, advanced sensors, miniaturized electronics and instrumentation, and even human genetics and environmental science.

A hallmark of the Defense Program (DP) laboratories is their multidisciplinary approach to solving complex scientific and technical problems. Nuclear weapons work (be it the design and development assignments of the past or the stewardship responsibilities of today and the future) involves many disciplines of science—physics, chemistry, materials, engineering, and computation, among others—plus a wide spectrum of technologies—explosives, electronics, instrumentation, aerodynamics, and automated control, to name a few (see Table 1).

Major inventions and breakthroughs have been made by the DP laboratories in the course of their nuclear weapons work that have spun out to provide the basis for new capabilities and new non-

Table 1. Examples of the multidisciplinary nature of nuclear weapons science and technology.

Discipline	Key areas: weapons applications
Atmospheric science	• *Weapons effects*: nuclear nonproliferation detection, nuclear incident emergency response
Chemistry	• *Nuclear chemistry*: weapons performance, nuclear test diagnostics, nuclear materials production, cleanup, and disposition
	• *Organic chemistry*: high explosives, polymers, material aging, weapons safety and performance
Computing science	• *Massively parallel computing*: systems and applications software, visualization, data storage, weapons design, weapons performance, safety, and manufacturing
	• *Numerical simulation*: models, algorithms, databases, all aspects of weapons science and technology (from weapons design to testing, manufacturing processes, weapons safety and aging, and response of the environment to the dispersal of radioactive materials)
	• *Signal processing and data fusion*: weapons science experiments, weapons testing, manufacturing process control, nuclear proliferation detection
Earth science	• *Geology, hydrology, seismology*: weapons effects, nuclear test containment, nuclear materials disposition, nuclear proliferation detection, treaty verification
Engineering	• *Design and prototyping*: solid modeling, artificial intelligence, stereo-lithography, 3D printing, net shape forming, weapons component manufacturing, refurbishment, and assembly
	• *Precision fabrication*: dry machining, spin forming, laser welding, liquid-jet cutting, weapons manufacturing, weapons safety, performance, and dismantlement
	• *Process control*: automation, robotics, remote sensing and control, nondestructive evaluation, weapons component manufacturing, assembly, and dismantlement
	• *Electronics and photonics*: microelectronics, integrated optics, weapons components, weapons assembly, stockpile surveillance, use control, nonproliferation detection, weapons test diagnostics
	• *Pulsed power and accelerators*: power conditioning, radiofrequency induction linear accelerators, beam transport, weapons effects, inertial fusion, radiography, weapons testing, tritium production

Table 1. Continued.

Discipline	Key areas: weapons applications
Lasers and optics	• *High-power lasers and diode lasers*: lidar, nonlinear optical materials, laser materials, inertial fusion, weapons test diagnostics, weapons manufacturing and dismantlement, nuclear materials processing, weapons components, stockpile surveillance, nuclear nonproliferation detection
Materials science	• *Materials*: alloys, composites, ceramics, weapons component manufacturing, weapons performance
	• *Material properties*: equations of state, phase transitions, static and dynamic mechanical properties, chemical stability, weapons manufacturing, weapons performance, aging, and safety
Physics	• *Atomic physics*: opacities, radiation flow, weapons performance, spectroscopic diagnostics of inertial fusion plasmas
	• *Fluid dynamics*: hydrodynamic flow, instabilities, material mix, turbulence, weapons performance
	• *Nuclear physics*: fission, fusion, weapons performance, radiography, nuclear materials detection, tritium production, accelerators, nuclear test diagnostics, weapons effects
	• *Plasma physics*: weapons performance, inertial fusion, weapons effects, plasma processing of materials

weapons programs. In many instances, further capabilities and innovations developed through these new programs have spun back to benefit the laboratories' national security mission.

For example, the idea of laser-driven nuclear fusion had not been conceived when the laboratories were founded. When the concept of the laser was first proposed (in 1958, by Charles H. Townes and Arthur L. Schalow), scientists at the DP laboratories drew on their experience with thermonuclear fusion in nuclear weapons and began investigating the possibility of using lasers to drive the fusion reaction in the laboratory. Through these efforts, they advanced the state of the art in electro-optics, microfabrication, plasma physics, and many other areas. Today, Livermore is a world leader in laser science and technology. This expertise is spinning back to benefit the laboratories' nuclear weapons mission, as it enables them to design and construct the National Ignition Facility, a crucial experimental facility for stockpile stewardship and management (Figure 1).

For another instance, the laminar-flow clean room was invented by Sandia in the 1960s for weapons assembly. The techniques and technologies devised for ultraclean parts fabrication and assembly enabled the entire microelectronics industry. Microelectronics are now integral to nuclear weapons technology and to many aspects of stockpile surveillance and maintenance (Figure 2).

The transition to science-based stewardship of the U.S. nuclear stockpile (from the nuclear-test-based approach of years past) presents major new challenges to the DP laboratories as they carry out their primary mission—namely, ensuring the safety and reliability of the U.S. nuclear arsenal. Indeed, one must not underestimate the risks and uncertainties involved in this new approach to stewardship and management of the enduring U.S. stockpile. It will take at least a decade to develop the necessary new capabilities, bring upgraded and new facilities on line, and acquire sufficient experience within the Stockpile Stewardship and Management Program to evaluate the adequacy of the program and determine the need for any changes.

Particularly during this period of transition, the institutional vitality required by the DP laboratories to carry out their national security mission depends heavily on their integrated, multiprogram nature and on their multidisciplinary approach to solving complex scientific and technical problems. By exploiting the synergy of multiple programs, Los Alamos, Livermore, and Sandia can ensure their ability to meet their national security responsibilities, help solve other nationally important problems, and maximize the return on investment that the nation has made in these laboratories.

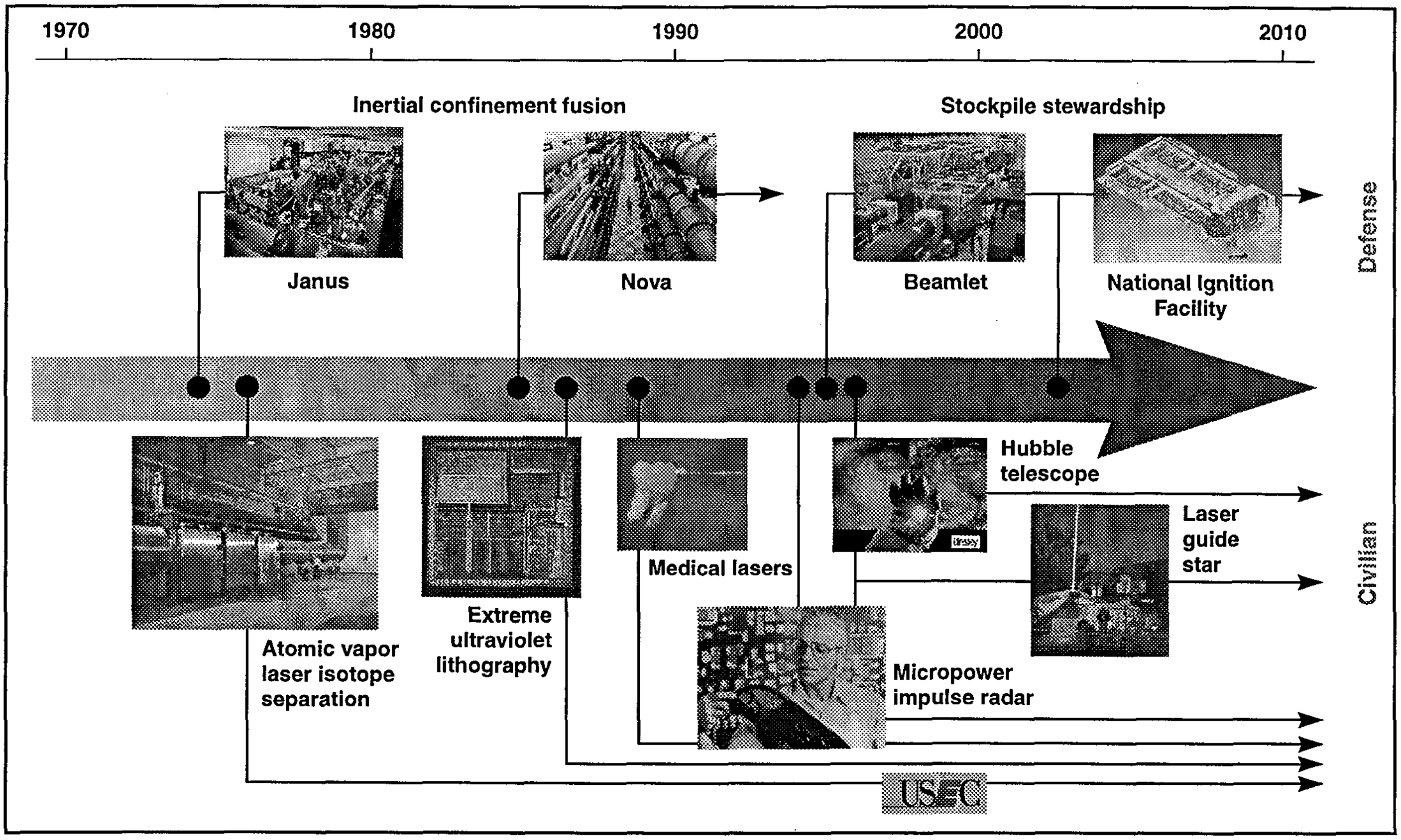


Figure 1. Advances made by the DP laboratories in laser science and technology have spun out to the civilian industrial sector, and advances there are spinning back to benefit the laboratories' national security work.

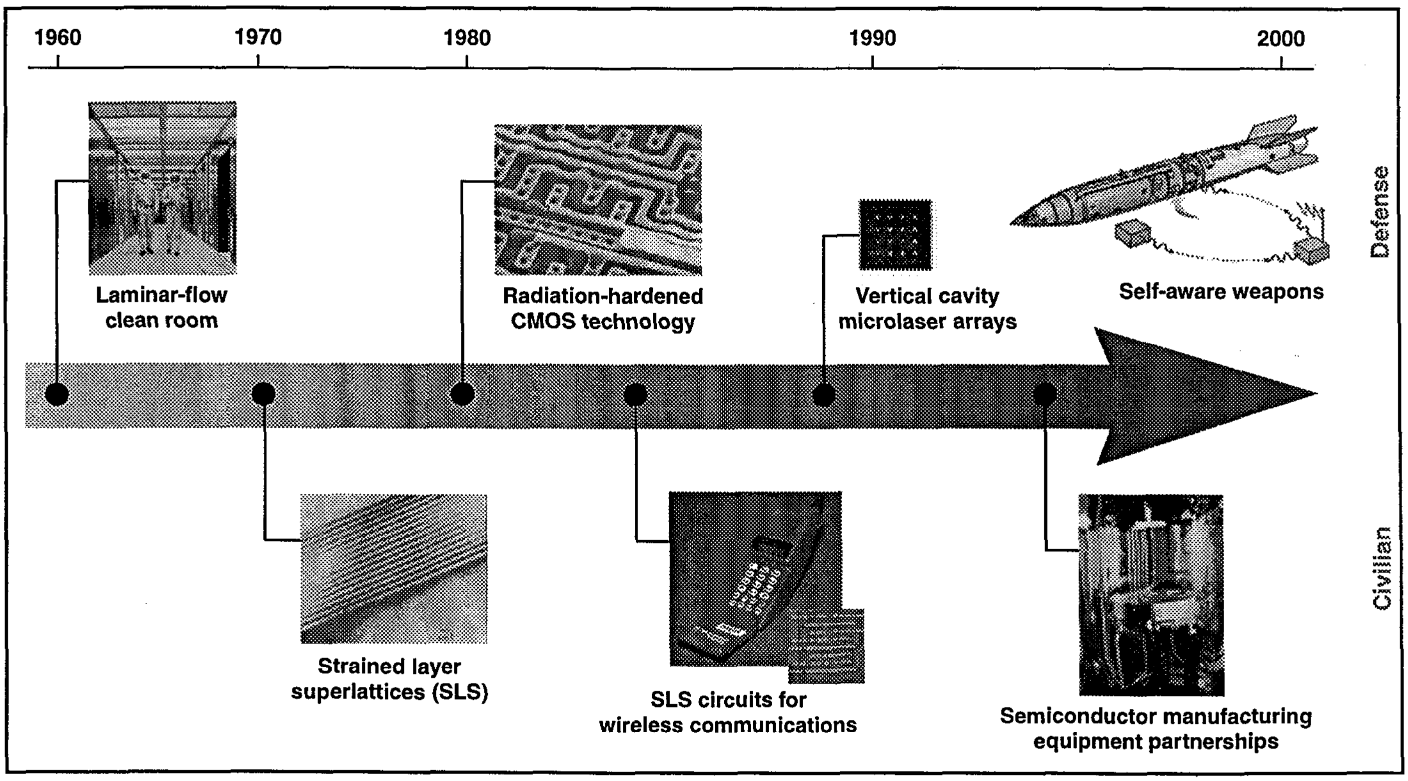


Figure 2. Techniques and technologies devised by the DP laboratories for ultraclean parts fabrication and weapons assembly were critical enabling elements for the entire microelectronics industry.

II. Nuclear Security in the Post-Cold War Era

WITH the end of the Cold War, the U.S. has stopped underground nuclear testing and has signed a Comprehensive Test Ban Treaty (CTBT). The production of new-design nuclear weapons has been halted and the size and diversity of the U.S. nuclear stockpile is being greatly reduced. However, nuclear deterrence remains an integral component of U.S. national security policy.

Official U.S. nuclear weapons policy is based on the Nuclear Posture Review, conducted by the Secretary of Defense and approved by the President in September 1994. This "lead plus hedge" policy states that the U.S. will lead in the careful downsizing of its nuclear stockpile while hedging against an uncertain future by maintaining the capabilities needed to reverse course in terms of stockpile size, nuclear testing, and new weapon design and production.

Thus, the DOE and the DP laboratories have a dual charge: (1) to certify the safety, security, and reliability of the U.S. nuclear stockpile without nuclear testing and without new-design weapon production, and (2) to preserve the intellectual and technical capabilities for performing nuclear tests and producing new-design nuclear weapons.

In addition, fiscal constraints are compounding the technical challenges facing the three laboratories. The DOE and its Office of Defense Programs, like the rest of the federal government, are responding to Congress' and the Administration's efforts to reduce government spending and balance the federal budget. With the downsizing and restructuring of the weapons production complex that has already taken place, an increasing proportion of actual nuclear weapons experience resides with the scientists and engineers at the DP laboratories (Figure 3).

The Challenge of Science-Based Certification

With the cessation of nuclear testing, a new approach is needed for certifying the safety and reliability of U.S. nuclear weapons. The DOE and the DP laboratories have developed a proactive and responsive strategy—science-based stockpile stewardship and management. Instead of using nuclear testing to certify the weapons' safety and performance, we will rely on an improved understanding of the fundamental science underlying nuclear weapons and their operation. Instead of

U.S. Nuclear Policy in the Post-Cold War Era

The end of the Cold War and the reduction in tensions between the U.S. and the former Soviet Union have permitted a reversal of the nuclear arms race. Russia and the U.S. are dramatically reducing their nuclear arsenals, and the other Newly Independent States have relinquished all Soviet nuclear weapons on their soil. Nevertheless, the total elimination of nuclear weapons is unlikely in the foreseeable future, and nuclear deterrence continues to be an important part of U.S. national security policy.

As the President announced on August 11, 1995:

> *"...the United States must and will retain strategic nuclear forces sufficient to deter any future hostile foreign leadership with access to strategic nuclear forces from acting against our vital interests and to convince it that seeking a nuclear advantage would be futile....the maintenance of a safe and reliable nuclear stockpile [is] a supreme national interest of the United States."*

However, while the U.S. and Russia are reducing their nuclear forces, concerns about the proliferation of nuclear weapons by other states are increasing. These concerns are anything but abstract, as attested to by the discovery of Iraq's clandestine nuclear weapons program, evidence of plutonium production in North Korea's reactors, and the interception of smuggled nuclear materials in Eastern Europe. Thus, curbing the proliferation of nuclear weapons, nuclear materials, and weapons technology is crucial to national security.

The Nuclear Non-Proliferation Treaty (NPT) is a cornerstone of international nonproliferation efforts. In May 1995, countries party to the NPT extended the treaty indefinitely. One of the disarmament principles agreed to at the NPT extension conference was the successful conclusion of a Comprehensive Test Ban Treaty (CTBT).

U.S. support of a CTBT is based on the belief that it is possible to adequately maintain this nation's nuclear deterrent without nuclear testing. In fact, confidence in a science-based stockpile stewardship program was generally recognized as a precondition for U.S. entry into a CTBT. On September 24, 1996, the President signed the CTBT, which had been opened for signature at the United Nations that day.

introducing new-design weapons into the stockpile to replace older systems, we will apply first-principles understanding to predict aging-related changes in existing weapons, to design fixes and retrofits as necessary, and to certify the weapons' continued safety and reliability.

Acquiring this fundamental knowledge is a formidable task, encompassing many areas of science and technology and requiring enhanced experimental and computational capabilities. We need a detailed understanding, on the one hand, of physical phenomena that occur at extreme pressures and temperatures and last only a fraction of a second. On the other hand, we must understand the subtle processes that develop at ambient conditions over many years. We must fully understand these complex, interrelated phenomena and processes so that we can accurately model them with numerical simulations and predict their occurrence and effects.

The ability to predict the effects of aging-related changes in weapon materials and weapon components is essential. Nuclear weapons are not static objects. They contain radioactive materials that decay. Being radioactive, these materials have limited lifetimes. This is particularly true for tritium, which has a 12.5-year half-life. Such limited-life components must be replaced periodically throughout the weapon's lifetime. In addition, radioactive decay produces heat and decay products that cause changes in the radioactive material itself and in adjacent materials. For example, plastics and other organic materials are highly susceptible to heat-related damage, and many metals become brittle after long exposures to radiation. As the weapons age, changes occur, and these changes may, singly or in combination, affect weapon safety and reliability.

The current U.S. nuclear stockpile is older than it has ever been before, and weapons in the enduring stockpile will age well beyond their original design lifetime. We are entering uncharted territory as weapons in the stockpile age beyond our base of experience. No matter how carefully we prepare now, we know we will have to deal with new and unanticipated problems that are beyond our experience base.

The Challenge of Nuclear Readiness

The DOE is also charged with "preserving the core intellectual and technical competencies of the U.S. in nuclear weapons" (Public Law

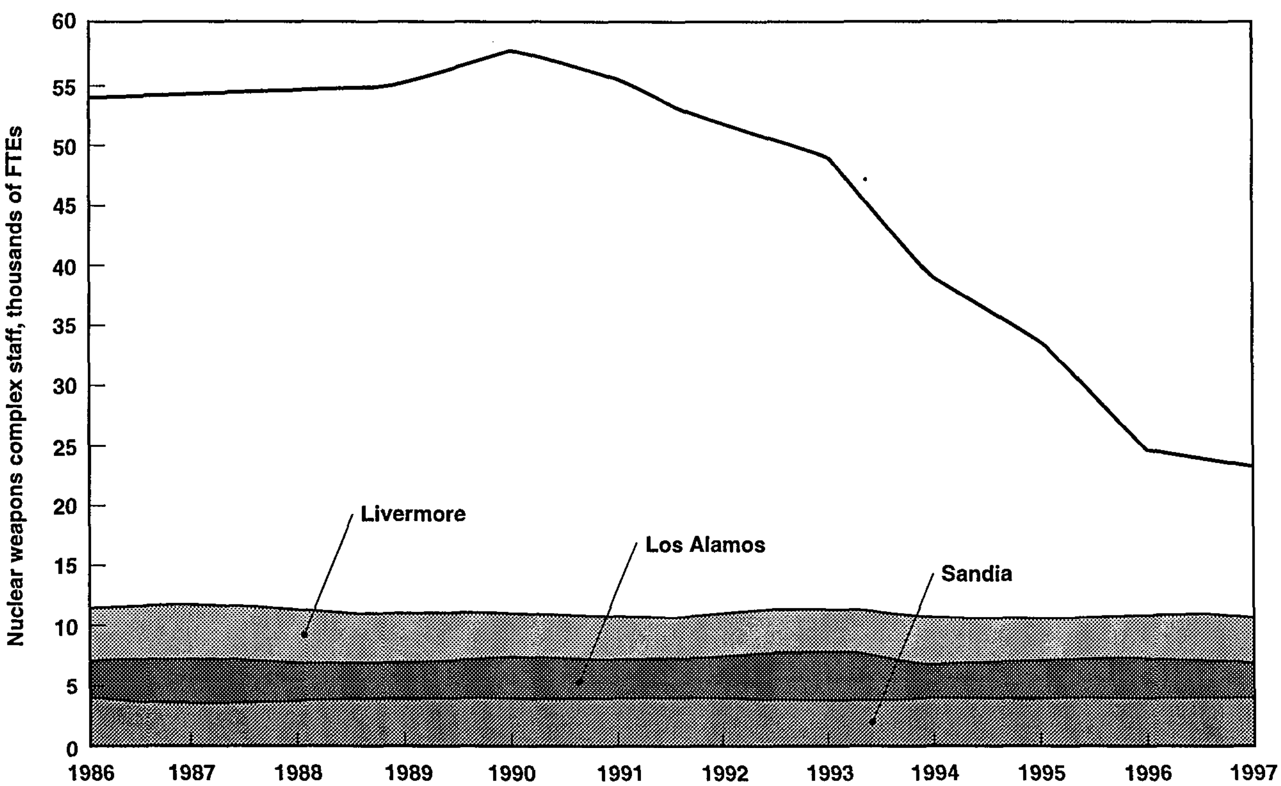


Figure 3. *With the downsizing and restructuring of the U.S. nuclear weapons complex over the past several years, an increasing proportion of the nation's nuclear weapons expertise and experience resides at the DP laboratories.*

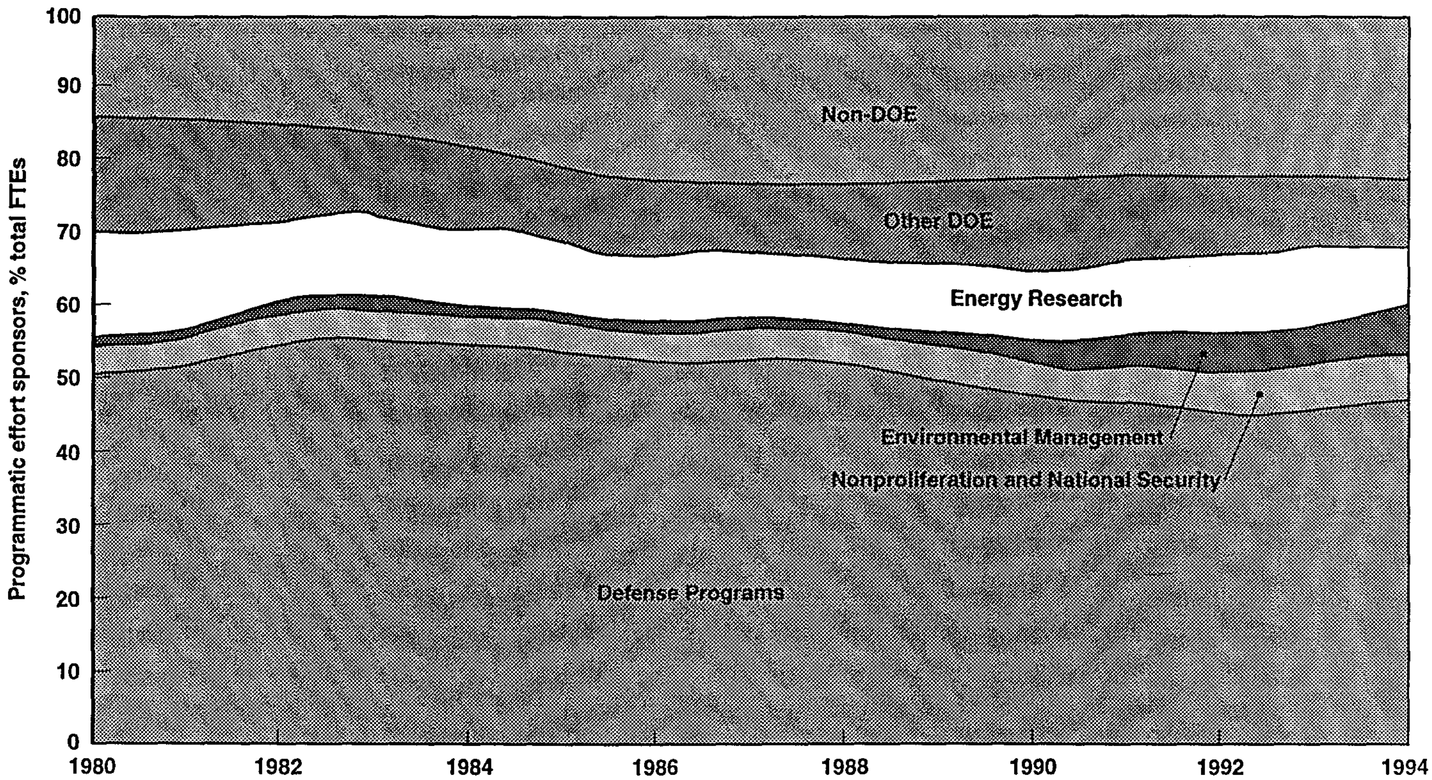


Figure 4. *The DP laboratories have pursued multiple programs for many years, to the mutual benefit of their national security mission and their other programs. Shown here is the relative division of effort among various DOE and non-DOE sponsors.*

An Analogy for Stockpile Stewardship and Management

To better understand the challenges posed by science-based stockpile stewardship and management, consider the difficulties involved in predicting, preparing for, and responding to earthquakes. Like stockpile stewardship, comprehensive earthquake preparedness requires the anticipation and understanding of many possible scenarios (i.e., the science base) as well as the development of procedures and technologies to deal with them (i.e., readiness).

The foundation of earthquake preparedness is scientific understanding. We must understand the behavior of earthquakes and the effects on the surrounding region and structures (location of earthquake faults, likely range of magnitudes, probable types of earth motion, etc.). To minimize property damage and loss of life, building codes for structures in earthquake-prone areas must be based on a scientific understanding of the phenomena involved (e.g., seismic motion, soil–structure interactions, stress– strain behavior of building materials). Because it is not feasible to conduct full-scale simulations of earthquakes, we must devise test methods for gathering data, develop computer models to investigate conditions for which we cannot test, and validate our models against data from experiments and actual earthquakes.

Earthquake preparedness also requires readiness. Technologies and operational procedures for responding to earthquakes must be developed and put into place ahead of time, and previously developed earthquake-response capabilities must be preserved and refined. Earthquake drills allow us to practice various emergency-response activities, incorporate new technologies and equipment. train new personnel, and find and solve unanticipated problems.

Information from experiments, drills, and earthquakes must be incorporated into both the science base and readiness. Each earthquake uncovers areas where our scientific understanding is incomplete and where emergency response needs improvement. For example, recent earthquakes in California and Japan revealed severe weaknesses in bridges, freeways, and buildings, even though many of the damaged structures were built to the most current codes (which were based on the best understanding of previous earthquakes) and had been expected to withstand even more powerful temblors.

Like science-based stockpile stewardship and management, confidence in earthquake preparedness is based on the twin pillars of scientific understanding and readiness. Scientific understanding provides the certification of safety analyses, structural specifications, and other technical steps taken to ensure safety and reliability. Readiness is ensured and demonstrated through drills and in response to actual events.

103-160; November 30, 1993). Maintaining readiness—in nuclear testing, weapons design, and weapons manufacturing—involves more than archiving current capabilities and collective nuclear memory. At the very least, we must maintain capabilities for producing and replacing limited-life components. In addition, sometime in the future, a decision may be made to resume nuclear testing or to produce new-design weapons.

In both cases, we will need to do more than activate past processes and capabilities. Some past processes and capabilities will not be available; for example, previously used materials may be unavailable, and older processes may not meet current environment, safety, and health (ES&H) requirements. We will need new materials, processes, and capabilities, and thus we must be able to take full advantage of the scientific and technological progress made between now and then.

How can the DP laboratories maintain state-of-the-art readiness for activities that cannot be carried out at the present time? The solution to this readiness problem lies in the multidisciplinary character of nuclear weapons science and technology and in the multiprogram nature of the DP laboratories. Indeed, the DP laboratories have pursued multiple programs for many years, to the mutual benefit of their national security mission and their other programs (Figure 4).

The multiprogram character of the DP laboratories enables them to tackle non-nuclear-weapons problems requiring groundbreaking advances in scientific and technical areas related to their nuclear weapons mission. By meeting their readiness mandate while solving other nationally important problems, they provide maximum return to the nation on the investments made in these laboratories.

III. Scientific Vitality at the DP Laboratories

CONTINUED scientific excellence in research and development (R&D) programs that are nationally important and technically challenging, together with state-of-the-art experimental facilities and capabilities, are key to attracting and retaining a top-quality staff at the DP laboratories. (Table 2 summarizes the educational background of the DP laboratories' scientists and engineers.) The excellence of the scientists and engineers at the DP laboratories is widely recognized. For example, between 1980 and 1995, researchers at the DP laboratories received 139 R&D 100 awards (these awards are given annually by *Research Magazine* for the 100 most significant technological advances made that year). Indeed, the technical difficulty of the laboratories' national security mission, and in particular the challenge of science-based certification of stockpile safety and reliability, demands a level of scientific excellence and vitality equal to that required for the Manhattan Project and during the Cold War years.

A remarkably effective science and technology infrastructure exists in the U.S., the major components of which are research universities, federal laboratories (including the DP national laboratories), and industry research centers. By working together, the components of this national R&D infrastructure can maximize the return on the nation's investment in science and technology. As the 1996 report by the Council on Competitiveness states:

> "Federal laboratories and other agencies are an enormous reservoir of scientific and engineering expertise. The national laboratories, in particular, are a fundamental part of the nation's R&D enterprise, and many of their unique user facilities and equipment are essential to university and corporate researchers as well as to the government. The national labs offer a continuity and scale of operation that cannot be matched by any other sector or even by foreign governments. The federal system [of laboratories] makes a decisive contribution to national security, and a number of laboratories have also proved to be very effective collaborators with academia and the private sector."

Although national debate is continuing as to how best to manage the federal component of this investment in science and technology, several things are clear. First, all components of the R&D infrastructure are essential. Each one has different responsibilities and a different goal or customer base in the overall R&D process.

Second, some overlaps in responsibilities and activities are necessary and desirable. For example, basic research is conducted by universities, national laboratories, and industry—but with different emphases. The same is true for technology demonstration and engineering development. These overlaps provide areas for scientific collaboration and cross-calibration of capabilities, which are necessary for maintaining the scientific vitality of the nation's R&D

Table 2. Educational background of scientists and engineers at the DP laboratories (as of 1995).

	Los Alamos		Livermore		Sandia		Total	
	Ph.D.	All degrees	Ph.D.	All degrees	Ph.D.	All degrees	Ph.D.	All degrees
Total number of scientists and and engineers	1474	2887	1230	2769	1383	3734	4087	9390
Number with highest degree from top 25 universities*	683 46%	915 32%	688 56%	1123 41%	695 50%	1139 31%	2066 51%	3177 34%

*Universities ranked by journal citation impact (Institute of Scientific Information database) in the various scientific and technical disciplines relevant to the DP laboratories.

infrastructure. These overlaps also make it possible for the DP laboratory scientists to recognize the value of science and technology advances made on the "outside" and to adapt them to weapons applications.

Third, collaborations between the DP laboratories and other DOE laboratories, other federal laboratories, universities, and industry engender close technical cooperation and synergy. These collaborations help all involved parties—the DP laboratories and the other institutions—get the most leverage from their R&D funds, facilities, and capabilities.

The Los Alamos, Livermore, and Sandia laboratories are closely linked by their national security mission and, as such, form an integrated R&D complex. Together, they have primary responsibility for ensuring the safety and reliability of the nation's nuclear weapons—they "own" the implementation of science-based stockpile stewardship.

These DP laboratories have common capabilities in critical core areas as well as individual specialties in various supporting technologies and certain unique facilities. They coordinate their efforts, with each laboratory tackling different pieces of an integrated program and different laboratories pursuing different approaches to a common problem. This combination of overlap and specialization ensures the wide range of capabilities required for science-based stockpile stewardship and makes for cost-effective use of major experimental facilities.

Partnerships with the wider scientific community enhance the DP laboratories' ability to address the challenge of science-based stockpile stewardship and meet their national security responsibilities. In particular, to be on the leading edge in science, the laboratories must be connected with the academic community. Likewise, to be on the leading edge in technology, the laboratories must be connected with industry.

These essential ties were recognized when Los Alamos,

The National Science and Technology Infrastructure

Thousands of institutions in the U.S. conduct R&D, with funding from the federal government, state and local governments, industry, private foundations, colleges and universities, and other sources.

- ***Industrial research*** *is carried out by thousands of firms, large and small. Some 100 large firms account for more than 50% of all industrial R&D spending; the largest performers of industrial R&D are the aircraft, communications equipment, chemical, and computer industries. Industrial laboratories typically pursue R&D that can be translated into product ideas and brought to market in two to three years.*

- *Nearly every* ***academic institution*** *conducts research, traditionally in the basic sciences and in other scientific and engineering disciplines where small laboratories and small research teams are appropriate. About 100 universities account for more than 80% of all academic R&D spending.*

- *There are more than 700* ***federal laboratories*** *doing R&D. A few dozen laboratories conduct most of the R&D done in such facilities.*

- ***Nonprofit institutions*** *also make important R&D contributions. These include medical research institutions not associated with universities and nonprofit research organizations such as Battelle Memorial Institute, Southwest Research Institute, and others.*

Types of Federal Laboratories

- ***Government-owned, government-operated (GOGO) laboratories*** *are owned, operated, and funded by the federal government and staffed by federal employees. Examples include the National Institute of Standards and Technology laboratories, the Department of Defense's laboratories, and the Department of Agriculture's regional laboratories.*

- ***Government-owned, contractor-operator (GOCO) laboratories*** *are owned and funded by the federal government and operated and staffed by private contractors. The contractor may be a profit-making firm, a nonprofit organization, or one or more academic institutions.*

  * ***Federally funded R&D centers (FFRDCs)*** *are laboratories or research centers funded wholly or substantially by the federal government. Some FFRDCs are GOCOs whereas others are contractor-owned, contractor-staffed laboratories. FFRDCs are operated by academic institutions (e.g., the Lincoln Laboratory by the Massachusetts Institute of Technology) or nonprofit organizations (e.g., Project Air Force at RAND), acting alone or in consortia, as well as by profit-making firms (e.g., Oak Ridge National Laboratory operated by Lockheed-Martin Corporation).*

  * ***National laboratories*** *are the large, multipurpose laboratories of the Department of Energy, including the Los Alamos, Livermore, Sandia, Argonne, Brookhaven, Oak Ridge, Berkeley laboratories as well as the Idaho National Engineering Laboratory, the Pacific Northwest National Laboratories, and the National Renewable Energy Laboratory. National laboratories are one type of FFRDC.*

  * ***The three DP laboratories*** *are GOCO national laboratories with national security as their primary mission. The DP laboratories are distinguished by their multidisciplinary, multiprogram nature, their wide range of critical core competencies, their ability to undertake long-term projects, their track record in executing cutting-edge science and technology, and the unique experimental facilities they build and operate.*

Table 3. Interactions of the DP laboratories with academia and industry.

	Los Alamos	Livermore	Sandia	Total
Research associates[1] at DP laboratory facilities (1995):				
University faculty	155	352	25	532
Students[2]	1245	490	441	2176
Industry researchers	50	101	88	239
Post-doctoral fellows at DP laboratories (1995)	360	168	100	628
Number of coauthored publications[3] in scientific journals (1991–1995):				
With university coauthors	3378	2113	1573	7064
% of total publications	47%	44%	46%	46%
With industry coauthors	927	559	592	2078
% of total publications	13%	12%	17%	14%
CRADAs[4]:				
Total number	181	175	262	618
Total value (million $)[5]	$400	$570	$680	$1650

[1]On site for 1 month to 1 year.
[2]Summer or part-time hires.
[3]Institute of Scientific Information database.
[4]Cooperative research and development agreements.
[5]Total dollars from all partners (laboratories and industry participants; cash and in-kind contributions).

Livermore, and Sandia were founded. Los Alamos and Livermore were created and staffed by academics, and they have been managed since their inception by the University of California. Similarly, Sandia was deliberately staffed and managed by industry, first AT&T and now Lockheed–Martin (Table 3).

Science-based stockpile stewardship is a "grand challenge" that touches on almost every discipline of science and technology. It cannot be carried out in isolation from the broader scientific and technical community. In addition, in an era of tightly constrained budgets, it is essential that the DP laboratories carry out their mission responsibilities as cost-effectively as possible. Thus, the laboratories must enhance existing partnerships and establish new partnerships with universities, industry, and other research institutions. The inspiration that arises out of associations with university research, the bottom-line pragmatism that develops through interactions with industry, and the intellectual stimulation that accompanies interlaboratory collaborations all play crucial roles in fostering the scientific and technical vitality of the DP laboratories.

IV. The DP Laboratories: Meeting the Challenge

THE technical challenge facing the DP laboratories is two-pronged: (1) ensuring the safety and reliability of the enduring U.S. stockpile without nuclear testing and without new-design weapons and (2) sustaining the intellectual and technical capabilities for nuclear testing and new-design weapon production, should they be needed at some future date.

Some of the activities required for maintaining the U.S. stockpile are unique to that mission—in particular, the design and assessment of the nuclear explosive package and work with plutonium—and these activities must be carried out at the DP laboratories within the nuclear weapons program. However, given the multidisciplinary nature of nuclear weapons work, much of the science and engineering and many of the capabilities required for science-based stewardship can be developed and

Special Facilities at the DP Laboratories

Many of the major experimental facilities at Los Alamos, Livermore, and Sandia are special or unique. Often, the development, construction, and operation of these facilities are beyond the capabilities and resources of industry, universities, and other private research institutions. The laboratories make many of their facilities available to outside researchers, often through collaborations with laboratory scientists. Benefits accrue to both parties. Outside researchers gain access to otherwise unavailable, cutting-edge experimental facilities. The joint projects and "connectivity" with scientists from academia, industry, and other government laboratories enhance the DP researchers' scientific and technical vitality in disciplines and technologies relevant to their national security mission. Often, these collaborations bring to the laboratories young investigators, such as graduate students and postdoctoral researchers, who form a pool for recruiting new staff members. Below we give examples of such outside use of special facilities at each of the DP laboratories.

• ***Livermore's Nova Laser.*** *The Inertial Confinement Fusion (ICF) Program supports an initiative that makes Nova, the world's largest laser, available to outside researchers. Approximately 10% of the shots on Nova are allocated for this purpose (Nova averages 1000 to 1100 shots per year). Proposals for experiments using Nova are submitted for peer review to a committee of experts in plasma physics and laser–matter interaction from outside laboratories and universities. For the 1996 fiscal year, nine projects were approved on such topics as supernova hydrodynamics, x-ray optics development, and new techniques in plasma spectroscopy. All of the projects fall into disciplinary areas relevant to the laboratories' national security mission. As a result of these and other collaborations, more than 15% of the refereed publications from Livermore's ICF Program (a total of 175 in 1995) include university researchers as coauthors.*

• ***Los Alamos' Neutron Science Center (LANSCE).*** *The LANSCE accelerator (previously called LAMPF, the Los Alamos Meson Physics Facility) is the most powerful proton accelerator in the world and is used for a wide range of basic science and defense-related research. It is supported jointly by DOE's Offices of Defense Programs and Energy Research (Basic Energy Sciences). Its capabilities as a source of intense proton and neutron beams are in high demand, particularly for stockpile stewardship and management activities (e.g., accelerator production of tritium) and for research in materials science, chemistry, structural biology, fundamental nuclear and particle physics, and geology. A great advantage of this accelerator facility is that multiple R&D projects can be carried out simultaneously, providing for valuable synergism among the disciplines and permitting the flow of ideas among academic, industrial, and DP laboratory scientists. Proposals for experiments at LANSCE are evaluated by peer-review committees for scientific merit of the proposed basic research and/or relevance of defense-related research to stockpile stewardship and management. Some 50 to 100 users a month conduct experiments at LANSCE.*

• ***Sandia's Combustion Research Facility.*** *This DOE user facility is available to visiting scientists from industry, universities, and other government laboratories (typically 100 or more each year). An active post-doctoral research program provides advanced training for scientists and engineers in combustion science. A primary thrust of research at this facility is the development of advanced combustion diagnostic techniques, particularly noninvasive and versatile laser-based optical techniques, for measuring temperatures, chemical species concentrations, and other combustion-related parameters. Complementing diagnostic development is a combustion modeling program, in which researchers are developing numerical methods for predicting the mutual influences of chemical reactions, fluid transport, and other important combustion processes. Many of the diagnostic and modeling techniques developed to provide a fundamental understanding of combustion are directly applicable to the surveillance, assessment, remanufacturing, and certification aspects of science-based stockpile stewardship.*

advanced through programs addressing other national needs.

The benefits of these non-nuclear-weapons programs are multifold. Because the DP laboratories have developed experimental facilities and capabilities that are unavailable elsewhere (Table 4), they are in a position to make vital and unique contributions to these other programs. Indeed, the spin-outs from the laboratories' weapons work have had a major impact on science and technology in other areas of national importance, including energy supply, environmental preservation, and human health (Table 5).

More important, these other programs help preserve scientific vitality at the DP laboratories, which is essential for meeting their national security responsibilities. These programs provide weapons scientists with valuable interactions with the wider scientific community, connections that help maintain the critical mass of expertise required for their nuclear weapons work. Through these interactions and collaborations, the unique capabilities and facilities available at other laboratories, universities, and industries can be applied to the DP laboratories' national security mission.

Table 4. Some of the special or unique experimental facilities at the three DP laboratories.

Los Alamos	• Antenna and pulsed-power outdoor range	
	• Beryllium atomization and thermal spray facility	
	• Combustion-driven supersonic flow facility	
	• Detonation systems facilities	
	• Explosive pulsed-power facility	
	• Ion Beam Materials Laboratory	
	• Large-scale explosives formulation and fabrication facility	
	• Los Alamos Neutron Science Center	
	• National High-Magnetic Field Laboratory	
	• Plasma processing research facility	
	• Pulsed High-Energy Radiographic Machine Emitting X Rays	
	• Subpicosecond high-brightness accelerator facility	
	• Supercritical fluids experimental facility	
	• TA-55 plutonium facility	
	• Thick-film processing and deposition facility	
	• Trident laser	
Livermore	• Advanced Manufacturing Technology Deployment Center and User Facility	
	• Atomic vapor laser isotope separation facilities	
	• Big Explosives Experimental Facility (at NTS)	
	• Center for Accelerator Mass Spectrometry	
	• Electron Beam Ion Trap facility	
	• Experimental Test Accelerator	
	• Flash X-Ray facility	
	• Forensic sciences laboratory	
	• High Explosives Applications Facility	
	• Large Optics Diamond Turning Machine	
	• Linear electron accelerator	
	• Microtechnology Center laboratories	
	• Nova laser	
	• Petawatt and ultrashort-pulse lasers	
	• Plutonium facility	
	• Two-stage gas guns (2)	
Sandia	• Advanced Manufacturing Processes Laboratory	
	• Combustion Research Facility	
	• Explosive Components Facility	
	• Hermes III accelerator and gamma simulator	
	• High Pressure Laboratory	
	• Integrated Manufacturing Technologies Laboratory	
	• Integrated Materials Research Laboratory	
	• Kauai Test Range (in Hawaii)	
	• Liquid metal processing and thermal spray laboratories	
	• Massively Parallel Computing Research Laboratory	
	• Microelectronics Development Laboratory	
	• National Solar Thermal Test Facility	
	• Particle Beam Fusion Accelerator II	
	• Primary Standards Laboratory	
	• Robotic Manufacturing Science and Engineering Laboratory	
	• Rock mechanics laboratory	
	• Saturn pulsed-power facility	
	• Thermal Battery Development Facility	
	• Tonopah Test Range (in Nevada)	

Benefits of Other Programs to the DP Laboratories' National Security Mission

Through their contacts with the wider scientific community, the DP laboratories have been able to build upon scientific discoveries made by other researchers and to adapt technologies developed on the "outside" to meet weapons program needs. In addition, the use of weapons-related innovations by the DP laboratories' non-weapons programs as well as by industry and the wider scientific community has led to further discoveries that have benefited the nuclear weapons program and enhanced national security.

Work on these other programs and the "spin-ins" and "spin-backs" that result help the DP laboratories carry out their national security mission. Multiprogram work enhances the transfer of ideas, the science and technology base, computational modeling capabilities, etc. As the following examples illustrate, this broader and richer portfolio of expertise enables the DP laboratories to address nuclear weapons and national security issues more rapidly and effectively than would otherwise be possible (Table 6).

Magnetic Fusion Energy, Strategic Defense, and Advanced Hydrotesting

The U.S. program in magnetic fusion energy (originally called Project Sherwood) was initiated at the DP laboratories during the early years of the nuclear weapons program. Weapons scientists were among the first to recognize the potential for harnessing the thermonuclear fusion process for civilian energy production. The Magnetic Fusion Energy (MFE) Program, now supported by DOE's Office of Energy Research, has had many synergistic couplings to the nuclear weapons program and the laboratories national security work.

For example, the MFE Program developed the technology for producing neutral particle beams for injecting power and particles into magnetically confined fusion plasmas. This technology formed the basis for the Defense Department's effort to develop intense neutral beams for a space-based missile defense system. In particular, the accelerator required to produce the negative ion beam and much of the technology for transporting and neutralizing the beam were adapted from the MFE Program.

The induction linear accelerator was invented as part of the laboratories' Astron Project (one of the first major MFE projects) in controlled thermonuclear fusion and was developed further through application to numerous magnetic fusion experiments. Subsequently, linear accelerators were used to generate powerful microwave beams, using free-electron lasers, for a potential antimissile defense system. Today, linear accelerators are at the heart of Livermore's Flash X-Ray (FXR) facility and Los Alamos' Dual Axis Radiographic Hydrodynamic Test (DARHT) facility, generating the high-energy beams of x rays required for hydrodynamic testing of imploding primaries.

(text continued on p. 18)

Fundamental Physics Research, Proton Radiography for Advanced Hydrotesting, and Brookhaven's Advanced Gradient Synchrotron

Through their non-DP programs, DP researchers engage in valuable collaborations with the wider scientific community. Not only do these programs bring outside researchers to the DP laboratories, they also allow DP researchers to gain access to expertise, capabilities, and facilities not available at the DP laboratories. This is particularly true in nuclear science, where experimentation often requires accelerators and other large physics machines.

Nuclear science is one of the disciplines critical to nuclear weapons work, and the DP laboratories conduct research at the forefront of nuclear physics and related technologies. For example, as part of the Nuclear Physics Program of DOE's Office of Energy Research, DP scientists are collaborating with researchers from universities and other national laboratories on experiments to probe the fundamental nature of nuclear matter at the extreme conditions that are created when protons or other nuclei collide with heavy nuclei at relativistic velocities (i.e., near the speed of light).

In particular, recent experiments at the Alternating Gradient Synchrotron (AGS) at the Brookhaven National Laboratory focused on understanding the equation of state of nuclear matter and on searching for strange particles, such as the H_0 particle containing six quarks, that are produced in collisions with fixed targets at GeV energies. DP scientists are also part of a collaboration that is developing the PHENIX detector for the Relativistic Heavy Ion Collider (RHIC), the next-generation "flagship" facility of the DOE's Nuclear Physics Program (now under construction at Brookhaven).

Some of these experiments at Brookhaven's AGS are providing essential data for the Stockpile Stewardship and Management Program. DOE/DP is considering the development of an Advanced Hydrotest Facility (AHF) to provide improved understanding and experimental validation of the hydrodynamic behavior of implosions under a variety of conditions. X-radiography is a key experimental tool for obtaining time-dependent images of imploding objects in laboratory nonnuclear experiments and is a strong candidate for deployment at the AHF. However, the DP laboratories are also exploring an alternative technique—proton radiography—for obtaining three-dimensional, time-dependent images with high spatial resolution. Proton radiography would use multiple, high-intensity, high-energy (20-GeV), pulsed proton beams generated by a single accelerator.

To evaluate the potential of this advanced radiography concept, DP scientists must first understand the nuclear physics underlying the interaction of the protons with the target (i.e., the proton-induced reactions of the heavy nuclei). The ongoing fundamental science experiments at Brookhaven's AGS, involving high-energy proton collisions with fixed targets, are enabling DP researchers to measure nuclear cross sections for the various elements from beryllium to uranium that are required for proton radiography. In addition, DP scientists recently used 10-GeV protons to image a test object at the AGS, confirming the promise of proton radiography as an advanced imaging technique.

Table 5. Highlights of spin-outs from the DP laboratories' nuclear weapons work to other areas of science and technology.

Spin-out	Weapons program activity
Advanced Manufacturing	
Microelectronics	
• Laminar-flow clean room	• Ultraclean assembly techniques
• Automatically reprogrammable robotic-cleaning process for integrated circuit boards	• Expertise in computer control of complex systems; precision fabrication techniques
• Demonstration that low-flux soldering (which produces few to no harmful emissions) meets military specifications for printed circuit boards	• Experience in developing and qualifying materials, materials, processes, and components for stringent nuclear weapons applications
Manufacturing processes	
• Diamond turning and precision machining technologies for the optics, semiconductor, and computer industries	• Weapons-related precision fabrication expertise
• Near-net-shape casting processes	• Precision fabrication expertise; experience with exotic metals
• Processes, materials, and computational tools for large-area flat-panel displays for high-performance communications and information-processing systems	• Weapons-related expertise in precision and nanofabrication, materials processing and characterization, and computer modeling
• Extreme-ultraviolet projection lithography for next-generation microcircuit fabrication	• Expertise in x-ray generation, x-ray optics, nanofabrication, and lasers
Advanced materials	
• Aerogels, including production processes, for use in energy-storage devices, integrated dielectrics, and water deionization	• Production and characterization of specialty materials for nuclear weapons and weapons experiments
• Optically active ceramics for optical memory devices	• Expertise in ceramic materials for defense applications, precision fabrication, and computers
• Advanced synthesis and processing methods, including joining and bonding techniques, corrosion-resistant coatings, superplastic metal forming, and computer design of novel materials	• Expertise in materials processing for tailored properties, computational simulation, and fundamental physics and chemistry
Energy	
Fission energy	
• Atomic vapor laser isotope separation technology for enriching uranium fuel for commercial nuclear power reactors	• Expertise in physics and chemistry of nuclear materials, lasers and electro-optics, computer control, and systems engineering
• Probabilistic risk assessment methodology for reactor safety analyses; radiation effects studies on reactor materials	• Nuclear safety analyses; expertise in radiochemistry and materials science
Fossil energy	
• Underground coal gasification	• Geoscience expertise; directional drilling techniques from underground nuclear testing
• Oil-shale retorting	• Geoscience expertise from underground nuclear testing
• Detailed understanding of gasoline combustion and emissions formation processes	• Advanced diagnostics techniques; computational modeling capabilities
Renewable energy	
• Geothermal energy technologies, including underground imaging of geothermal sources	• Geoscience expertise; diagnostics from underground nuclear testing
• Hot-dry-rock concept for mining and harnessing heat from deep within the Earth	• Drilling technology from underground nuclear testing

Table 5. Continued.

Spin-out	Weapons program activity
Fusion energy • First-time-ever laboratory demonstration of thermonuclear plasma	• Expertise in atomic and nuclear physics and complex experimentation
Environment	
Atmospheric science • National Atmospheric Release Advisory Center for modeling, in near-real-time, the atmospheric dispersal of hazardous materials	• Meteorological modeling for nuclear testing; chemical physics physics expertise
• Regional and global climate modeling, including effects of natural and human activities processes	• Meteorological modeling for nuclear testing; expertise in numerical simulation, chemical physics, and dynamic
• Rapid reduction process for destruction of nitrogen oxides (a major contributor to smog and acid rain) in exhaust streams	• Experience with energetic materials and controlled combustion; expertise in chemical physics
Environmental remediation • Sensor systems, underground imaging technologies, and computer simulations of environmental remediation alternatives	• Instrumentation, geoscience, and computational modeling expertise from underground nuclear testing
• Innovative in-situ cleanup technologies, including dynamic underground stripping and biofiltration	• Instrumentation, geoscience, and computational modeling expertise from underground nuclear testing
• Isotope fingerprinting technique for determining sources of uranium and plutonium contamination at the weapons production plants	• Geoscience and radiochemistry expertise from underground nuclear testing
Geoscience • Studies of radionuclide transport in rock for the for proposed Yucca Mountain nuclear waste repository	• Geoscience expertise; computer modeling codes developed underground nuclear test containment
• Studies of radionuclide chemistry and mobility brine environment envisioned for the Waste Isolation Pilot Plant	• Geochemistry expertise; computer modeling codes in the developed for underground nuclear test containment
Health	
Bioscience • Studies of the effects of human health risks associated with mutagens and carcinogens, including ionizing radiation and chemicals	• Expertise in nuclear physics, nuclear chemistry, toxic materials, ultrasensitive detectors and instrumentation
• Discovery of mutagens in cooked meats and demonstration of their binding to DNA, supporting the link to cancer in humans	• Ultratrace analysis techniques, including accelerator mass spectrometry
• Database on subtypes of HIV and tracking of new strains and rates of mutation (part of an international effort to develop an HIV vaccine)	• Expertise in computing science and advanced information management
• Bioassays and biodosimetry methods, including monoclonal antibodies, whole chromosome paints, and fluorescence in-situ hybridization	• Expertise in lasers, nuclear and organic chemistry, and computer-controlled instrumentation
Genomics • Participation in the international Human Genome Project, including construction of world's largest library of DNA clones (available to researchers worldwide) and maps of chromosomes 16 and 19	• Expertise in physics, chemistry, engineering, instrumentation, and computational science

Table 5. Continued.

Spin-out	Weapons program activity
• Identification and cloning of DNA repair genes	• Expertise in physics, chemistry, engineering, instrumentation, and computational science
Bioinstrumentation • Advanced imaging methods, including high-resolution 3D x-ray imaging, high-speed 3D image analysis, atomic-force and scanning tunneling microscopy, and cryo-crystallography	• Expertise in nondestructive evaluation of weapons assemblies, x-ray instrumentation, material surface characterization, and complex image reconstruction
• Several generations of automated high-speed flow cytometers	• Expertise in precision engineering, lasers, radioisotopic tagging, and computer control of complex systems
Health-care technologies • Digital mammography, including software for computer-assisted examination of mammograms	• Weapons-test-related expertise in x-ray detection, instrumentation, and data-analysis techniques
• Noninvasive sensor for blood glucose	• Technology for measuring gases in nuclear weapon high explosives
• Techniques for in-vivo imaging of the progression and treatment of osteoporosis	• Three dimensional computed tomography developed for imaging nuclear assemblies and waste containers
• Microsurgical tools for breaking up blood clots and repairing aneurysms	• Expertise in micro- and nanofabrication, device miniaturization, fiber-optics, and lasers
• Accurate dose calculations for radiation treatment of cancer	• Computational methods and nuclear reaction data for simulating radiation transport in nuclear weapons
Fundamental Science and Technology	
Computing science • Pioneering advances in supercomputing, including operating systems, data transmission, storage, and retrieval, applications and modeling codes, and computer architectures	• Weapons-development-driven expertise in all aspects of computers and computing science
• Photonics technologies and all-optical networks for ultrahigh-speed communications and data transmission	• Techniques and equipment developed for weapons components, nuclear testing, and weapons-related experiments
• Numerous innovative mathematical approaches for computational modeling, including Monte Carlo methods, automatic mesh generation, models for chaotic behavior, and models for massively parallel processing	• Expertise and innovation in computational modeling and numerical simulation of weapons performance
• Numerous computer codes and models with civilian and commercial applications, including COYOTE, DYNA, EQ3/6, JAS, NIKE, and TRACER3D	• Codes developed to model behavior of weapons, weapons components, target structures, and weapon residues for a wide range of conditions (e.g., dynamic impact, long-term storage)
Physics • Technique for detecting neutrinos, for which the DP researchers were awarded the 1995 Nobel prize in physics	• Expertise in atomic and nuclear physics and complex experiment design
• First-ever metallization of hydrogen, an accomplishment with major implications for inertial confinement fusion, superconductivity, and planetary science	• Expertise in condensed-matter and high-pressure physics, hydrodynamics, and experimentation under extreme conditions
• Experimentally validated theory of the fundamental electro-weak and electro-strong interactions between nuclear particles	• Nuclear physics, atomic physics, and complex experimentation expertise
• Novel ion traps for generating and investigating the fundamental properties of ionized atoms	• Expertise in atomic physics, spectroscopy, and the design of innovative experimental apparatus

Table 5. Continued.

Spin-out	Weapons program activity
• Experimentally validated theory of the opacity of stellar matter, which had a major impact on the interpretation of astrophysical phenomena (e.g., pulsating stars)	• Expertise in atomic and plasma physics; techniques developed for laboratory weapons physics experiments
Chemistry and materials science	
• Interfacial force microscope for measuring the force of chemical bonds between atoms for studies of the fundamental structure and properties of materials	• Expertise in materials science, chemistry, physics, and instrumentation; development of numerical models of aging effects on adhesive bond interfaces
• High-temperature superconducting materials (i.e., materials with essentially zero electrical resistance)	• Expertise in materials science, chemistry, physics; magnetic fusion experiments
• Improved understanding of the electronic structure of materials, leading to a better scientific interpretation of superconductivity	• Expertise in materials science, chemistry, physics; magnetic fusion experiments
• Strained-quantum-well-compound semiconductor technology, the basis for today's highest-performance microelectronic devices	• Materials science, chemistry, physics, and microelectronics expertise; arming, fuzing, and firing components; use-control devices; microelectronics for self-aware weapons
Lasers and accelerators	
• Discovery of the principle of laser-beam relaying to suppress optical damage in lasers, permitting cost-effective ultrahigh-power lasers	• Expertise in lasers and electro-optics developed for inertial-confinement fusion experiments
• Various semiconductor lasers for optical communications networks, industrial-scale precision manufacturing, metal and ceramic processing, and advanced medical therapeutics	• Expertise in lasers and electro-optics developed for inertial-confinement fusion experiments
• Invention of the side-coupled radiofrequency cavity, leading to high-power, low-cost, compact particle accelerators for physics research, medicine, (e.g., cancer therapy), materials processing, and energy applications	• Electron accelerators developed for weapons diagnostics; expertise in electromagnetics and pulsed-power technologies
National Security	
Nonnuclear weapons	
• Free-form shaped-charge technology for high-performance, small, lightweight munitions	• Expertise in materials science, dynamic engineering, and high explosives
• Advanced ceramic armors	• Expertise in high explosives and advanced materials, including design, synthesis, processing, and characterization for specific applications
• All-electronic fuze for conventional weapons	• All-electronic fuze developed for and used in nuclear weapons
• One-container, storage-stable sticky foam that creates a personnel barrier, a potential nonlethal weapon for military and law-enforcement use	• Sticky foam developed initially for nuclear weapons security
Reconnaissance	
• Advances in synthetic aperture radar (SAR), including new image formation algorithms, precision motion compensation, automatic focusing, and high-speed signal processing	• Data manipulation and analysis techniques developed initially for underground nuclear testing and later refined in laser-related experiments
• Miniaturized SAR, SAR interferometry, and automatic target recognition systems for airborne reconnaissance and high-resolution terrain elevation maps	• Data manipulation and analysis techniques developed initially for underground nuclear testing and later refined in laser-related experiments

Energy and Environmental Research Computer Codes and Weapons Safety

Numerical simulation codes are developed and advanced at the DP laboratories in a wide range of projects and applications. A major goal of DP computer modeling efforts is the development of three-dimensional, full-system, detailed models of phenomena of interest (Figure 5). For example, programs in oil shale and waste transportation, funded by the DOE's Office of Fossil Energy, supported the initial development of a family of exceptionally powerful and accurate nonlinear solid-mechanics finite-element codes. Today, these codes are used to simulate weapon crashes, warhead penetration into hardened or underground structures, and weapon manufacturing processes.

The DOE's Offices of Environmental Management and Civilian Radioactive Waste Management funded most of the development of another set of codes through the Waste Isolation Pilot Plant (WIPP) Program as well as much of the development of finite-element codes for modeling the response of geologic media to the storage of nuclear waste packages for the Yucca Mountain Project. These codes provide a level of speed, detail, complexity, and accuracy unavailable elsewhere. They have evolved into a suite of codes for simulating such complex weapon manufacturing processes as brazing, welding, encapsulation, and glass-to-metal bonding.

Deep Borehole Disposition of Plutonium from Dismantled Weapons

Large quantities of surplus plutonium have resulted from the dismantlement of thousands of nuclear weapons by both the U.S.

(text continued on p. 21)

Table 5. Continued.

Spin-out	Weapons program activity
• Gamma-ray detectors to study the effects of space-generated nuclear particles, gamma rays, and x rays on the functioning of satellites and ground-based electrical systems	• Instrumentation and nuclear detection and data analysis techniques developed initially for underground nuclear testing
Strategic missile defense	
• High-intensity accelerators and free-electron lasers for space- and ground-based strategic missile defense concepts	• Expertise in nuclear weapons effects and weapons effects testing
• Advanced charge-coupled device technology for robust sensors and instrumentation	• Development of charge-coupled devices for weapons experiments and underground nuclear testing
Arms control	
• Seismic analysis techniques for treaty verification, proliferation detection, and nuclear emergency response applications	• Understanding of nuclear weapons effects; geoscience expertise from underground nuclear testing
• Imaging gamma-ray detector for nonintrusive inspection of nuclear warheads for treaty verification	• Instrumentation developed initially for underground nuclear testing
• Technical advice about treaty verification technologies and foreign nuclear weapons programs for arms-control negotiations	• Expertise in all aspects of the U.S. nuclear weapons program, including nuclear-test related instrumentation and data analysis
Nuclear nonproliferation	
• Nuclear material assay methods and accountability procedures for tracking stocks and flows of nuclear materials worldwide	• Methods and procedures for handling nuclear materials developed for nuclear testing and weapons development
• Remote sensing and detection technologies for identifying signatures of foreign nuclear weapons programs and for intercepting smuggled weapons and weapon material	• Instrumentation, detection, data analysis, and nuclear materialsexpertise from nuclear testing; in-depth knowledge of all aspectsof the U.S. nuclear weapons program
• Neutron detectors for tracking and attribution of surplus nuclear material	• Weapons- and test-based expertise in nuclear materials and measurements

Table 6. Highlight spin-back and spin-in contributions to the DP laboratories' national security mission with origins in the laboratories' non-DP work.

Non-DP program	Technology	National security application
	Advanced Hydrotesting and Weapons Research	
• Magnetic Fusion Energy Program (DOE Office of Energy Research)	• Induction linear accelerator (Astron Project)	• Linear accelerators for Livermore's FXR facility and Los Alamos' DARHT facility
• Repetitive High-Energy Pulsed- Power Program (DoD Strategic Defense Initiative Organization)	• High-peak-power, high-average power magnetic switching, high-repetition-rate power compressors, and pulsed-power systems developed for the RHEPP I and RHEPP II accelerators	• Accelerator and magnetic switching technology for future advanced hydrodynamic test facility • High-repetition-rate pulsed-power technology required for future high-intensity test facilities facilities for weapons testing in x-ray and high-energy-density environments
	Computational Simulation	
• Oil Shale Program (DOE Office of Fossil Energy)	• Suite of powerful and accurate transient dynamics codes	• Nonlinear solid-mechanics finite-element codes for simulating weapons crashes and penetration into hardened structures
• National Energy Research Supercomputing Center (DOE Office of Energy Research)	• National Storage Laboratory, interactive batch gang scheduler for massively parallel processors; ESnet; adaptive mesh refinement techniques	• Massively parallel processing expertise, high-speed networks, remote communications, and advanced computational algorithms and modeling tools for high-resolution, three-dimensional simulation of weapons performance
	Weapons Manufacturing	
• Atomic Vapor Laser Isotope Separation (AVLIS) Program (DOE Office of Nuclear Energy)	• AVLIS laser technology; vapor deposition process; electron-beam melting technology; robotic equipment	• Laser technology for high-precision cutting for weapons assembly and disassembly • Processes for precision fabrication of uranium-niobium alloy
• Repetitive High-Energy Pulsed-Power Program (DoD Strategic Defense Initiative Organization)	• High-power ion beams produced by the RHEPP I and RHEPP II accelerators	• Accelerator-based ion-beam techniques for surface treatment of metals, ceramics, and polymers
• Waste Isolation Pilot Plant Program (DOE Office of Environmental Management) • Yucca Mountain Project (DOE Office of Civilian Radioactive Waste Management)	• Finite-element codes for modeling response of geologic media to storage of nuclear waste packages	• Finite-element codes for simulating weapons manufacturing processes
	Stockpile Maintenance	
• Basic nuclear physics research at LANSCE and LAMPF (DOE Office of Energy Research)	• Neutron production studies of proton bombardment on elements from beryllium to uranium	• Neutron production measurements, neutron activation, and radiation damage studies for the Accelerator Production of Tritium (APT) Program
• Demilitarization activities (Department of Defense)	• Chemical processes for disposing of surplus explosives and propellants	• New, less expensive process for synthesizing TATB high explosive
• Magnetic Fusion Energy Program (DOE Office of Energy Research)	• Metallurgy expertise and fabrication technologies developed for the Tore Supra tokamak	• New metal–ceramic brazing techniques for refurbished weapons components

Table 6. Continued.

Non-DP program	Technology	National security application
• Magnetic Fusion Energy Program (DOE Office of Energy Research) • Ground Test Accelerator Program (DoD Strategic Defense Initiative Organization)	• Los Alamos Plasma Source Ion Implantation Facility, process for wear-resistant coatings of diamond-like carbon on aluminum parts	• Ion implantation and deposition process for erbia coatings for plutonium containment vessels (weapon pits, crucibles, molds)
	Stockpile Surveillance	
• Materials science research (DOE Office of Basic Energy Science)	• Interfacial force microscope for studies of fundamental aspects of adhesive bonding	• Interfacial force microscope for atomic-level studies of adhesion and bonding in weapons components, required for accurate models of effects of aging on bonds and interfaces
• Biophysical research (DOE Office of Health and Environmental Research)	• Superconducting quantum interference devices (SQUIDs) for magneto-encephalography and magneto-cardiography	• SQUID sensors for evaluating material defects and corrosion in stockpile weapons
	Environmental Cleanup	
• Applied plasma physics research (DOE Office of Energy Research) • Plasma physics technology development (DOE Office of Environmental Management)	• Plasma processing technologies, such as large-scale reactive ion etching	• Plasma decontamination techniques for glovebox interiors, hydrotest blast shields, and other apparatus contaminated with organics, actinides, and nuclear materials
	Nuclear Materials Disposition	
• Continental Scientific Drilling Project (DOE Office of Basic Energy Sciences)	• Deep borehole drilling techniques, geoscience of continental crust	• Drilling and earth science expertise for study of the feasibility of plutonium disposal in deep boreholes
	Nuclear Test Readiness	
• Defense Advanced Research Projects Agency (Department of Defense)	• Photonics technology for optical interconnects and optical networks, required for massively parallel computing systems and high-performance telecommunications	• Photonics technology required for collecting high volumes of data in remotely controlled, short-duration experiments
	Strategic Defense	
• Magnetic Fusion Energy Program (DOE Office of Energy Research)	• Induction linear accelerator, negative ion-source technology, beam transport and neutralization technologies	• Linear accelerators, free-electron lasers, and neutral beam technology for missile defense concepts
	Treaty Verification and Arms Control	
• Alternative energy projects (DOE Office of Basic Energy Sciences)	• Geoscience and seismology expertise gained from hot-dry-rock alternative energy technology	• Advanced seismic techniques for detecting distant underground nuclear tests
• Biophysical research (DOE Office of Health and Environmental Research)	• Superconducting quantum interference devices (SQUIDs) for magneto-encephalography and magneto-cardiography	• SQUID sensors for examining storage drums containing treaty-controlled weapons items and materials and for locating buried landmines and unexploded ordnance

Table 6. Continued.

Non-DP program	Technology	National security application
	Nonproliferation	
• Combustion Research Center (DOE Office of Basic Energy Sciences) • Waste management studies (DOE Office of Environmental Management) • Atmospheric Radiation Measurement Program (DOE Office of Health and Environmental Research) • SPECTRE Project (U.S. Army)	• Laser-based diagnostics for Combustion Research Center • Laser-based detectors for hazardous chemicals at DOE landfill sites • Lidar system for measuring atmospheric water vapor and aerosols • Information analysis techniques; spectroscopy of aerosols and complex chemicals in air	• Laser-based diagnostics, lidar technology, and data analysis techniques for remote monitoring and detection of atmospheric chemical signatures indicative of nuclear, chemical, or biological weapons activities
• Biophysical research (DOE Office of Health and Environmental Research)	• Superconducting quantum interference devices (SQUIDs) for magneto-encephalography and magneto-cardiography	• SQUID sensors for locating and characterizing covert underground weapons facilities

Criteria for DP Laboratory Involvement in Other Programs

Experience has shown that the DOE's national laboratories are most valuable when:

- *The national interest is at stake.*
- *Leading-edge science and technology are required.*
- *Large and complex research facilities are needed.*
- *Expertise in a variety of disciplines must be integrated.*
- *The technical risk is high.*
- *A sustained commitment is necessary.*

In addition, involvement of the DP laboratories in nondefense programs is appropriate when the other programs:

- *Are synergistic with the laboratories' national security mission. Work conducted at the DP laboratories must benefit the laboratories' primary mission.*
- *Involve the laboratories as full partners. Although the DP laboratories do not need to own these other programs, as they own their stockpile stewardship mission, they do need to be more than contractors or job shops. Rather, they need to share in the responsibility for the success of these missions.*
- *Contribute to the laboratories' scientific vitality. By advancing the frontiers of knowledge and the state of scientific art, the laboratories enhance their ability to solve future stockpile and national security problems.*
- *Promote permeability with the wider scientific community. In order to maintain the critical mass of expertise required for their national security mission, the laboratories need to be able to draw upon the wider scientific community, applying or adapting outside expertise to address weapons-specific issues.*
- *Are beyond the chosen pursuits of academia and industry. The DP laboratories are highly connected with other research laboratories, industry, and academia. They use their non-DP programs to strengthen their connections with these institutions, not compete with them.*

and Russia. The safe and secure disposal of this plutonium is a growing national and global security problem. The DP laboratories are working with Nevada Test Site (NTS) staff to examine the feasibility of disposing of excess plutonium in 4-km-deep boreholes drilled in stable continental crust. Much of the expertise for this project comes from laboratory participation over the last decade in the Continental Scientific Drilling Project, sponsored by the DOE's Office of Basic Energy Sciences. The goal of this project was to gain an understanding of the continental crust as related to energy production, industrial minerals, and natural hazards, and the resulting experience and knowledge is proving to be directly applicable to the problem of plutonium disposal.

Accelerator Production of Tritium for Stockpile Management

An assured supply of tritium is an essential component of the

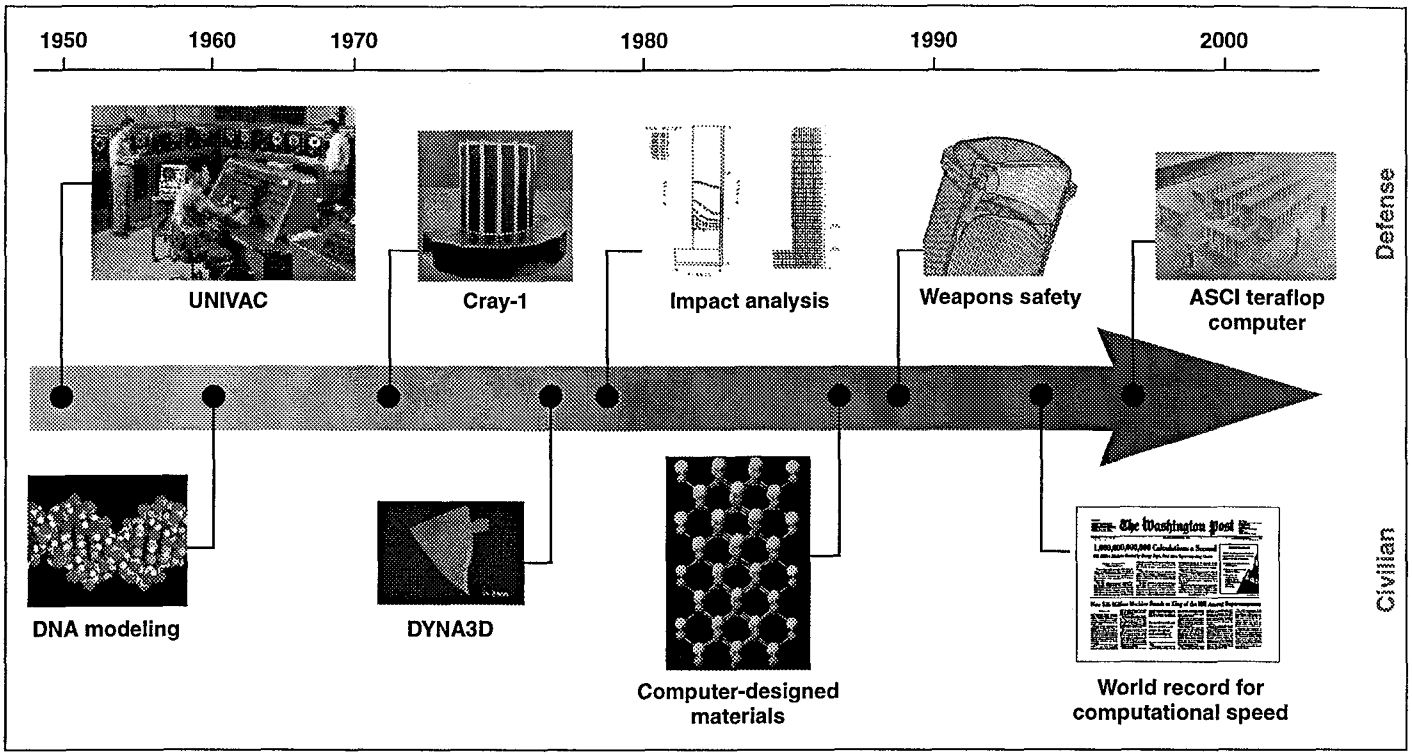


Figure 5. *To meet the demands of their nuclear weapons work, the DP laboratories pioneered computing science and drove the development of supercomputers. Today, the laboratories are partnering with the U.S. computer industry in the development of the next-generation computers required to run the complex, three-dimensional numerical simulations that are required now that the U.S. has ceased nuclear testing.*

Stockpile Stewardship and Management Program. Accelerator production of tritium (APT), one of two approaches being pursued by the DOE, has benefited extensively from research at the Los Alamos Neutron Science Center (LANSCE) and the Los Alamos Meson Physics Facility (LAMPF). These facilities and the research conducted there have their origins in programs supported by the DOE's Office of Energy Research.

In the 1980s, as part of the basic nuclear physics research funded by the Office of Energy Research, measurements were made at LANSCE to characterize neutron production by the bombardment of 100- to 800-MeV protons on thin and thick targets made from elements ranging from beryllium to uranium. These measurements were used recently by DP researchers to develop the LAHET code system for calculating high-energy particle transport. This code is the primary design tool for the APT target.

Ongoing experiments at LANSCE are benchmarking the total neutron production in prototype APT target assemblies. Additional experiments are being conducted to optimize the tritium production efficiency of the targets. Other experiments at LANSCE are measuring radionuclide production and radiation damage in candidate materials for the APT target system. These results are being used to quantify issues related to target handling, target lifetimes, safety, and environmental impact. Continuing weapons-related work at LANSCE includes studies of material damage due to exposure to intense neutron beams, the development of advanced radiography techniques using neutron and proton beams, and tests of the effects of intense radiation on the functioning of electronic circuits.

Surplus Explosives and TATB for Weapons Refurbishment

High explosives intimately affect both the safety and performance of nuclear weapons and thus are an area of continuing concern for the DP laboratories. Stockpile life extension projects will likely require the replacement of aged explosives, the properties of which can change considerably over time. High explosives are also critical components of conventional munitions (the purview primarily of the Department of Defense). Through work with the Defense Department to develop chemical processes for disposing of surplus explosives and propellants, the DP laboratories devised a new and improved process for synthesizing TATB, the most widely used high explosive in modern nuclear weapons.

In years past, TATB was synthesized from 1,3,5-tricholoro-benzene, which is expensive and available only from foreign suppliers (e.g., Japan, Germany, China). The laboratories' new process for synthesizing TATB uses starting materials derived from surplus Department of Defense explosives and propellants. This new process, called vicarious nucleophilic substitution (VNS), can be carried out in just two steps at ambient pressure and temperature conditions and involves no halogenated hydrocarbons. The VNS process benefits the DP laboratories' stockpile stewardship efforts in that it is less expensive, requires less energy, and uses fewer hazardous materials than the previous TATB synthesis procedure.

AVLIS Technologies for Advanced Manufacturing

Livermore's development of the atomic vapor laser isotope separation (AVLIS) process to enrich uranium fuel for civilian nuclear power reactors required the invention and production-scale demonstration of numerous technologies—copper vapor lasers, dye lasers, robotic equipment, and materials handling processes, to name a few. Several of these technologies are well suited for advanced manufacturing of weapons components.

For example, AVLIS laser technologies have been used to demonstrate the feasibility of high-precision laser cutting of weapons materials. These lasers can make very narrow, very accurate cuts, permitting precision disassembly of retired weapons and reuse of parts. Laser-cutting technology has the potential to save a hundred million dollars over the next decade in weapons dismantlement and stockpile refurbishment efforts.

Physical-vapor-deposition processes, developed for collecting the AVLIS-separated isotope product, are being demonstrated for precision fabrication of uranium–niobium alloy parts. These parts are currently fabricated using a complex combination of forming and heat-treatment operations. With the AVLIS vapor-deposition process, the uranium–niobium alloy can be deposited on a mandrel or mold, offering the possibility of single-step manufacturing for these parts.

In addition, AVLIS-developed electron-beam melting technology is being applied to recycle the uranium–niobium alloys used in weapons manufacturing. With current

Brazing Technology for Metal-to-Ceramic Joining

As a result of work on the development of components for the Tore Supra fusion reactor, Sandia developed unique expertise in metal-to-ceramic brazing. The design and construction of the Tore Supra was an international effort in which DOE's Magnetic Fusion Energy Program participated. It was built in France in the late 1980s and has been used since then for plasma diagnostics experiments. Sandia was responsible for the design, fabrication, and installation of the reactor's first-wall limiter.

The limiter has to withstand extremely high heat flux conditions and thus must be actively cooled. Fabrication of the limiter is very difficult because it requires brazing of pyrolytic graphite tiles to copper and copper-alloy cooling tubes. Trial-and-error approaches to solving such metallurgy problems are expensive and time consuming. Computational modeling is the obvious approach, but data on the mechanical properties of the materials involved are required as input. Sandia researchers characterized the mechanical properties of several special braze alloys at elevated temperatures. Compression creep testing was conducted on the braze alloys, and constitutive models were developed for the secondary creep behavior of these materials.

In 1990, braze-related failures were uncovered in the Trident II spark-gap detonator assembly (used to separate the D5 missile stages) and ceramic cracking was discovered in the plasmatron (a vacuum electronic component) used in the firing set for the W88 warhead. The Trident II spark-gap problem was solved by changing to one of the special braze alloys that had been investigated for the Tore Supra limiter. Computational analysis, using the constitutive models developed in the Tore Supra work, confirmed that the residual stresses in the spark-gap ceramic were significantly lower with the special alloy and that cracking would not occur. Electron microprobe analysis of the cracked plasmatrons determined that extensive alloying of the copper brazement at a critical seal had occurred. The solution to this problem involved the use of a faster braze process cycle to minimize alloying of the brazement. Computations also indicated that an extended braze cooldown would reduce the residual stresses in the ceramic.

Spin-back from the original Tore Supra work is continuing to benefit stockpile stewardship and management. Recent Sandia work on metal–ceramic brazing is focusing on the use of special metal brazing in the fabrication of new limited-lifetime components. Not only does this technology produce braze joints that are less susceptible to cracking and leakage, it also simplifies the fabrication process by eliminating the lengthy metallization and plating processes needed to prepare ceramic surfaces for conventional brazing.

fabrication processes, less than 5% of the alloy ends up in usable parts; the other 95% ends up as unusable scrap and waste. Electron-beam melting provides a way of recycling this scrap material, reducing the need for new alloy and decreasing the waste streams resulting from the manufacture of the uranium alloy components.

Pulsed Power, Advanced Manufacturing, and Weapons Research

Through the Repetitive High-Energy Pulsed-Power (RHEPP) Program, funded by the Department of Defense's Strategic Defense Initiative Organization (SDIO), the DP laboratories collaborated with industry and university partners to develop and demonstrate the high-peak-power and high-average-power capability of magnetic switching. On the basis of these demonstrations, two high-power rapid-pulse accelerators (RHEPP I and RHEPP II) were constructed at Sandia.

The availability of these accelerators opened up many new capabilities that are directly relevant to DP missions. For instance, high-power ion beams make possible a new industrial process for surface treatment of metals, ceramics, and polymers. This process, called ion-beam surface treatment (IBEST), produces hardened, corrosion- and wear-resistant surfaces that lengthen the life and increase the reliability of various nuclear weapons components. IBEST also increases the performance of the high-power vacuum transmission lines required for pulsed-power accelerators, such as those used for x-ray simulators and high-energy-density weapons research facilities.

In addition, using high-repetition-rate power compressors and pulsed-power systems, it is now possible to test accelerator components much more stringently than ever before. This capability will be crucial to the development of future high-intensity test facilities for x-ray and high-energy-density environments. For example, an advanced hydrodynamic test facility will be able to generate many frames of data at successive times, taken from multiple views, from a single hydrodynamic event, making it possible to create essentially three-dimensional movies of an implosion. The facility concept calls for the use of an accelerator to generate successive, intense bursts of x rays during the hydrodynamic experiment. Magnetic switching technology appears to be an excellent means of generating these multipulse x-ray bursts.

Plasma Technologies and Weapons Complex Cleanup

Apparatus and techniques initially developed for DOE's Office of Energy Research and Office of Environmental Management are being adapted for various stockpile management applications. In particular, plasma processing technologies are being used to remove organic and nuclear materials from surfaces that are too intricate and complicated for more traditional cleaning methods. For example, initial work on plasma decontamination, funded by the Office of Environmental Management, has been extended to

Erbia Coatings and Fire-Resistant Pits

In the early 1990s, Los Alamos engaged in a collaborative research and development agreement (CRADA) with the University of Wisconsin and General Motors to devise a process for increasing the thickness and improving the adhesion of wear-resistant coatings of diamond-like-carbon on aluminum engine parts. Conventional wisdom was that delamination limited such coatings to thicknesses no greater than 1 micron. Using the Los Alamos Plasma Source Ion Implantation Facility, established and supported in large part by the Magnetic Fusion Energy Program and the Strategic Defense Initiative Organization's Ground Test Accelerator Program, laboratory researchers developed an ion implantation process (since patented) for depositing coatings up to 10 microns thick.

In 1995, weapons scientists adapted this ion-implantation process to improve the adherence of the erbia coatings used in fire-resistant pits of nuclear weapons. Erbia (erbium oxide) is used to provide a barrier between molten plutonium and the containment vessel. However, because erbia is a brittle ceramic, erbia coatings are prone to delamination when subjected to thermal stress or shock or when the underlying metal substrate deforms.

Considerable work was required to develop the necessary source of a pure erbium metal plasma and to match the ion-implantation process to the characteristics of the erbium plasma source. The result is a three-step implantation and deposition process that produces erbia coatings that adhere tenaciously, even when the underlying metal substrate is severely deformed. Molten plutonium tests of these coatings are being conducted to fine-tune the process. This process is also being adapted to coat the crucibles and near-net-shape molds used to cast plutonium weapons components.

develop processes for cleaning organics from the interior surfaces of 6-foot-long gloveboxes. This process is also being adapted to the removal of depleted uranium from blast shields used for hydrodynamics tests. In addition, a plasma physics research facility at Los Alamos, originally developed under the auspices of the Office of Energy Research, is being used for large-scale reactive ion etching to remove organics and actinides from contaminated apparatus and devices. Also, through various collaborative activities with industry, the DP laboratories are "importing" best commercial practices in plasma cleaning and etching from the microelectronics industry.

Materials Science Studies and Stockpile Aging

Atom-level materials science studies, funded in large part by DOE's Office of Basic Energy Sciences, are benefiting the materials aging research required for enhanced stockpile surveillance. For example, the interfacial force microscope makes it possible to examine interfaces of adhesively bonded materials at the level of individual atoms. The imaging technique was first explored using Laboratory Directed Research and Development funds; it then became the focus of a Basic Energy Sciences program to study fundamental aspects of interfacial adhesion. This new microscopy technique is now providing a molecular basis for modeling and predicting the performance of adhesive joints in weapon components.

Important contributors to aging-related concerns in stockpile weapons are the changes in chemistry, phase constituency, and adhesion of interfaces that occur over time. Virtually all weapon components contain critical interfaces between dissimilar materials—films deposited on ceramic substrates, encapsulated components, adhesively bonded and laminated components, etc. Aging of these materials frequently results in the segregation of impurities into precipitates that, in turn, introduce microscopic flaws and cause a loss of adhesion. Flaws and stresses can

The National Energy Research Supercomputing Center

From 1977 to 1996, the National Energy Research Supercomputing Center (NERSC) was sited at and operated by Livermore (it was moved to the Lawrence Berkeley National Laboratory in late 1996). Supported by DOE's Office of Energy Research, NERSC led the development of high-end computational infrastructures, high-speed networks, and advanced computational techniques for three-dimensional modeling—areas of direct importance to the DP laboratories' stockpile stewardship charge.

Over the years, computer scientists affiliated with NERSC collaborated with their nuclear-weapons-program colleagues in the development of computational capabilities required by both groups. For example, the National Storage Laboratory is sited at NERSC, and scientists funded by Energy Research worked together with DP researchers to develop the high-performance storage system. This collaboration is continuing, now focusing on the development of a high-performance storage system for parallel computing systems. In addition, an interactive batch gang scheduler for massively parallel processors (MPPs), developed by NERSC, provides enormous flexibility in the use and scheduling of MPPs and will be a key contributor to the increases in computational capability required for the Accelerated Strategic Computing Initiative (ASCI) of the Stockpile Stewardship and Management Program.

NERSC also houses the Energy Sciences Network (ESnet), which pioneered satellite-linked and fiber-optic remote communications and data exchange and provides the highest level of production-capable networking in the nation. The capabilities of the ESnet and the expertise of ESnet personnel are making essential contributions to ASCI. For example, a secure network linking Los Alamos, Livermore, Sandia, and Oak Ridge was recently approved for transmission of classified data and will soon be extended to the weapons production plants.

NERSC's mathematicians are world-renowned for their adaptive mesh refinement techniques, and the DP laboratories' nuclear weapons program has benefited from their advanced computational tools. For example, parallel radiation diffusion solvers, based on research funded by the DOE's Office of Energy Research and conducted at NERSC, are being developed further under ASCI.

NERSC scientists also have leading-edge expertise in massively parallel processing. Through a number of collaborations between NERSC and the nuclear weapons program, this expertise is being tapped to develop high-performance parallel versions of a suite of weapons modeling codes.

Some of the NERSC scientists have joined Livermore's classified computing center to work on ASCI and other defense-related projects, and others remaining at Livermore have joined the new Center for Applied Scientific Computing. Many of the NERSC mathematicians have moved to Lawrence Berkeley and their collaborations with Livermore weapons scientists will continue under contract.

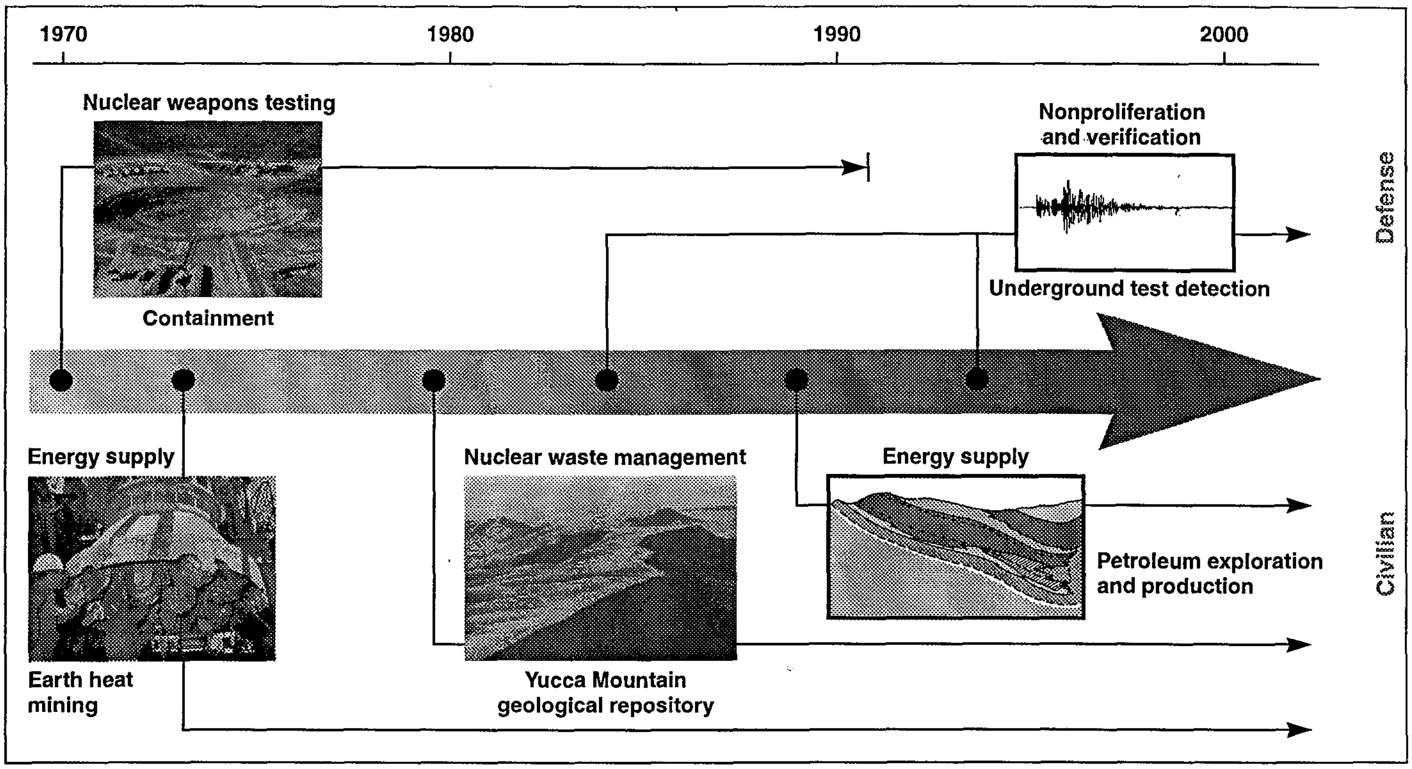


Figure 6. *DP laboratory expertise in geology, geochemistry, hydrology, seismology, deep drilling, and other aspects required for underground nuclear testing has spun out to benefit the oil and gas industry, has been integral to the continuing effort to design underground nuclear waste repositories and is now central to monitoring and verification of the Comprehensive Test Ban Treaty.*

accumulate and cause the adhesive bond to rupture and the component to fail. Interfacial force microscopy is providing essential fundamental information for the development of accurate models of the effects of aging on adhesive interfaces. Once the models are validated with experimental data, they will be used to assess structural integrity and predict failure of these bonds.

SQUIDs, Brain Imaging, Nonproliferation, and Stockpile Surveillance

Superconducting quantum interference devices (SQUIDs) are presently the most sensitive magnetic sensors known, able to measure magnetic fields as small as a few femtotesla (10^{-15} T, less than a billionth of the Earth's magnetic field). The ultrasensitivity of these sensors is opening new areas of research and new applications for electromagnetic sensing and detection methods. Indeed, the measurement of magnetic fields from living organisms, or biomagnetism, is a rapidly growing field that owes its existence almost exclusively to the extraordinary sensitivity of SQUIDs.

DOE's Office of Health and Environmental Research recently funded one of the DP laboratories to develop techniques for using SQUID sensors in biomagnetic applications in magneto-encephalography (MEG) and magneto-cardiography (MCG). Through a CRADA with a California company, this technology has been developed into a large MEG sensor system that will cost one-quarter that of previously available commercial systems.

SQUID technology from these biomagnetism studies is being applied to such defense and nonproliferation problems as locating and characterizing covert underground weapons facilities, locating land mines and unexploded ordnance, nondestructive evaluation of defects in stockpile weapons, and discrimination of the contents of storage drums for verification of international arms control, dismantlement, and nonproliferation agreements. For example, recent experiments have demonstrated the feasibility of using SQUID technology to detect underground structures and hidden weapon pits. Advanced stockpile surveillance technologies using SQUID sensors are also being developed to nondestructively evaluate material defects and corrosion in weapons components.

Advanced Photonics and Nuclear Test Readiness

Photonics is an essential nuclear weapons technology, both for weapons components and for underground nuclear testing. The DP laboratories are maintaining their cutting-edge expertise through weapons-related activities and through non-DP projects. Photonics technology is being incorporated into stockpile nuclear weapons to increase safety and reliability. One example is the all-optical fireset, in which optical fibers replace the electrically conducting cables currently used.

With the cessation of nuclear testing, the DP laboratories have found other ways to maintain expertise in test-related photonics. (Fiber optics are used to rapidly transmit large quantities of data from the buried nuclear test device to the recording instruments at the surface.) The laboratories are involved in a number of non-DP projects that are extremely challenging and require cutting-edge information technology. For example, photonics are integral to the optical interconnects intended for massively parallel computing systems and to the high-speed optical networks required for high-performance telecommunications. The Defense Advanced Research Projects Agency (DARPA) is taking advantage of the DP laboratories' expertise in photonics, funding R&D in optical interconnects and advanced optical networks to meet the Defense Department's need for improved battlefield communications and information transmission (e.g., three-dimensional terrain visualizations derived from satellite data).

The R&D on optical interconnects and optical networks conducted for DARPA is being directly applied to the Accelerated Strategic Computing Initiative (ASCI). The computing performance (a ten-thousandfold improvement over current capabilities) and the connectivity of remote sites required for the Stockpile Stewardship and Management Program cannot be accomplished without advanced photonics technologies like optical interconnects. DARPA-sponsored R&D on automated packaging of the optical interconnects will greatly reduce the cost of this essential technology. Thus, by advancing the photonics technology for telecommunications and high-performance computing, the DP laboratories are maintaining essential nuclear-testing capabilities.

Geoscience, Energy Resources, and Treaty Verification

The DP laboratories are involved in several partnerships with individual oil and gas companies and with industry-wide consortia to build on the laboratories' specialized abilities in seismology, flow and transport simulations, and related areas of geoscience. During the energy crisis of the 1970s, this expertise was applied to develop the hot-dry-rock alternative energy technology (sponsored by DOE's Office of Basic Energy Sciences). The concept involved the engineering of an underground heat exchanger to extract the Earth's natural heat and convert it to a usable energy source. In the late 1970s, knowledge gained from the hot-dry-rock project was applied in the development of a geologic repository for spent fuel from civilian power reactors. In the 1980s and 1990s, DP laboratory expertise in geoscience and seismology was further extended to develop seismic techniques for detecting underground nuclear tests in distant regions, a continuing national security need for monitoring the recently signed Comprehensive Test Ban Treaty (Figure 6).

Laser Diagnostics, Remote Sensing, and Nonproliferation

Shortly after the laser was invented in the 1960s, the DP laboratories began developing laser-based diagnostic instruments, first for weapons experiments (e.g., to better understand gas flows in gas-transfer systems) and later for experiments in fusion research, high-pressure physics, and combustion science. Indeed, laser-based diagnostics are integral to the unique experimental capabilities of the Combustion Research Facility, established by the DOE's Office of Basic Energy Sciences at Sandia. Much DP laboratory expertise in laser diagnostics is a direct result of work at this facility.

Laser diagnostics have found increasing use in a wide variety of programs requiring remote sensing and monitoring. For example, the DOE's Office of Environmental Management funded the development of laser-based instrumentation to detect and monitor hazardous chemicals (e.g., volatile organic compounds) at laboratory landfill sites. In the early 1990s, a lidar system (the laser analog of radar) was developed by the DP laboratories to measure atmospheric water vapor and aerosols for the Atmospheric Radiation Measurement Program, sponsored by the DOE's Office of Health and Environmental Research.

Lidar and other laser-based remote-sensing technologies developed through such non-DP projects are finding extensive use in nonproliferation programs. For example, the CALIOPE (Chemical Analysis by Laser Interrogation of Proliferation Effluents) Program is developing laser-based remote-sensing technologies for detecting the chemical signatures of nuclear proliferation activities. These remote-sensing programs require innovative work in other areas, such as determining the wavelengths of laser light to stimulate fluorescence from the chemicals being monitored and computer algorithms for unfolding the spectral signatures of the targeted chemicals.

Other national security programs are building off the CALIOPE Program. For example, the Army's SPECTRE Project for detecting biological warfare agents is pushing the limits of the information-analysis techniques developed by the DP laboratories for CALIOPE. SPECTRE is also stimulating advances in the spectroscopy of aerosols and complex chemicals to broaden U.S. capabilities for detecting signatures of weapons proliferation activities. Advances made through SPECTRE are spinning back not only to CALIOPE but to many elements of national security and nuclear weapons work at the DP laboratories.

Multiprogram Synergy in the Future

The benefits of the DP laboratories' multiple programs will continue in the future. For example, advances in supercomputing, developed through the ASCI project, will spill over into the wider scientific and civilian sectors. Completely new computing capabilities will arise from the ten-thousandfold increases in computing power, data storage, and network speed and from the simulation and modeling advances that are the goals of ASCI. Since much of the ASCI work is being done in collaboration with industry, ASCI spin-outs will be readily transferred to the private sector.

Advanced materials, processes, and manufacturing technologies developed for stockpile refurbishment will have similarly broad-reaching spin-outs. Miniaturized electronics, sensors, and other devices developed for enhanced stockpile surveillance will give rise to a host of micromachines and imaging technologies for industrial, medical, environmental, nonproliferation, and consumer applications. New materials will lead to new consumer products. Improved manufacturing processes will benefit industry (and the public) through increased productivity, reduced environmental impact, and decreased costs.

Fundamental scientific research—whether conducted for programs in climate change, advanced energy technologies, or environmental remediation or for collaborations with academia and industry—will contribute to the knowledge and skill bases required for stockpile stewardship and management. Advances in three-dimensional simulation, being developed through climate modeling work, will be directly applicable to the modeling needs of stockpile stewardship. Improved understanding of materials behavior under extreme conditions, gathered through fusion energy research, will benefit studies of materials interactions and aging in stockpile weapons. Remote-sensing technologies, developed for environmental monitoring and remediation, will find application in the DP laboratories' stockpile surveillance and nonproliferation programs.

Synergism among the DP laboratories' multiple programs and between the laboratories and the wider scientific community greatly accelerates the pace of technical innovation and scientific problem solving. Indeed, much of the power of science comes from open communication and critique across disciplines and programs. Significant and often unexpected discoveries emerge from the productive friction that occurs when different perspectives rub against each other and spark new insights. With federal funding for scientific R&D tightly constrained, this productive friction is essential.

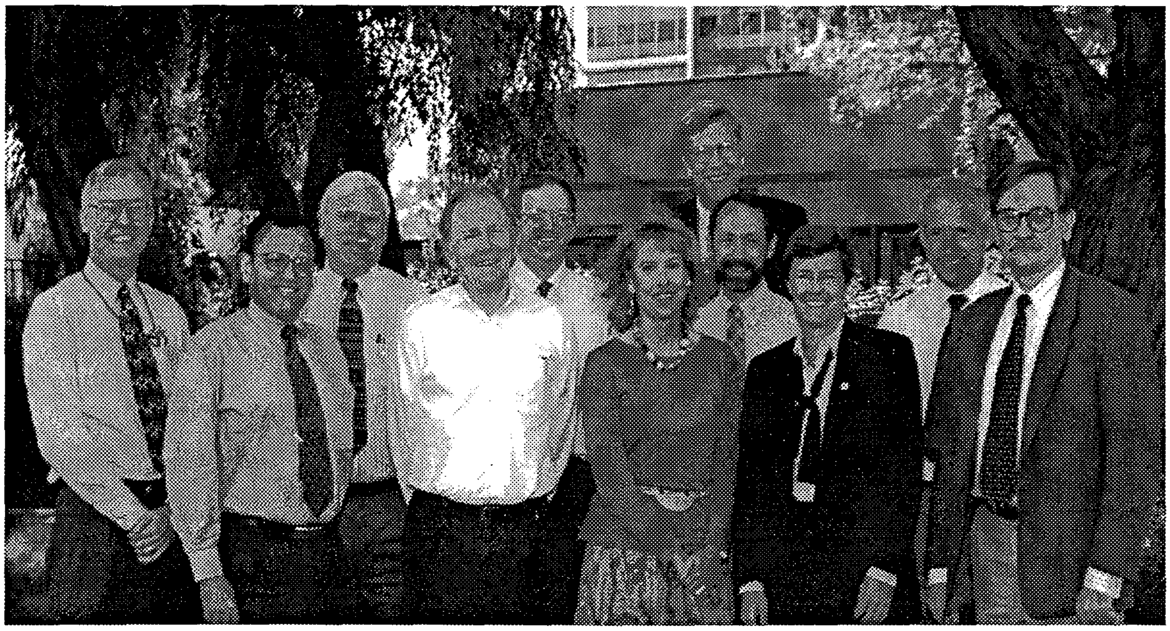
V. Conclusion: Multiple Programs Enhance the DP Laboratories' National Security Mission

SINCE the inception of the DP laboratories, the challenge and importance of their national security mission has required and attracted some of the most talented and skilled scientists and engineers in the nation. The laboratories' history of scientific and technical achievement attests to the outstanding creativity of these individuals. The dual charges of science-based stockpile stewardship and nuclear readiness present challenges of the magnitude and importance that will continue to require and attract top-caliber scientists and engineers to the DP laboratories.

In addition, an increasing number of nationally important issues involve science and technology—preserving the environment, developing new sources of energy, inventing nonpolluting manufacturing processes, improving health care, enhancing economic prosperity, as well as ensuring national security. The three DP laboratories can make unique and valuable contributions in all of these areas.

By working on multiple programs, including those not directly related to stockpile stewardship and management, the laboratories' scientists and engineers are able to take different approaches to technical issues, view problems from new perspectives, and apply their skills and knowledge in different ways. These other programs also bring the laboratories' scientists and engineers into contact with the wider scientific and technical community, creating an environment of collaboration and synergy.

By engaging in appropriate nondefense programs in addition to their nuclear weapons work, the Los Alamos, Livermore, and Sandia laboratories sustain their cutting-edge expertise in a broad range of science and technology and thereby maintain the institutional vitality required for their national security mission. In so doing, they ensure their ability to make science-based certifications of the safety and reliability of the enduring U.S. nuclear stockpile and to meet their nuclear readiness mandate. They also make unique contributions to other programs that are critical to the nation's security and well-being.



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