DOE Research and Development Portfolio

National Security

Volume 5 of 5

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U.S. Department of Energy

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U.S. Department of Energy

Department of Energy
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Reducing the global danger posed by weapons of mass destruction while maintaining a safe, secure nuclear deterrent is one of the most important elements in our country's national security strategy. Since its foundation, the Department of Energy has been a leading agency responsible for our nation's efforts in this area. The Department is making significant progress in meeting its national security mission responsibilities. To ensure continued progress in national security goals, the Department will maintain and invest in an aggressive and balanced research and development program.

Over the past year, the Department of Energy (DOE) has undertaken a major effort to ensure that our research and development programs are balanced and that our Federal investments are appropriately coordinated with the needs of the national security community. We have begun instituting a new portfolio approach to managing our R&D activities. This entails building a comprehensive document that, for the first time, provides in one place, a clear description of our entire $7 billion research portfolio. Attached is DOE's *National Security R&D Portfolio* covering $2.6 billion of that research. It is Volume V of the DOE's five volume R&D Portfolio.

This document is intended to help (1) describe our current R&D activities and showcase recent accomplishments, (2) evaluate whether our portfolio is appropriately balanced to meet our long term strategic mission goals, (3) align our technology investments with broader national policy goals, and (4) plan for future investments through technology roadmapping.

The investments presented in the *National Security R&D Portfolio* are important steps toward bringing forth the knowledge, innovation, technologies, and partnerships required to meet the challenges of the next century successfully. We believe that this document will provide the means for illuminating our proposed investments for Fiscal Year 2000 and beyond, as a unified portfolio, and serve as a useful framework and resource for further analysis and dialogue among all interested parties.

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Foreword

National Security is an important part of the Department of Energy's mission, accounting for $6.0B of DOE's $17.9B budget in FY1999. The Department is making significant progress in meeting its national security responsibilities to reduce the global danger posed by weapons of mass destruction while maintaining a safe, secure, and reliable nuclear deterrent. An aggressive R&D component is an important element of the Department's strategy for making further progress.

In FY 2000, this National Security Research and Development Portfolio will require investments of $2.6B in science and technology to help maintain the nuclear deterrent, monitor nuclear treaties and agreements, prevent and detect proliferation, and counter weapons of mass destruction terrorism. This volume examines the Department's investments from 1998 through the year 2000. It describes the major national security technical challenges that our nation faces and the specific Department of Energy research and development activities being undertaken to address them.

Chapter 2 of this document provides an analysis of the National Security Portfolio, including discussions of the uncertainties and other external factors affecting research and development, the distribution of investments by investment areas, and trends in funding levels. Chapters 3 through 7 describe the background and specific details of each problem area and how specific R&D investments are being undertaken to meet the Department's national security strategic goals and objectives. Each of these portfolio chapters further defines the national context and drivers, strategic goals and objectives, uncertainties, investment trends and rationale, federal role, and key accomplishments for each technical challenge.

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Executive Summary

The post Cold War national security environment is increasingly complex. At least 20 countries are known to be or are suspected of developing weapons of mass destruction (WMD), as underscored by the recent underground nuclear tests of India and Pakistan. The fragmentation of the former Soviet Union has led to concerns about the accountability, control, and disposition of weapons, components, materials, and information. The threat that nuclear weapons or materials could fall into the wrong hands through theft or diversion is a clear and present danger. The increased activity and technical sophistication of non-state actors is a further concern.

The DOE national security mission is driven by national security policies that have developed in response to this environment. Key among these policies are support to the Strategic Arms Reduction Treaties (START I, II, and planning for III), the Comprehensive Nuclear-Test-Ban Treaty, Treaty on the Non-Proliferation of Nuclear Weapons (NPT), the Nuclear Weapons Stockpile Plan, and Presidential Decision Directives (PDDs) on the Nonproliferation of Weapons of Mass Destruction, and Countering Terrorism. These policies require:

- A science-based stockpile stewardship program to maintain the stockpile without further underground testing,
- An effective nuclear treaty monitoring research and development program,
- A robust verification technologies research and development program to reduce the nuclear danger by identifying problems before they become crises,
- A proliferation prevention program to ensure that nuclear weapons useable materials are dispositioned subject to the highest standards of safety, security, and international accountability, and
- A counter terrorism program focused primarily on supporting domestic first responders.

Until the current cessation of testing in 1992, underground nuclear testing was the principal means to assure the performance of nuclear weapon systems and to benchmark design codes used in the assessment of nuclear weapon safety, reliability, and performance. The development of computer simulation models to extrapolate system performance from underlying physical models is a primary objective of the Department's national security research and development program. Methodologies must be developed to assess the impact of aging and manufacturing defects and changes based on scientific concepts, research, simulations, and archived test data rather than on further underground testing.

Likewise, uncertainties exist regarding the detection sensitivities for sensing in verification activities and the ability of countries to evade detection of their proliferation activities. The ability to verify the activities of concern is often confounded by the proliferant nation’s efforts to conceal

them. Primary challenges facing the developers of new systems include: designing a system that will help overcome deception and denial efforts, improved measurement accuracy, and finding new detection techniques not possible with existing state-of-the-art sensors.

Nuclear materials such as plutonium and highly enriched uranium are highly valued by potential proliferators. This situation is made more complicated by the dissolution of the Soviet Union, and the political and economic turmoil currently affecting Russia. The development of technologies and systems to monitor, protect, and account for nuclear fissile materials must keep pace with the increasingly sophisticated efforts of smugglers to move such material, or thieves to remove them from safe keeping in sites throughout Russia and other countries. The U.S. will also strive to eliminate, where possible, accumulation of stockpiles of fissile materials through disposition and assist Russia in the demonstration of plutonium disposition technologies.

Responding to the threat of weapons of mass destruction terrorism is an extremely complex problem. The current world political and economic situation may make access to weapons of mass destruction technology more readily available. Nuclear smuggling is an acknowledged threat and detection of chemical and biological agents is constrained by the current state of technology. DOE's approach for these activities will leverage its science and technology expertise and prior R&D investment to support cooperative developments that serve the best interest of the U.S. Government to address this difficult problem.

The National Security R&D Portfolio is accomplished by three principal organizations: the Office of Defense Programs, the Office of Nonproliferation and National Security, and the Office of Fissile Materials Disposition. Fulfilling the Department's national security mission requires these organizations to manage the national security R&D portfolio for:

- Maintaining the U.S. nuclear weapon stockpile design, production and maintenance capability.
- Preventing the spread of WMD materials, technology and expertise.
- Securing nuclear weapon materials.
- Verification or compliance of WMD, treaties and agreements.
- Reversing the proliferation of nuclear weapons capabilities.
- Responding to emergencies.

Federal Role and Linkage to DOE Strategic Goals

DOE has the sole legislated oversight responsibility for maintaining the viability of the nuclear weapon stockpile and for oversight of all classified nuclear weapons technical information and for the production and handling of nuclear weapons components and special nuclear materials. DOE owns and operates, through contractors, the Defense Programs national laboratories and the production plants and facilities to meet its nuclear weapons stockpile mandate. The Department is also responsible for the management, storage, and disposition of fissile materials from weapons and weapon systems that are excess to U.S. national security needs. By virtue of its historic expertise in nuclear weapons technology, DOE has been assigned principal R&D responsibilities in nuclear nonproliferation, arms control, and countering WMD terrorism.

In order to fulfill its responsibilities and to meet the strategic goals in the national security mission area, DOE maintains a robust portfolio of research and development. This R&D is centered on solving the following problems:

Maintaining the Nuclear Deterrent

- Provide a scientific basis for assessing the performance of the stockpile with no further underground testing. Major objectives to accomplish this will include the development of:
  - Capabilities to conduct experiments in physical regimes important for understanding nuclear weapons performance.
  - Understanding of the effects of aging on nuclear weapons materials and components.
  - Experimentally validated computational methods for simulating nuclear weapons performance.
- Develop new technologies for production of special nuclear materials and components in order to reduce cost, minimize environmental impact, and improve component reliability.

Monitoring Nuclear Treaties and Agreements

- Develop technologies to enable nuclear test ban treaty monitoring and to ensure compliance with nuclear nonproliferation and arms control treaties and agreements.

Preventing Proliferation

- Develop and adapt technologies that convert U.S. weapons-usable plutonium to a form that will prohibit the plutonium from ever being used for nuclear weapons.
- Assist Russia in the demonstration of plutonium disposition technologies.

- Develop core security technologies which can be deployed to increase the security of U.S. facilities and to decrease program costs, including:
  - Nuclear materials measurement, accountability, and surveillance technologies to increase the accuracy of our nuclear materials accounts, to prevent and detect diversion of nuclear materials from their authorized locations, and reduce employee exposure to radiation.
  - Physical security of the DOE complex.

Verification Technologies

- Develop verification technologies to reveal proliferation or spread of weapons of mass destruction.

Countering Weapons of Mass Destruction Terrorism

- Develop technologies and methods to detect, deter or counter terrorism involving weapons of mass destruction.
- Develop information protection technology to prevent unauthorized access to data and to prevent disruption of classified or sensitive information systems.

Investment Trends

Maintaining the Nuclear Deterrent Through Science-Based Stockpile Stewardship

The requirements for the conduct of research and development to support the nuclear weapons stockpile flow from the necessity to ensure the performance of each warhead in the stockpile. The R&D portfolio is designed to address the following principal functional areas:

- **Primary Initiation**—the electromechanical systems that control the sequence of arming, fuzing, and weapons detonation functions after authorized release and normal trajectory to target.
- **Primary Yield**—ensuring that aged or remanufactured energetic materials, fissile materials and other engineering materials do not affect the ability of the primary to provide the necessary yield to drive the secondary.
- **Secondary Yield**—understanding the impact of variations in primary performance and aging effects on the yield produced by the secondary system.
- **Systems Integration**—ensuring that the integrated system functions in the harsh stockpile-to-target sequence.

- **Safety, Security, and Use Control**—ensuring that the weapon is safe to handle and can only provide a significant nuclear yield under use authorized by the President.

The principal technical areas of investment are:

- **Computing**—including the Accelerated Strategic Computing Initiative (ASCI). In the absence of testing, the nuclear weapons program will rely heavily on computer simulation to assess the impact of changes on nuclear weapons performance. Requirements for 100 Teraflop machines and weapon simulation software are established by the complexity of a nuclear weapon and the level of detail and resolution necessary to capture the relevant physics in the problem in full three-dimensional geometries.

- **Theory and Experiment**—providing and validating detailed physical models used in computer codes to assess weapons' performance margins.

  - High Energy Density Physics Experiments—to provide an understanding of systems and materials under conditions relevant to primary boost and secondary implosion and burn. Inertial Confinement Fusion is a major component of this research, which includes the construction of the National Ignition Facility (NIF).

  - Hydrodynamic Test Facilities—at the national laboratories that are used to implode full-scale systems that mimic primary devices but with simulants for the nuclear materials. Tests will also include "Subcritical Experiments" using non-critical assemblies of special nuclear materials in underground experiments to provide important data on materials properties and as a measure of the readiness of the Nevada Test Site to conduct nuclear testing if directed.

  - Chemistry and Materials Research—including research into the properties of special nuclear materials and the effect of aging or radiation environments on electronic components.

- **Integrated Engineering Tests**

  - Flight Tests—test of mock warheads on ballistic missile flights. This includes the development of improved instrumentation to provide the highest achievable fidelity to the launching of a war reserve system.

  - Above Ground Tests—the Defense Programs national laboratories maintain a suite of facilities for testing the non-nuclear performance of the nuclear weapon system when subject to shock, vibration, thermal transients, and hostile environments. This includes facilities to simulate electromagnetic, blast, neutron, and ionizing radiation effects of a nearby warhead detonation.

- **Surveillance and Production Technology Development**—technologies to monitor the state of the aging stockpile and to develop improved manufacturing capabilities.

The total Stockpile Stewardship research and development budget request for FY 2000 is approximately $2.4 Billion. Within inflation and small variations, this budget is not expected to change in the foreseen future.

Monitoring Nuclear Treaties and Agreements Through Enhanced System Development

- **Ground-based Monitoring Technologies**, including the development of sensors and systems to enable effective U.S. monitoring of the Comprehensive Nuclear-Test-Ban Treaty (CTBT).

- **Improved Satellite Sensors**, including the development of next-generation sensors to detect nuclear detonations in the atmosphere and in space.

- **Improved Radiation Detection Sensors,** including the development of sensors to permit monitoring of warhead dismantlement and storage of nuclear weapons and materials for arms reduction treaties and agreements.

Preventing Proliferation Through Weapon Materials Disposition and Protection

The strategy for the disposition of surplus U.S. weapons-usable plutonium is to immobilize some of it in a ceramic form surrounded by high-level waste, and to burn the rest as mixed-oxide (MOX) fuel in existing, domestic reactors. The strategy to assist Russia in the disposition of Russian surplus plutonium is to conduct small-case tests and demonstration of disposition technologies jointly with Russia and initiate procurement for a pilot-scale system in Russia to convert weapons plutonium to forms suitable for disposition and international inspection. The research and development program to support this strategy involves:

- The development, testing, and demonstration of a technology for the disassembly and conversion of nuclear weapons components to a plutonium oxide form that can be used as feed in either disposition technology.

- The development, testing, and demonstration of a technology to immobilize plutonium in a ceramic and incasing the plutonium in high-level waste glass.

- Tests and demonstrations associated with assessing the performance of MOX fuel fabricated from weapons plutonium.

- Assisting Russia with tests and demonstrations of technologies for the disposition of Russian plutonium.

In the near future, warhead pits of different types will be disassembled and converted to an oxide to establish operating parameters for a pit disassembly and conversion plant. In the immobilization activity, tests and demonstrations will be advanced sufficiently to provide the technical data to establish the technical baseline for ceramic immobilization. For the reactor

option, work will continue on examining the performance of MOX fuel fabricated with weapons plutonium and depleted uranium and initiating a MOX lead test assembly program. In Russia, small-scale tests involving burning plutonium in reactors and immobilization of plutonium in glass and ceramic matrices will continue.

Verification Technologies for Improved Sensor Development

- **Chemical Detection**, including the development and demonstration of sensor systems for detection of chemical signatures indicative of nuclear proliferation non-compliance.

- **Physical Detection**, including the development and demonstration of sensor systems for detection of physical signatures that indicate nuclear proliferation non-compliance.

Countering Weapons of Mass Destruction Terrorism

- **Nuclear Materials Detection**, including the development and demonstration of nuclear radiation detection sensor systems to deter nuclear smuggling activities as well as to enhance nuclear material accountability and control.

- **Chemical/Biological Detection**, including the development and demonstration of capabilities to detect the presence of chemical and biological materials and agents, to enhance biologic forensics tools and understanding, and to counter or remediate the presence of such weapons.

- **Critical Infrastructure Protection**, including cyber security improvements to assure DOE's information security.

The Chemical/Biological portion of the countering terrorism R&D research area, that is developing technologies to deter, detect, and effectively respond to the use of chemical and biological weapons, will receive increased emphasis in fiscal year 2000, growing from approximately $20M to over $30M, with more growth anticipated in the out years. This program builds upon ongoing activities in other agencies, and addresses specific scientific and technical areas in which DOE has unique expertise. The development of verification technologies sensors will continue to be a top priority, so that timely information can be provided to policy makers with sufficient notification to allow the U.S. to intercede early in the proliferation cycle, before national security is significantly compromised.

Key Accomplishments

- Established records for computing performance on ASCI computers as milestones to achieving the required computational capability. As an example, 1.6 trillion operations per second (Teraflops) achieved on the Blue Mountain computer on November 11, 1998.

- Revalidated the W76 warhead through a new dual revalidation process without underground testing.

- Obtained data on the behavior of plutonium at near weapons conditions through subcritical experiments at the Nevada Test Site.

- Won the national "Excellence in Plasma Physics" award for research on the behavior of hydrogen at high pressures that matter in nuclear weapon analysis and understanding the planet Jupiter.

- Completed the first arm of the Dual Axis Radiographic Hydrodynamic Test (DARHT) Facility.

- Initiated research and development to see and understand simulation data sets of unprecedented size (see "Data and Visualization Corridors" edited by Paul H. Smith and John Van Rosendale, CalTech Report CACR-164, September 1998, http://www.cacr.caltech.edu/pulications/DVC).

- Developed and delivered an increased capability x-ray instrument that will enable detection of the evasive testing in space of primitive nuclear weapons. This instrument will be flown on the latest models of the Global Positioning System satellites.

- Utilized the DOE Fast On-orbit Recording of Transient Events (FORTÉ) small research satellite, launched August 1997, to successfully demonstrate the next generation autonomous electromagnetic pulse sensor technologies for monitoring nuclear test ban treaties. FORTÉ is also providing scientists information on lightning and the structure of the ionosphere for possible use in weather forecasting and understanding the relationship of the ionosphere to environmental phenomena affecting the Earth.

- Developed an approach to measure unclassified nuclear weapon attributes such as threshold mass and $^{240}Pu/^{239}Pu$ isotopic ratio for verification of warhead dismantlement and reductions.

- Demonstrated the feasibility of a fully solid state, low power, no moving parts cryogenic cooling system that will enable the fielding of advanced cryogenically cooled sensor systems.

- Developed and tested major components of the technology to disassemble and convert nuclear weapon pits to a plutonium oxide form. The components have been integrated into a system, and a demonstration of the system has been initiated.

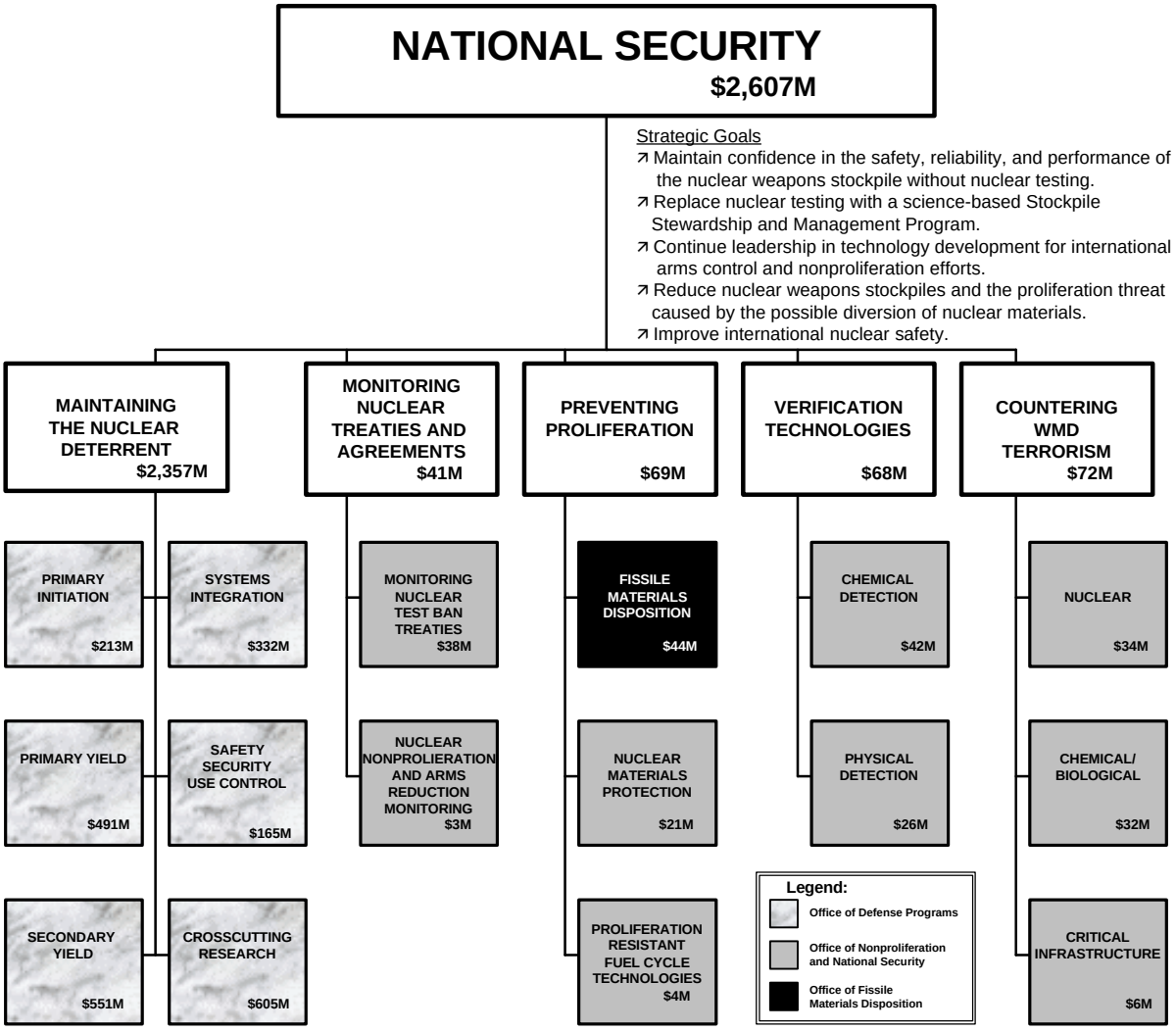
- Selected the baseline ceramic formulation for immobilizing plutonium. The process concept has been defined, and feasibility demonstrations of several key processes have been completed.

- Fabricated irradiated and examined MOX fuel samples to study the effects of gallium on the performance of MOX fuel. Basic research was completed on the interaction of gallium with fuel clad materials.

- Initiated studies, tests and demonstrations in Russia to assist in selecting a process to convert plutonium from Russian weapons to an oxide form suitable for fabrication into a MOX fuel. Tests and demonstrations of immobilization of plutonium in glass and ceramics were initiated as well.

- Completed the DNA sequencing of the virulence plasmids in two key biological threat pathogens, *B. anthracis* (anthrax) and *Y. pestis* (plague) to enable detection and attribution technologies.

Chapter 1
Introduction



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Background

The Department of Energy has the national security mission of acting as responsible steward of the nation's nuclear weapons and reducing the global nuclear danger through its national security, nuclear safety, and nonproliferation activities. DOE is an integral member of the U.S. national security community and plays an essential role in the provision of unique technical expertise in support of the Department of Defense, the Department of State, and other agencies focused on reducing the global danger from nuclear weapons and other weapons of mass destruction.

The post Cold War national security environment is dangerous and increasingly complex. U.S. national security continues to require the maintenance of a safe, secure, and reliable stockpile of nuclear weapons. For over 50 years this has been – and continues to be – one of the core missions of the Department of Energy. The maintenance of the nuclear weapon stockpile is a primary deterrent to threats to the national interest.

> *"As a part of our national security strategy, 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. In this regard, I consider the maintenance of a safe and reliable nuclear weapon stockpile to be a supreme national interest of the United States."*
>
> — President William J. Clinton

The Department is responsible for the safeguarding and security of all U.S. facilities at which nuclear weapons information, expertise, technologies, or material are available. The domestic mission includes reducing the number of sites where surplus weapons plutonium is stored, and disposing of surplus highly enriched uranium and plutonium.

Concerns over the proliferation of weapons of mass destruction have grown considerably in recent years. At least 20 countries are known to be or are suspected of developing weapons of mass destruction (WMD). This concern was underscored by the recent underground nuclear tests of India and Pakistan. The fragmentation of the Soviet Union has led to concerns about the accountability, control, and disposition of weapons, components, materials, and information. The threat that nuclear weapons or materials could fall into the wrong hands through theft or diversion is a clear and present danger. The increased activity and technical sophistication of non-state actors is a further concern.

The U.S. national security leadership has clearly stated that there is a close relationship between maintaining our national security and controlling the spread of weapons of mass destruction.

> *"The dangers we face are unprecedented in their complexity. Ethnic conflict and outlaw states threaten regional stability. Terrorism, drugs, organized crime, and proliferation of weapons of mass destruction are global concerns that transcend national boundaries and undermine economic stability in many countries."*
>
> —President William J. Clinton

> *"As the new millennium approaches, the United States faces a heightened prospect that regional aggressors, third-rate armies, terrorist cells, and even religious cults will wield disproportionate power by using – or even threatening to use – nuclear, biological, or chemical weapons against our troops in the field and our people at home."*
>
> —Secretary of Defense William S. Cohen

> *Those out to do us harm are no longer just political zealots with a few sticks of dynamite. These are determined operatives, with access to very sophisticated information and technology. Unable to confront or compete with the United States militarily, they try to achieve their policy objectives by exploiting small groups to do the dirty work for them.*
>
> —General John M. Shalikashvili, USA
> Chairman, Joint Chiefs of Staff

DOE has shifted its priorities over the past several years to reflect the new an evolving geopolitical military realities of the post Cold War world. To deal with the change, DOE has enhanced activities that advance U.S. nonproliferation policy while maintaining the viability of deterrence with a smaller, more agile, secure nuclear weapons complex.

Continual improvements to monitoring and verification capabilities both protects U.S. interests and enables global efforts to ensure that treaties are upheld. Verifiable treaties enhance world-wide interest in nonproliferation goals by reducing the danger to both nuclear and non-nuclear states.

In addition to its role in monitoring and verifying nuclear treaties, DOE has a major role in research and development to prevent the spread of nuclear weapons in other countries. DOE and its national laboratories are involved in providing international safeguards for foreign nuclear facilities, in supporting the entire range of International Atomic Energy (IAEA) activities, and in making sure that technologies related to nuclear materials and weapons are not deliberately or inadvertently transferred to countries of proliferation concern.

Verification technologies are an integral part of the U.S. national security strategy. These measures, designed to reduce existing military threats and prevent new ones from arising, are an essential complement to our military programs to respond to such threats, allowing the United States to maintain greater security at lower cost. Improved verification technologies enable us to focus on problems before they become crises.

DOE sponsors and is responsible for an extensive R&D program, most of which is carried out at the DOE national laboratories. DOE-sponsored R&D is focused on advancing applied, and sometimes basic research. Implementation is jointly planned with national security users at other agencies.

The DOE Research and Development Portfolio

DOE assembled its research and development portfolio recognizing the complexity of the U.S. national security challenge, and the requisite continuity implicit in DOE's current research activities, which in part reflect past and present Congressional and Executive guidance and intent. The Department also acknowledged in assembling its portfolio that the complexity and inter-relatedness of the U.S. Government national security establishment means research in any particular scientific or technological area may have direct as well as indirect effects on setting objectives for the national security research and development portfolio.

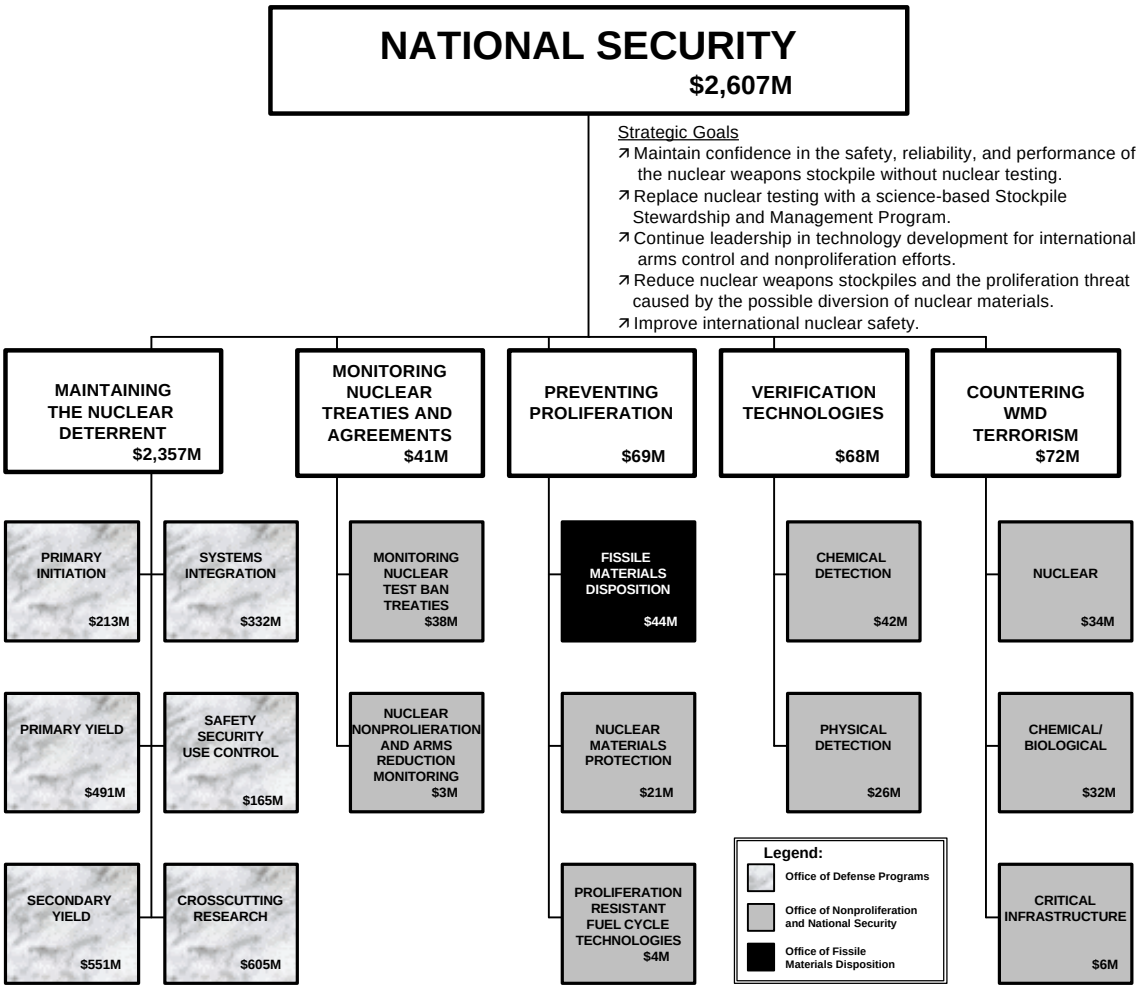
The DOE national security research and development portfolio has been structured into five primary activity areas that respond to DOE objectives:

- Maintaining the Nuclear Deterrent.
- Monitoring Nuclear Treaties and Agreements.
- Preventing Proliferation.
- Verification Technologies.
- Countering Weapons of Mass Destruction Terrorism.

Primary research and development efforts will be described in detail in Chapters 3 through 7.

The structure of the DOE National Security research and development portfolio and organizational responsibilities is shown on the following page.

National Security Research and Development



Maintaining the Nuclear Deterrent

Until the current cessation of testing in 1992, underground nuclear testing was the principal means to assure the performance of nuclear weapon systems and to benchmark design codes used in the assessment of nuclear weapon safety, reliability, and performance. In 1993 the President challenged the Department of Energy and the Department of Defense "to explore other means of maintaining our confidence in the safety, reliability and performance of our weapons." In the 1994 National Defense Authorization Act, the Congress directed the Secretary of Energy "to establish a stewardship program to ensure the preservation of the core intellectual and technical competencies of the United States in nuclear weapons."

Three particular challenges must be met:

- Fully supporting, at all times, the U.S. nuclear deterrent with safe, secure, reliable nuclear weapons.

- Preserving the core intellectual and technical competencies of the weapons laboratories. Without nuclear testing, confidence in the U.S. nuclear deterrent will rest with confidence in the competency of the people who must make the scientific and technical judgements related to safety and reliability.

- Ensuring that the activities needed to maintain the stockpile are coordinated and compatible with the nation's arms control and nonproliferation objectives.

Now, confidence in the stockpile must be maintained by using an improved set of scientific and engineering tools. To meet this challenge new facilities are being established to measure physical phenomena occurring in weapons or scientifically scalable to those occurring in weapons. Examples include: the behavior of plutonium; the evolution of material, including fusion burn, when suddenly, it is converted to plasma and compressed by high temperature radiation at extreme pressures; the effects of aging, radiation and neutrons on the electro-mechanical performance of weapon control systems. New or upgraded facilities for this research include: the Dual Axis Radiographic Hydro Test (DARHT); the National Ignition Facility (NIF); the OMEGA laser at University of Rochester; the ATLAS and Z pulsed power facilities; the Los Alamos Neutron Science Center (LANSCE); gas guns; and the U1a complex at the Nevada Test Site. Computer simulations will be relied on to an unprecedented extent to predict the complete end-to-end performance of the weapons and to design and interpret the experiments that reveal behavior of selected phenomena. The development of computer simulation models to extrapolate system performance from underlying physical models is a primary objective of the Department's national security research and development program. Methodologies must be developed to assess the impact of aging and manufacturing defects and changes, among other scientific and engineering challenges.

Monitoring Nuclear Treaties and Agreements

The goal of this program area is to develop technologies and systems, and the attendant scientific basis thereof, to enable detection, characterization, and attribution of nuclear treaty violations with sufficient timeliness and confidence to permit effective national and international treaty verification. The current focus is largely on development of a robust capability to monitor the Comprehensive Nuclear-Test-Ban Treaty (CTBT), when it enters into force. However, the underlying conditions that shape U.S. monitoring requirements will remain in effect, whether or not official entry into force of CTBT ever occurs.

Preventing Proliferation

United States policy is to seek to eliminate, where possible, accumulation of stockpiles of highly enriched uranium and plutonium, and to ensure that where these materials already exist they are

subject to the highest standards of safety, security, and international accountability. DOE is committed to safely dispose of the nuclear material made surplus by the downsizing of the nuclear arsenal in conformance with arms control and nonproliferation treaty requirements. Disposition strategies include immobilizing plutonium in a ceramic matrix and surrounding it by high-level waste and 'burning' plutonium as mixed-oxide (MOX) fuel in commercial U.S. reactors. The research and development portfolio in the area of preventing proliferation addresses completing the necessary process development and technology tests that will provide the design and operational basis for facilities that can disposition surplus plutonium.

The threat that nuclear weapons or materials could fall into the wrong hands through theft or diversion is a clear and present danger. Nuclear materials such as plutonium and highly enriched uranium are highly valued by potential proliferators. The danger exists not only in the potential for proliferation of nuclear weapons, but also in the potential for environmental, safety, and health consequences, if surplus fissile materials are not properly managed. This situation is made more complicated by the dissolution of the Soviet Union, and the political and economic turmoil currently affecting Russia. The development of technologies and systems to monitor, protect, and account for nuclear materials must keep pace with the increasingly sophisticated efforts of smugglers to move such material, or thieves to remove them from safe keeping in sites throughout Russia and other countries

To reduce the danger of nuclear weapons proliferation, the Department of Energy supports the Reduced Enrichment for Research and Test Reactors (RERTR) program. One of RERTR's most important and successful activities has been the development of low enriched uranium (LEU) fuels to permit conversion of research reactors from high enriched uranium (HEU) fuel to LEU.

Verification Technologies

Proliferating nations go to great lengths to conceal their proliferation activities and take other actions to prevent their detection. We are constantly faced with new and demanding technical problems that need to be solved. Efforts to stem proliferation activity rely upon remote sensing and other technologies, for which numerous technical challenges remain. Primary challenges facing the developers of new systems include: designing a system that will overcome deception and denial efforts, all weather and day/night operation, improved measurement accuracy, and providing new detection techniques not possible with existing state-of-the-art sensors. The development of verification technologies sensors will continue to be a top priority, so that timely information can be provided to policy makers with sufficient notification to allow the U.S. to intercede early in the proliferation cycle before national security is significantly compromised.

Countering Weapons of Mass Destruction Terrorism

While deterring terrorism is not new to DOE (which sustains a modest Nuclear Emergency Search Team program within its Stockpile Stewardship and Management Program), the breadth of the WMD terrorism problem and its overlap with nonproliferation programs is much greater than before the dissolution of the Soviet Union. This program builds upon ongoing activities in other agencies, and addresses specific scientific and technical areas in which DOE has unique

expertise. There are three primary activity areas: nuclear material detection, including the development and demonstration of nuclear radiation detection sensor systems to deter nuclear smuggling activities as well as to enhance nuclear material accountability and control; chemical/biological detection, including the development and demonstration of capabilities to detect the presence of chemical and biological materials and agents, to enhance biologic forensics tools and understanding, and to counter or remediate the presence of such weapons; and critical infrastructure protection, including cyber security improvements to ensure DOE's information security.

Role and Relationship with Technology Partners

DOE or its predecessor agencies have developed and supplied all of the nation's nuclear weapons. The Los Alamos National Laboratory and the Lawrence Livermore National Laboratory were originally established to design nuclear weapons and the Sandia National Laboratories to design and develop sophisticated engineering control systems for those weapons. These missions remain the principal focus of these three DOE laboratories which constitute the core of research and development to maintain the stockpile. The Nevada Test Site, where about 1000 weapon tests have occurred, is maintained ready for tests, should it become necessary as a supreme national interest, and at the same time provides technical support to the laboratories as well as the capability to expend plutonium in scientific, non-nuclear, studies. Other DOE laboratories as well as universities and industry provide basic science and engineering support to the weapons laboratories.

Because of the increased reliance on science in maintaining our nuclear deterrent, the contribution of the nation's science infrastructure is of increased value. Atomic physics, nuclear physics, plasma physics, chemistry, engineering science, and materials science that can be applied to Stockpile Stewardship are supported by other components of DOE and by other agencies as well as by industry and universities. The weapons laboratories conduct the research and development to apply all of these sciences to analyzing and maintaining the stockpile and in their efforts they contribute to the scientific infrastructure and increasingly engage with the larger national community of science and technology developers. Through DOE's Advanced Strategic Computing Initiative, high energy density physics programs, and direct contracts by the weapons laboratories, universities conduct over $75 million dollars of research annually funded from Defense Programs for its value in maintaining the nuclear deterrent. The weapons laboratories engage in cooperative research and development with industry where DOE's capabilities can contribute to national interests.

The Department of Defense (DoD) shares responsibility with DOE for maintaining the nuclear weapon stockpile. The requirements for the stockpile are stated in the Nuclear Weapons Stockpile Plan which is developed annually by DOE and DoD and is approved by the President. The DoD sets military requirements, jointly manages test flights of weapon systems, participates in planning for surveillance of the stockpile, and participates in certification and refurbishment of weapons. The DoD relies on DOE capabilities, including the Nevada Test Site, and provides some personnel resources to DOE in planning and management activities.

DOE or its predecessor agencies have been charged with providing the technologies and systems needed for the United States to monitor the compliance with nuclear test treaties for over 35 years. Requirements to enable treaty monitoring as established by the Department of Defense (DoD) and the Intelligence Community (IC) drive the development of sensor technology for detecting nuclear explosions conducted underground, underwater, in the atmosphere, and in space. They also specify the needs for data management and analysis tools to process and correlate the enormous amounts of data produced by these sensor systems.

DoD requirements for sensor and data systems to support their nuclear warfighting mission (specifically Nuclear Force Management and Integrated Tactical Warning and Attack Assessment) significantly overlap atmospheric and space treaty monitoring requirements. Accordingly, our satellite-based sensor systems are designed to address both missions. DoD provides the funding for the deployment and operation of these systems.

Congress directed that the Department be responsible for all activities relating to the management, storage, and disposition of fissile materials from weapons and weapons systems that are surplus to the national security needs of the United States. DOE executes R&D activities associated with the disposition of surplus plutonium through the expertise and facilities provided by the national laboratories, universities, and, in some instances, industry.

Success in developing new capabilities to detect proliferation will require an end-to-end approach, with detailed attention to the range of alternative proliferation paths, the phenomenology of the collection technology, and the interplay of potential new forms of technical data with other existing sources of information in assessing a target activity. In partnership with the Intelligence Community and the Department of Defense, DOE provides end-to-end system concepts for new technical approaches which can augment our national capabilities, along with technical risk mitigation through the development and field demonstration of prototype systems. DOE's partnerships with these agencies are facilitated through Memoranda of Agreement (MOA).

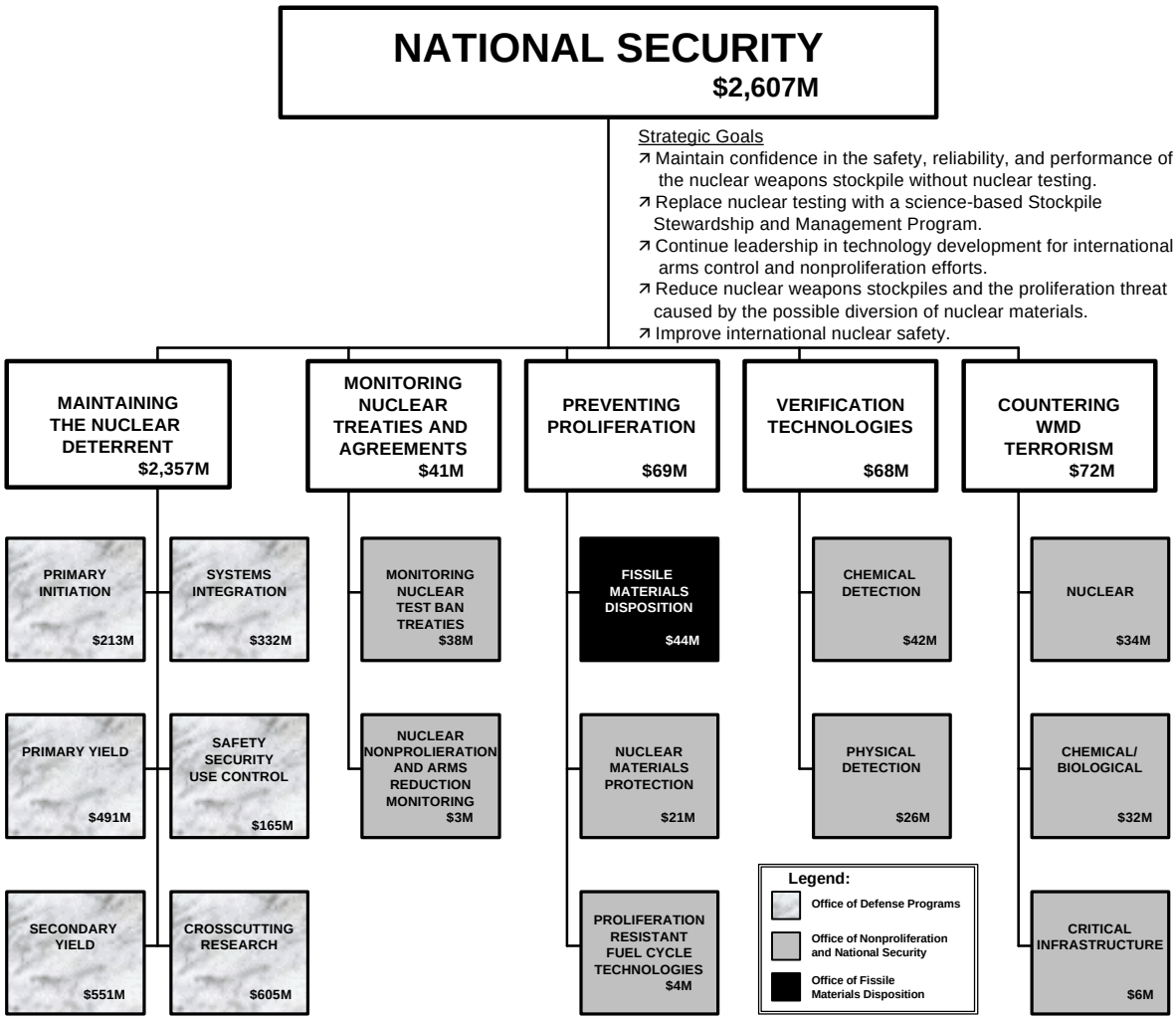
The Department of Energy has unique roles because of its nuclear weapon responsibilities, and the DOE laboratories are uniquely qualified to meet these national challenges. The production of weapons-quality fissile material is the greatest challenge faced by a would-be nuclear state. In many instances technologies developed to remotely monitor the proliferation of weapons of mass destruction also are well suited to support other important national needs. DOE's national laboratories feature unique assets in sensor technology development. Furthermore, efforts that address the detection of biological and chemical agents for counterproliferation, force protection, and anti-terrorist applications can be spun off and will be supported.

Presidential Decision Directives have established a role for the Department of Energy in addressing nuclear terrorism. This is an element of the total WMD terrorism picture and complements the responsibilities of other agencies. The DOE and its Laboratories have a history of working with others to address this problem in a structured way so that national technology investments will yield the greatest result.

Deterring and responding to chemical and biological terrorism presents formidable technological challenges. The chemical and biological nonproliferation R&D capitalizes on an annual DOE R&D investment of over $1B in relevant chemical and biological sciences. Through close coordination with other agencies, the Department provides applications-oriented direction to the Laboratories performing R&D in areas such as detection, modeling and prediction, decontamination, and biological forensics. The Laboratories' efforts are coordinated with each other and with R&D programs supported by other agencies.

The R&D in its early phases is generally executed at the DOE national laboratories. DOE is sensitive not only to requirements from those agencies which must use its technology but also to the opportunities to partner with companies which ultimately produce much of the equipment DOE develops.

Chapter 2
Portfolio Analysis



Chapter 2
Portfolio Analysis

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The Context for the National Security Research and Development Portfolio

The Department of Energy's national security research and development responsibilities have traditionally been focused on matters regarding nuclear weapons, special nuclear materials, nuclear security and safety, arms control, and nonproliferation. DOE is an integral part of the U.S. national security community and plays an essential role in the provision of unique technical expertise in support of the Department of Defense, the State Department, and other agencies focused on reducing the global danger from nuclear weapons or other weapons of mass destruction, and improving international nuclear safety.

Over the past several years, the United States national security policies have undergone profound change to reflect the new and evolving geopolitical and military realities of the post Cold War world. Reflecting these changes, DOE has shifted its priorities toward enhancing activities which advance the Nation's nonproliferation and international nuclear safety policies while maintaining the viability of deterrence with a smaller, more agile, secure nuclear weapons complex.

In this environment, DOE is committed to a science-based program to maintain confidence in the nuclear weapons stockpile without testing, as required under the Comprehensive Nuclear-Test-Ban Treaty. DOE is also committed to safely disposition the nuclear fissile materials made surplus by the downsizing of the nuclear arsenal in conformance with arms control and nonproliferation treaty requirements, counter the proliferation of weapons of mass destruction, and further international safeguards. The Department foresees a future national security environment with continued uncertainty and risks of international terrorism from weapons of mass destruction.

The Department's goals are reflected in its seven national security objectives:

- **Objective 1**—Maintain confidence in the safety, reliability, and performance of the nuclear weapons stockpile without nuclear testing.

- **Objective 2**—Replace nuclear testing with a science-based Stockpile Stewardship and Management Program.

- **Objective 3**—Ensure the vitality of DOE's national security enterprise.

- **Objective 4**—Reduce nuclear weapons stockpiles and the proliferation threat caused by the possible diversion of nuclear materials.

- **Objective 5**—Continue leadership in policy support and technology development for international arms control and nonproliferation efforts.

- **Objective 6**—Meet national security requirements for naval propulsion and for other advanced nuclear power systems.

- **Objective 7**—Improve international nuclear safety.

The research and development activities described in the following chapters demonstrate both significant activity changes since the end of the Cold War and how DOE is investing its resources to solve the current critical national security issues the nation faces.

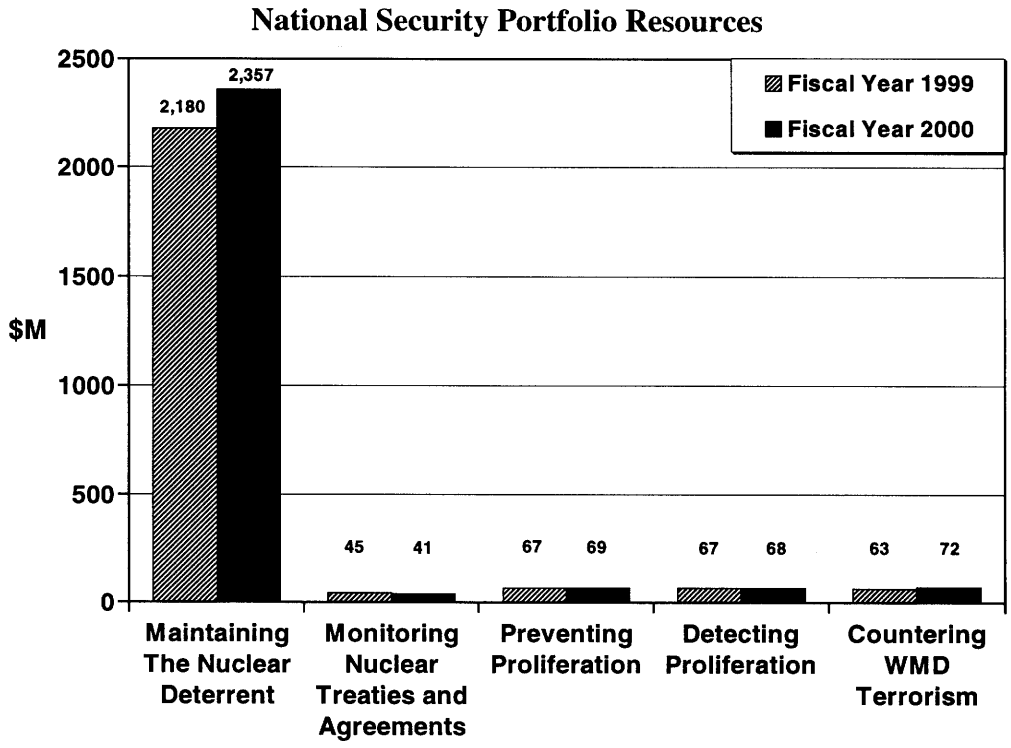
The DOE Research and Development Portfolio

National security is the constitutional mandate of the Federal Government, without a commercial/industrial analog. Resource allocations and funding are entirely driven by the need to maintain the country's national security in a rapidly changing post Cold War world facing a less defined, more diffused threat. While most of DOE's national security activities are not usually widely publicized, we are acutely aware of our need to uphold the public's trust that we will fulfill our important national security mission.

The DOE national security research and development portfolio has been structured to address five primary activity areas that respond to DOE objectives:

- Maintaining The Nuclear Deterrent.
- Monitoring Nuclear Treaties and Agreements.
- Preventing Proliferation.
- Verification Technologies.
- Countering Weapons of Mass Destruction Terrorism.

The distribution of the portfolio's resources to address these issues is shown in the figure on the following page.



The National Security Research and Development Portfolio's resources have been balanced in accordance with DOE's strategic plan along with numerous factors related to national needs. Maintaining the nation's nuclear deterrent in the absence of underground nuclear testing is a very resource-intensive challenge for the Department of Energy. The Department's goal for a science-based stockpile stewardship approach requires a large investment in new technology and research to develop and validate science-based methods to ensure the safety and reliability of the nuclear deterrent.

The nuclear weapons research and development activities are considered to be "applied research." Some of the research is quite basic in nature but is pursued under this portfolio because of its value to specific applied problems of maintaining the stockpile. All of the budget of the "stewardship" portion of Defense Programs has been included in the funding summaries provided here. The "management" portion of the budget has not been included except for the Enhanced Surveillance Program that develops new means of examining weapons from the stockpile. The budget accounted here is consistent with the budget submissions to Congress and with that reported to the National Science Foundation as applied research and development. However, this is the first time that the funds have been attributed to the strategic functions described herein. This distribution has been done approximately; for example, the costs of the National Ignition Facility construction have been attributed 1/3 to Primary Yield and 2/3 to Secondary Yield, according to an ad hoc technical judgement. The budget and work described have not been managed or tracked to the strategic weapon functions used to describe the portfolio. Thus the budget information presented here is notional but provides a technical judgement as to the amplitude of research and development funding in each of the specified categories.

Although at a lower level of funding, the Department of Energy's other national security research and development programs are making considerable progress in meeting their important objectives. The Department of Energy continues its long history of developing technology to monitor nuclear treaties and agreements. In response to profound world-wide political changes, during the last decade, the Department has increased its activities in the areas of developing technology to detect and prevent proliferation. DOE's investments in preventing proliferation are 'opportunity driven' and we expect that changes in DOE's level of investment will be closely correlated with these new opportunities.

While research and development in countering weapons of mass destruction terrorism is not new to the Department of Energy, changing world events have clearly demonstrated that terrorism is rapidly becoming a primary threat to national security. The Department recognizes that its existing expertise in nuclear weapons is a valuable asset to meet the challenges of terrorism and is leveraging the DOE Laboratories' large investment in chemical and biological sciences to support the national effort.

DOE places a high priority on its R&D so that essential long-term goals are not sacrificed to address current problems. Solving challenging problems often involves long-term, long lead time research. Within the R&D planning process, decisions are continually being made in the planning-programming-budgeting process in order to keep the priorities in rank order. At the same time, however, it must be recognized that R&D, which is one of the most important DOE functions, cannot remain healthy and vibrant within a rapidly varying funding environment.

Next Steps

The portion of this R&D portfolio on "Maintaining the Nuclear Deterrent" is not comprehensive. Example activities are given to provide a concept of this research and development function in an unclassified manner. A comprehensive and classified description of the Stockpile Stewardship program is the "FY2000 Stockpile Stewardship Plan" and its predecessor documents, also known as the "Greenbook." These comprehensive documents describe both the nuclear weapon research and development activities and the weapon production and management activities of the DOE. The "Executive Overview: FY2000 Stockpile Stewardship Plan" (March 1999, DOE, Defense Programs) is a useful unclassified summary. The original definition of the Stewardship Program, "The Stockpile Stewardship and Management Program: Maintaining Confidence in the Reliability of the Enduring U.S. Nuclear Weapon Stockpile" (May 1995, DOE, Defense Programs), remains valid in setting out the program rationale.

This research and development portfolio describes the nuclear weapons program along the lines of its strategic components of weapon function: primary initiation; primary yield; secondary yield; system integration; safety, security, and use control. In addition a section on crosscutting research describes activities not uniquely or readily attributable to only one or two of these strategic elements. At the present time extensive program planning is underway linked to these strategic elements. Activities are being aggregated in "campaigns" that have specific deliverables and end dates related to these weapon function elements and to specific weapon certification and refurbishment. The first set of campaigns will extend to about the year 2005 and describe a

nuclear weapon program that depends, in part, on the nuclear test history and at the same time defines how the stockpile can be maintained without future nuclear tests, relying on research and development results. Both this R&D portfolio and the campaigns delineate improvements in research and development capabilities that extend well beyond the year 2005 and are critical to sustaining the stockpile indefinitely without testing.

For the nuclear weapons program, a recent survey identified eight categories of external reviews with multiple specific reviews attributable to each category. Many of these are science reviews, including: JASON, the National Academy of Sciences, ad hoc program review groups, and laboratory specific reviews. It is anticipated that this program will continue to be subject to multiple external reviews. The campaigns that are in planning and the anticipated reviews will lead to extensions of the nuclear weapons portion of this portfolio.

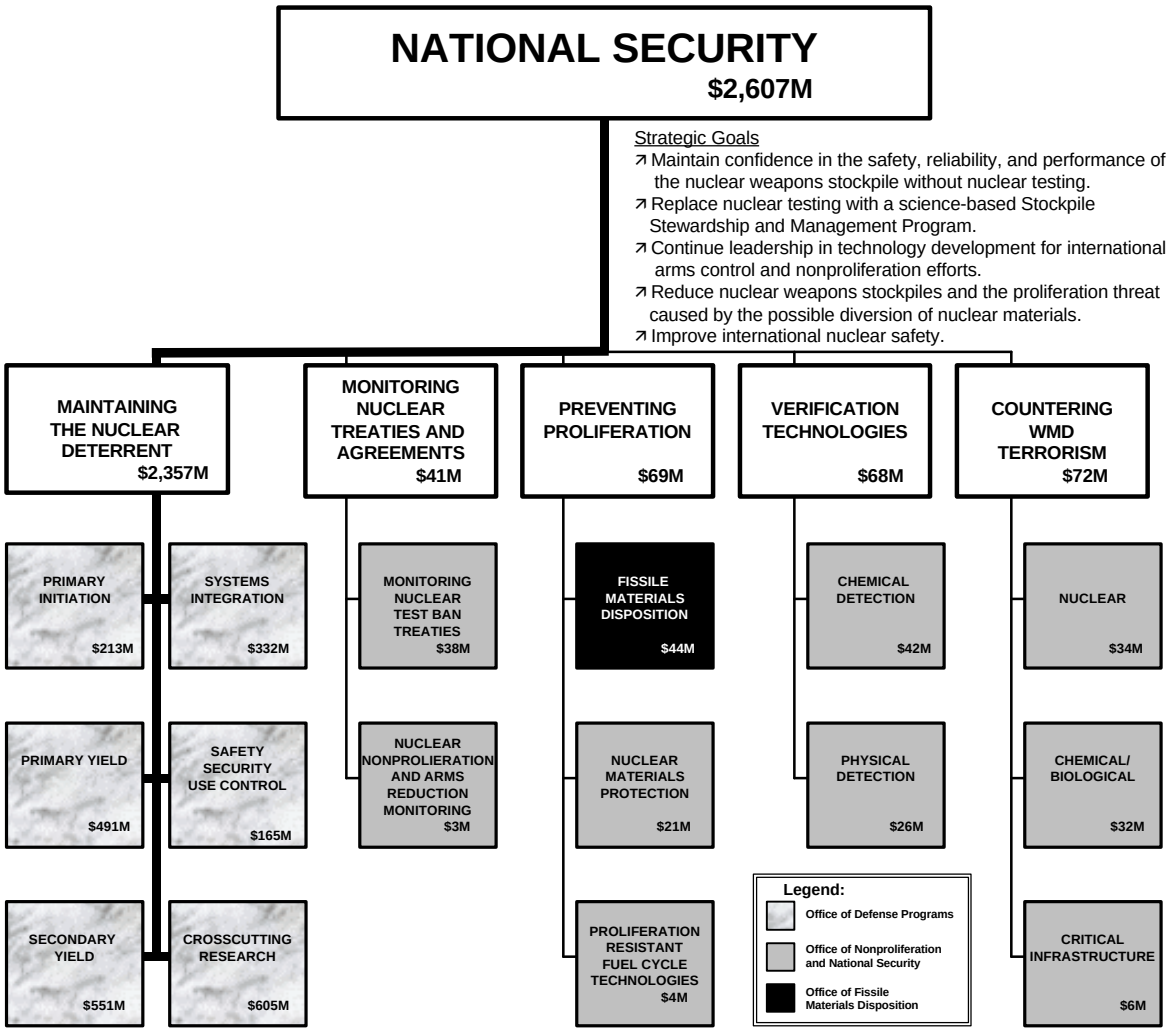
Portfolio descriptions provided in the following chapters on “Monitoring Nuclear Treaties and Agreements”, “Preventing Proliferation”, “Verification Technologies”, and “Countering Weapons of Mass Destruction Terrorism” represent comprehensive descriptions of their contributions to the DOE National Security R&D Portfolio. The relevance of each part of the Portfolio in the context of enhancing the nation’s national security is explained.

This presentation and description of the portfolio and its relevance to national interests is an important first step in portfolio development and analysis, but is only a beginning. This document demonstrates that the DOE portfolio meets multiple objectives with the robustness required for an uncertain future, but continued and expanded planning and analysis is needed to insure appropriate prioritization and efficient utilization of taxpayer funds applied to these efforts. Future steps should include expansion of current technology and program roadmapping.

The Department of Energy has initiated the process of establishing a Nonproliferation and National Security Advisory Committee in accordance with Section 9 of the Federal Advisory Committee Act, Pub. L,. No. 92-463, and Executive Order 12838. The Advisory Committee will be available to provide an external review of any research and development activity within the Office of Nonproliferation and National Security.

Future changes to portions of the portfolio will occur because of new opportunities, technological developments, and requirements from unfolding national and international events. Strategic planning, portfolio analysis, and technology roadmapping will provide the framework to keep pace with demanding national security needs.

Chapter 3
Maintaining The Nuclear Deterrent



Chapter 3
Maintaining The Nuclear Deterrent

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Overview

Definition of Focus Area

The Stockpile Stewardship Program is responsible for maintaining the safety, security and reliability of the nuclear weapons stockpile and maintaining the ability to respond to future threats to nuclear deterrence without nuclear testing.

National Context and Drivers

The post Cold War national security environment is increasingly complex. At least 20 countries are known to be or suspected of developing weapons of mass destruction, underscored by the recent underground nuclear tests of India and Pakistan. The fragmentation of the former Soviet Union has led to concerns about the accountability, control, and disposition of weapons, components, materials, and information. The increased activity and technical sophistication of non-state actors is a further concern.

The DOE national security mission is driven by national security policies that have developed from this environment. An August 11, 1995 Presidential Decision Directive announced the decision to maintain a strong nuclear deterrent while seeking a Comprehensive Test Ban Treaty. This decision required the establishment of a science-based Stockpile Stewardship program to maintain the stockpile without further underground testing. This is a fundamental programmatic change. In the past, weapons systems were replaced by new systems, certified through underground testing, before aging effects (other than tritium decay) became an issue. Although the Senate has not ratified the Comprehensive Test Ban Treaty, DOE continues to base its planning on the assumption that nuclear deterrence must be maintained without testing.

Linkage to Goals and Objectives

Research in this area is focused on the following National Security Objectives of the DOE strategic Plan:

1. Maintain confidence in the safety, reliability, and performance of the nuclear weapons stockpile without nuclear testing.

2. Replace nuclear testing with a science-based Stockpile Stewardship Program.

In support of these national security goals, the Stockpile Stewardship Program maintains three principal capabilities:

- **Design**—The scientific and engineering evaluation of materials and configurations to ensure that nuclear weapons meet military requirements.

- **Production**—The ability to produce the components necessary to support an aging stockpile and to manufacture new nuclear weapons in the future as a hedge against strategic uncertainty.

- **Stockpile Support**—Nuclear weapons maintenance and training support for operating military personnel.

In support of these national security objectives, DOE maintains a portfolio of research and development centered on meeting the following goals:

1. Provide a scientific basis for assessing the performance of the stockpile with no further underground nuclear testing:

   - Develop capabilities to conduct experiments in physical regimes important for understanding nuclear weapons performance.
   - Develop an understanding of the effects of aging on nuclear weapons materials and components.

   - Develop experimentally validated physical models and computational methods for simulating nuclear weapons performance.

2. Develop new technologies to insure the availability of special nuclear materials and other weapons components in order to reduce cost, environmental impact, and improve component reliability.

Uncertainties

The scope of the Stockpile Stewardship R&D portfolio is governed by a consensus of the nuclear weapons community about the contribution of this R&D to assessing and addressing risks to nuclear deterrence. These risks will be 1) technical design risk associated with aging 2) risks associated with production capabilities and capacities, and 3) risks that result from an evolving international strategic environment. The premise of stockpile stewardship is that technical risk in the nuclear weapons program can be understood and managed through a science-based approach without further nuclear testing.

Various approaches can be taken to risk assessment. Although it is a deliberate national security policy to classify nuclear weapons information, one principle of deterrence requires that a potential adversary should remain deterred even were it to possess complete knowledge of our designs and our operating procedures. This principle of deterrence requires that we have enough rigorous knowledge about designs and procedures to assure that such knowledge would deter such an adversary. This argument underlies the justification for a stockpile stewardship program that actively pursues a scientific understanding of the state of an aging stockpile and the impact on performance of measures taken to address those aging effects.

Although there are no current plans to introduce any new systems into the stockpile, the stockpile is not static, and change in the state of the stockpile and our assessment of the condition of the stockpile pose new risks to deterrence. These changes will include:

- Aging and the discovery of latent design and manufacturing defects.
- The evolving national technology base including the consequences of sunset technologies and the shift towards knowledge-based engineering in industry.
- Change in military requirements as the international strategic environment evolves.
- The imperative to maintain, or if required improve, safety, security, reliability, and maintainability.
- "Subliminal change" - small unintended changes in operations and processes made by individuals intentionally or unintentionally that fall below risk management thresholds.

Until the current cessation of testing in 1992, underground nuclear testing was the principal means to assure the performance of weapons systems and to benchmark design codes used in the assessment of weapons safety, reliability, and performance. The development of computer simulation models to extrapolate system performance from underlying physical models is a primary objective of the Department's national security research and development program.

Investment Trends and Rationale

The R&D portfolio is focused principally on supporting design and production requirements. The term nuclear weapons “design” refers to all technical activities involved in the development and evaluation of configurations and constituent materials used in components so that the weapon meets military requirements. Because of the complexity of the operation of a nuclear weapon, the evaluation of most proposed changes will become research projects themselves. Therefore R&D is integral to the operations necessary to carry out stockpile support. Research in these areas is principally conducted at the three nuclear weapons laboratories, although there is supporting R&D carried out at universities and in partnership with industry, particularly in areas to support underpinning science and computation.

The Department of Energy also maintains the ability to produce special materials and components required in nuclear weapons that are not available commercially and to assemble weapons systems. Research and development is conducted at the laboratories and at the production facility level to maintain currency in materials science, manufacturing technology and quality assurance assessment, and to solve problems in the application of improved technologies to nuclear weapons production and maintenance. It must be emphasized that a vigorous research activity will be necessary to maintain the intellectual vitality without which it will not be possible

to attract and retain those individuals upon whom national security policy makers will rely for advice about nuclear weapons matters.

The principal failure risks in the stockpile can be categorized in one of the five principal functional requirements for a nuclear weapon. DOE's portfolio of research is driven by the technologies necessary to mitigate the risk in each of these performance areas:

- **Weapon Initiation—**the electromechanical systems that control the sequence of arming, fuzing, and weapons detonation functions after authorized release and normal trajectory to target.

- **Primary Performance**—ensuring that aged or remanufactured energetic materials, fissile materials, and other engineering materials do not affect the ability of the primary to provide the necessary yield to drive the secondary.

- **Secondary Performance—**understanding the impact of degraded primary performance and/or aging of the secondary system on a weapon's yield.

- **Integrated Weapon System Performance—**ensuring that the integrated system functions in the harsh stockpile-to-target sequence.

- **Safety, Security, and Use Control**—ensuring that the weapon is safe to handle and can only provide a significant nuclear yield under use authorized by the President.

The total FY 2000 request for the Stockpile Stewardship R&D portfolio is approximately $2.4 Billion. Within inflation and small variations, this budget is not expected to change significantly in the foreseen future.

Meeting the goals of the stockpile stewardship program requires a well-integrated interdisciplinary program of research, and this portfolio discusses the research in terms of the functional performance requirements for a nuclear weapon. The principal cost drivers, however, are the facilities and efforts within particular discipline areas. The major facilities and activities that establish the cost scale for the stockpile stewardship R&D effort are:

- **Computing**—including the Advanced Strategic Computing Initiative (ASCI). The nuclear weapons program will rely on computer based methods to assess nuclear weapons performance in the absence of testing. Requirements for 100 Teraflop machines and weapon simulation software are established by the complexity of a nuclear weapon and the level of detail and resolution necessary to capture the relevant physics in the problem in full three-dimensional geometries.

- **Theory and Experiment**—providing a scientific understanding and validating detailed physical models used in codes to assess weapons performance margins.

- **High energy density physics experiments** to provide an understanding of systems and materials under conditions relevant to primary boost and secondary implosion and burn. Inertial Confinement Fusion is a major component of this research including the construction of the National Ignition Facility (NIF).

- **Hydrodynamic Test facilities** at the national laboratories that are used to implode full scale systems that mimic primary devices but with simulants for the nuclear materials. The cost of these facilities is largely driven by the need for accelerators to produce intense bursts of high-energy x-rays in order to radiograph the imploded primary system. A significant facility now under construction is the Dual Axis Radiographic Hydrodynamic Test (DARHT) facility. In addition, subcritical experiments will be performed using special nuclear materials in underground experiments to provide important data on materials properties and as a measure of the readiness of the Nevada Test Site to conduct nuclear testing.

- **Physics, Chemistry, and Materials Research** includes research in the nuclear and materials properties of special nuclear materials and the effect of aging or radiation environments on electronic and other components. This area also encompasses extensive research in energetic materials (explosives) as well as research to understand the aging of polymers. The major facility for this work is the Los Alamos Neutron Scattering Center (LANSCE), a proton accelerator that can be used for proton radiography and to drive a spallation source of neutrons, as discussed further under "Crosscutting Research."

- **Integrated Engineering Tests**

  - **Flight tests**—test of mock warheads on ballistic missile flights. This includes the development of improved instrumentation to provide the highest achievable fidelity to the launching of a war reserve system.

  - **Above ground engineering tests**—the DOE's national laboratories maintain a suite of facilities for testing the non-nuclear performance of the nuclear weapons system when subject to shock, vibration, thermal transients, and hostile environments. This includes facilities to simulate electromagnetic, blast, neutron, and radiation affects of nearby warhead detonation.

  - **Surveillance and production technology development**—technologies to monitor the state of the aging stockpile and to develop improved manufacturing capabilities. Modern manufacturing technologies are being adapted for use by the Department to improve quality, reduce costs, and lower worker exposure to hazards. This research and development is a component of the Department of Energy's Crosscutting Roadmap and Program Plan for Robotics and Intelligent Machines.

The cessation of testing has had its most profound impact on the assessment of the nuclear performance of weapons. Current designs are highly optimized for performance based upon a cycle of testing of new designs that are an extrapolation from data from previous tests. Design codes have been central to this process, but in each case these codes have been adjusted heuristically to previous nuclear test data. While deep physical insight often went into the development of the *ad hoc* models used, confidence has been based to a large extent on test experience, and these codes were not required to be validated for assessing the effects of aging. The requirement to assess the impact of aging on stockpile safety, reliability, and performance from fundamental scientific understanding rather than underground testing is therefore a radical departure from previous practice.

Non-nuclear design has undergone a similar change in methodology. Environmental and financial constraints, including the closing of test facilities have impacted non-nuclear assessments. More fundamentally, however, engineering practice, generally, has shifted from test-based methodologies to knowledge-based methodologies, of which simulation is an increasingly important tool. Simulation methods relying on only a few confirmatory experiments are becoming standard engineering practice, not only to reduce costs, but also because it has resulted in better understanding of underlying phenomena and therefore provides a better mechanism for making design tradeoffs.

Therefore, the development of high fidelity simulations, including research facilities to develop the required physical understanding and models and to validate simulation codes, is a central theme of the research portfolio. In particular, the Accelerated Strategic Computing Initiative (ASCI) and Inertial Confinement Fusion (ICF) are efforts that underlie and crosscut the stockpile focused research areas.

The strategic objectives of stockpile stewardship are the five principal functional areas mentioned above. Crosscutting research is discussed as a separate category in section VII. DOE Defense Programs is currently in the process of planning approximately ten "campaigns" to focus and integrate R&D efforts. These campaigns will be resourced, three-lab, mutlidisciplinary efforts, the completion of which will develop the required technical capabilities to support each of these five strategic functional requirements for a nuclear weapon. Each campaign is expected to be of approximately 4 to 6 year duration, with well defined goals and milestones. Each will drive the development of an interdependent set of experimental, theoretical and computational capabilities.

Federal Role

DOE has inherited the legislated mandate from the Atomic Energy Commission (AEC) for sole oversight of all classified nuclear weapons technical information and of the production and handling of nuclear weapons components and special nuclear materials. DOE owns and operates, through contractors, the Defense Programs national laboratories and the production plants and facilities to meet the legislated mandate in nuclear weapons.

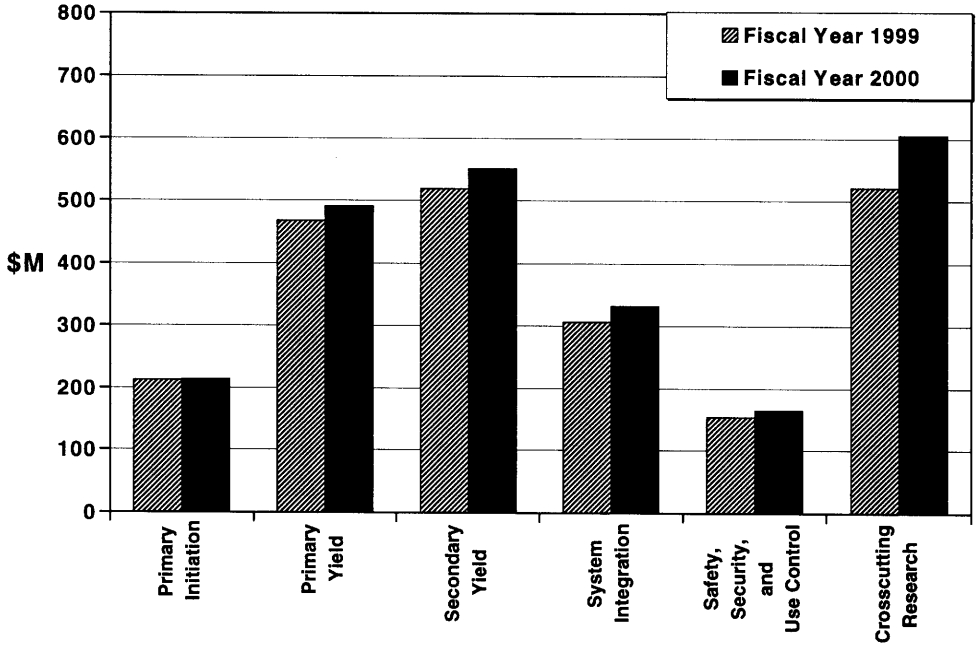
Key Accomplishments

Key accomplishments for Stockpile Stewardship are:

- Established records for computing performance on ASCI computers as milestones to achieving the required computational capability. As an example, 1.6 trillion operations per second (Teraflops) achieved on the Blue Mountain computer on November 11, 1998.
- Revalidated the W76 warhead through a new dual revalidation process without underground testing.
- Obtained data on behavior of plutonium at near weapons conditions through subcritical experiments at the Nevada Test Site.
- Won the national "Excellence in Plasma Physics" award for research on the behavior of hydrogen at high pressures relevant to nuclear weapon analysis as well as understanding the planet Jupiter.
- Completed, in FY-1999, of the first arm of the Dual Axis Radiographic Hydrodynamic Test (DARHT) Facility.
- Initiated research and development to see and understand simulation data sets of unprecedented size (see "Data and Visualization Corridors" edited by Paul H. Smith and John Van Rosendale, CalTech Report CACR-164, September 1998, http://www.cacr.caltech.edu/pulications/DVC).

The chart shown below shows investments by activity areas that will be discussed in the remainder of this chapter. Costs of major facilities are accounted where they are discussed except that construction of the National Ignition has been divided between primary and secondary research.

Maintaining the Nuclear Deterrent



Primary Initiation

Budget: FY98-$218M, FY99-$212M, FY00-$213M

Background

The primary initiation system consists of components that control and enable the chain of events that occur from launch, through normal trajectory to detonation. Weapon safety, reliability, and performance begin with the functioning of the initiation system. Components of this system include the arming, fuzing and firing system, the gas transfer system (tritium system), and neutron generators.

The principal challenge for the initiation system is to maintain simultaneously the required system reliability coupled with unprecedented safety requirements (less than $1x10^{-9}$ probability of accidental detonation over the lifetime of the weapon in normal handling and less than $1x10^{-6}$ in an accident). These requirements are 400,000 times stricter than those for a nuclear reactor and place very high standards on individual component reliability. New challenges arise because of sunset technologies used in many of the components in these systems, and therefore refurbished systems must necessarily use technologies that are different than those used when the stockpile was certified.

The initiation system is an essential part of the nuclear safety system and is the first step in reliable operation of the weapon system in the "stockpile-to-target sequence." In order to assess the health of the current stockpile components and to design, manufacture, and certify replacement components with currently supportable manufacturing technologies, a strong R&D base is essential.

Program Description

Arming, Fuzing, and Firing—In the past, the arming system has relied upon complex electromechanical coded switches. Built with better than a watchmaker's precision, these devices must operate to arm the weapon when they receive the correct coded train of electrical pulses, but otherwise lock-up to prevent any further arming action. Understanding how these components age and what technologies will replace these systems is a central part of the ongoing R&D effort. New technologies being explored would use micro electromechanical systems or electro-optical systems with a great potential to improve safety, security, reliability, and maintainability (refer to the section on safety, security, and use control).

The fuzing system is the system that determines the point at which the weapon should be detonated. Examples include radar altimeters, contact fuzes, and flight timers. Radar systems must operate in a hostile environment and be compact enough to fit in the small volume remaining in a reentry body outside of the nuclear explosive package. Contact fuzes must operate reliably on ground contact at very high velocities and detonate the system before the ground shock destroys the weapon system.

The firing system must generate precisely timed, high voltages. As an example of the aging issues faced in the stockpile, some systems generate these voltages by explosively depolarizing a ferroelectric material. This function of that ferroelectric material as it ages must be understood and checked to guarantee proper and safe initiation of the primary.

Gas Transfer—Tritium. Reliable tritium storage and transfer to the warhead is a complex technology as well. Absolutely reliable long-term containment is the first criterion because of radiological hazards. Storage is at high pressures, and hydriding and cracking of the containment are principal material concerns. Even small differences in metal alloying can have a large impact on the susceptibility to hydride cracking. As a result of the importance placed on the need to understand possible container failure, there has never been a leak in a fielded DOE tritium container.

Neutron Generators. Neutron generators formerly manufactured at the closed Pinellas plant are now manufactured at Sandia. These systems have had to be redesigned and certified using different production processes and different materials, since some materials are now classified as carcinogens and no longer available for use. Neutron generators operate as compact accelerators that must generate their own precisely timed high voltage. These neutron generators must be fully ruggedized and operational in a hostile environment.

Materials and Nano Science. Materials science is key to understanding nuclear weapons systems function and age and providing a foundation for the concurrent engineering, rapid prototyping, and agile manufacturing schemes that are needed for reliable, economic stockpile component replacement. In order to address the issues of aging, reliability, and surety, predictive understanding is required over a wide range of time scales. These scales extend from the slow processes associated with materials aging over time spans exceeding the original design lifetimes of systems, to the very high dynamic rates of explosive and radiatively driven events. An understanding is also needed of the fundamental processes underlying the synthesis of new materials for replacement components that provide improved functionality and performance.

The science base for microelectronics and microsystems provides a foundation for the incorporation of new technologies into weapon systems and stockpile stewardship operations. These technologies address control and operation of the weapons, as well as providing intelligent systems which monitor and diagnose the condition of weapons with regard to aging, functional status, intrusion or tampering, and anticipated performance. Key elements of nanosciences research include: aging science and analysis; self-aware sensors and systems; radiation environmental effects; advanced concepts for firing systems, arming and fusing; telemetry instrumentation; and optical communications.

Nanoscience research relevant to primary initiation addresses two specific task areas—Science of Semiconductor Technologies and Nanoscale Materials. These areas augment and support complementary tasks in Materials and Electronics research.

The science of semiconductor technologies has as its objective the development of novel tailored semiconductor materials and structures for microoptical and nanoelectronic devices and systems. The approach is to investigate quantum transport in novel semiconductor structures to provide the basis for ultra-high-speed electronic and optical devices. There is additional work investigating the integration of semiconductor microcavity lasers with other materials classes as the basis for novel sensing applications. In addition, research is investigating advanced materials growth and fabrication techniques for multi-functional, monolithic semiconductor structures and systems.

Research in nanoscale materials has the objective of developing atomic-level understanding of nanostructured materials and of shock and radiation induced phenomena, as well as complementary diagnostic capabilities, to create the scientific technology base needed by Defense Programs. Specific research activities underway on nanoscale materials include developing field-structured and nanocluster-assembled materials as well as materials with mixed bonding configurations with tailorable properties and anistropies. Work to understand surface modification and thin film deposition to tailor surface hardness, wear, friction, adhesion, optical, and electrical properties. Further research concentrates on developing and determining the range of validity of first-principles computational methods to describe the defect properties and dynamic response of materials.

In the area of mechanical shock and radiation effects on components, physics research is being conducted to develop continuum and atomic-level understanding and models of shock-induced phenomena as well as complementary advanced diagnostics capabilities. It is also necessary to better understand and predict the performance of microelectronic and optical devices in radiation environments.

Within materials research there is also a major thrust studying the aging and dynamic processes for enhanced reliability and life extension. This includes work to develop and validate materials models for reliable fabrication and predictive aging of materials and develop validated models for the chemical processes involved in synthesis and aging of thin films.

Some research activities are focused on the support of specific component areas such as neutron generator science for improved design and manufacturability. This work includes capabilities in plasma science, hydrogen and helium in metals, and shock response of ferroelectrics and encapsulants to develop fundamental mechanistic understanding and simulation models of neutron generators, and to solve development, production, and performance problems. Plasma science studies include generation systems, diagnostic tools, plasma models, and applications of plasma devices to provide a fundamental understanding and advance the utility of these tools and processing methods. This understanding provides the basis for improving the performance and reliability of neutron generators and other critical weapons components.

Integrated Microsystems. Exploit the advances in modern microelectronics technology to transcend the mere processing of information performed by modern microprocessor chips. Integrated microsystems incorporate ultra-miniature sensors, actuators, and wireless (optical or

radio-frequency) communication components – all within a single package. Integrated microsystems offer the potential to replace hundreds of individual parts with a multifunctional piece of silicon to eliminate thousands of solder joints, (a frequent source of failure) through single-chip integration, to reduce the cost of manufacturing relatively functionally-similar parts through batch fabrication methods of modern microelectronics, and to provide parts that can easily be replaced or upgraded.

Integrated microsystems for DOE applications must meet or exceed substantially more demanding requirements than those used for commercial applications and must provide higher confidence and greater reliability than their commercial counterparts. Thus, along with the concurrent engineering of fabrication methods and design methodologies, DOE missions also require concurrent development of friction and wear on the atomic scale to enable science-based predictive procedures for quantitative reliability assessment.

Radiation Effects Science is focused on ensuring that the integrated nuclear weapon system functions in the harsh stockpile-to-target sequence and requires an ongoing experimental, theoretical, and modeling program to understand and predict the complex behavior of electronics and mechanical systems in radiation environments. The ultimate goal is to be able to certify or qualify for radiation hardness without underground testing.

As an example, the MC4380 W76 warhead replacement neutron generator will be certified in FY 1999, the first time a modern generator has been certified without underground testing. The new certification methodology relies on small-scale materials-characterization experiments and computer simulations using experimentally-validated codes. Future projects include shields for the W76 replacement AF&F, and the MC4600 replacement generator for the W88 warhead. Improved physics understanding and new codes will form the basis for this new modeling certification methodology in mechanical effects arising in primary initiation analysis.

Electronics Radiation Effects. One cannot use old microelectronics in future stockpile replacement hardware. The old parts are no longer manufactured. The ever evolving nature of microelectronics and manufacturing technologies requires continual research. This R&D provides understanding of the radiation hardness vulnerabilities. Sandia National Laboratories' War Reserve Electronics Modeling and Simulation provides integrated circuit codes with aging and radiation models. These models will include the effects of x-rays, gamma rays, cosmic rays, and neutrons. This understanding should dramatically reduce the time and cost to realize the new electronic and optical devices required for future weapon upgrades (e.g., Mark4 AF&F for W76-1) by assuring radiation resistance in advance and by shortening the expensive design-build-test-fix cycle. Currently this project is working with Sandia's Microelectronic Development Lab to validate the DAVINCI three-dimensional charge transport device code for cosmic-ray effects, in addition to diagnosing radiation-induced failure mechanisms in commercial integrated circuits.

Primary Yield

Budget: FY98-$399M, FY99-$468M, FY00-$491M

Background

The primary system consists of the high explosive, fissile material, and boost system that produces the energy necessary to drive the secondary. Primary yield depends upon a number of factors relating to the compression of the plutonium pit. For reliable performance of a nuclear weapon, the primary must provide a minimum yield that adequately drives the secondary.

Program Description

Principal concerns are the changes in materials characteristics with aging, including that of the fissile materials and high explosives. Long term materials compatibility issues associated with engineering features in the weapon are also important. As weapons are remanufactured, differences in details of fabrication processes can have the effect of changing the properties of high explosive or fissile materials, altering the implosion and therefore the performance of the primary. The effect of such changes on the initial stages of the implosion can be understood through non-nuclear experiments. In the absence of nuclear testing the development of validated models of boost is a principal area of research.

Examples of R&D activities supporting primary yield are discussed below. These discussion are not comprehensive, and further details are contained in the classified "Green Book," the *FY2000 Stockpile Stewardship Plan.*

Tritium Production Technologies. Tritium is essential to the proper functioning of a boosted primary. Because tritium decays with a 12.6 year half-life, once the current excess inventory is drawn down, tritium will need to be replenished. The Secretary of Energy recently announced the decision to develop the Watt's Bar Reactor operated by the Tennessee Valley Authority as an irradiation source to produce tritium. The production of tritium is not accounted for in this R&D portfolio.

Pit Production Technologies. The stockpile surveillance program withdraws weapons from the stockpile each year for each warhead type. These weapons are then disassembled to be examined for aging and manufacturing defects, and must be replaced by new manufacture of similar components. Since Rocky Flats has been closed for environmental reasons, a new manufacturing capability is being established at the existing plutonium facility at Los Alamos, which has long had the capability to manufacture such components for research and development. Some process changes will occur relative to those used at Rocky Flats, and therefore extensive research is required to understand both the manufacturing process and to understand the materials properties of pits produced in this new manner, in order to understand how this might impact primary performance.

Hydrodynamic Test Facilities. One of the most critical program needs is the ability to see details of the compression of the pit at the time of primary detonation. Hydrographic facilities are now in use for this purpose but better spatial resolution and pictures at sequential times are needed. The Dual Axis Radiographic Hydrodynamic Test (DARHT) facility is a step to new capability. An Advanced Hydrographic Facility (AHF) with adequate resolution and multiple time pictures is a program goal.

The Flash X-Ray (FXR) at site 300 at Lawrence Livermore National Laboratory (LLNL), and Pulsed High-Energy Radiographic Machine Emitting X-Rays (PHERMEX) at Los Alamos National Laboratory (LANL) use radiography to view and otherwise diagnose the implosion of a primary. The PHERMEX facility has been undergoing improvements that have successfully increased the radiographic dose available (from 250 to 350 roentgens at 1 m) and incorporated a double pulsing capability for producing two sequential radiographic images of about 125 roentgens each. The double pulse capability also includes a new large format, two frame gamma-ray camera. This double pulse capability has been successfully used on several hydro-tests. DOE is constructing newer facilities to improve these capabilities, notably the DARHT at LANL, the first axis of which will become operational in FY1999, and the Contained Firing Facility, an upgrade of the FXR at LLNL. These facilities provide an understanding of how various changes in the primary system, due to aging or fabrication processes, change the imploded configuration. They also provide important data for constraining and validating computational models. It must be emphasized that these tests use a simulant for the fissile material in a weapon and therefore cannot replicate the nuclear behavior and its impact on materials. Therefore, the performance of the weapon subsequent to criticality (the crucial part of the implosion process) must be extrapolated from radiographic and other information through simulations.

Several improvements have recently been made, are in progress, or are planned for the FXR facility. The development of the gamma-ray camera has made possible an increase in resolution and an increase in sensitivity for measuring thicker objects. Changes to the accelerator are now in progress to increase resolution by decreasing the electron beam spot size and increasing beam current. Subsequently, the accelerator will be reconfigured so that two sequential pulses can be produced to record dynamic changes in a primary assembly. This project will incorporate an active readout to the gamma-ray camera so that the two closely spaced sequential images can be recorded.

In FY 1999, the FXR facility will be shut down for the construction of a containment addition. With the containment addition, all hazardous material will remain in the containment chamber to be removed and disposed of. The chamber will include a semiautomatic wash-down system to facilitate the rapid turnaround of experiments. The project will also include an addition to the space available for diagnostics, allowing the facility to better serve as a complement to the Underground Environmental Complex (U1A) at the Nevada Test Site (NTS)

Materials Research for the Primary System. Materials properties under relevant pressures and temperatures that are not easily achieved, but where chemical and constituitive properties are still important, is a principal focus of research to support this strategic objective.

Continued work to understand the chemistry of high explosives, particularly the impact of aging on safety and primary performance, is a critical part of the work in this area. High explosives are extraordinarily complex organic materials, highly susceptible to age-related changes, and much of our understanding remains heavily based on empiricism. Research in high explosives chemistry and physics provides the understanding necessary to predict weapon performance, reliability, and safety in both new and aged conditions, and provides the basis for a rigorous stockpile surveillance and refurbishment program.

Plutonium has a unique set of materials properties, and understanding these properties is essential to assessing the stockpile in the absence of nuclear testing. For example, measurements on the shock and stress-response of plutonium at Los Alamos are contributing to the necessary basis of technical rigor for future stockpile assessments. Time-resolved experiments determine the time-dependent behavior of plutonium as it responds to shock stress and release, when it is shocked by impact in the 40-mm gas gun. Recently, "soft recovery" has allowed an assessment of damage and spall of plutonium after it is put in tension. Measurements made on the "Split Hopkinson bar," provide data on the dynamic strength of plutonium at high strain rates. It also determines plutonium strength under intense cold and heat. Measurements on material “soft-recovered” from the 40mm shock experiments will quantify the effects of shock loading and phase transformation history on material properties. A new tensile "Hopkinson bar" will examine damage/spall of materials under various degrees of tensile stress. It will be able to do experiments at various stages of development of the damage process.

Further research in this area is conducted on the LANSCE facility described under crosscutting research and in subcritical experiments described next.

Subcritical Experiments. These are experiments performed underground in the U1A complex at the Nevada Test Site using special nuclear materials, but in quantities and configurations such that it is not possible to reach criticality. These experiments provide vital data on materials properties, validate modeling, and provide realistic assessments of data collection under the challenging conditions of underground experiments. In addition to providing important physical data, these experiments also exercise Test Site readiness to resume nuclear testing as required by national policy.

The 1998 Cimarron experiment, for example, measured the ejecta properties of two separate plutonium-and-high explosive packages. Leading up to this experiment, Los Alamos conducted 28 smaller scale shots, without plutonium, in the development of the diagnostics which included: holography, to measure particle distributions; x-ray shadowgraphy, to provide a two-dimensional measurement of the ejecta mass density; specialized measurements to provide localized ejecta mass measurements; pyrometry, to measure the surface temperature; electrical contact pins and VISAR experiments, to characterize the front surface velocity; and microwave interferometry and electrical contact pins to characterize the high explosive burn.

Boost Physics. Uncertainties in our understanding of boost physics has the greatest impact upon the ability to assess nuclear performance margins and the boost process integrates all of the other

uncertainties in the implosion of a boosted primary. Some aspects of the primary system evolution leading to boost are studied in subcritical experiments. Ultimately, boost physics is a high energy density physics problem and ignition and non-ignition experiments planned for the National Ignition Facility will help develop physical models that describe the boost process.

Baselining and Data Archiving. A major effort is underway to understand the test data base for each weapon in the stockpile and archive the information that is available. This effort involves recomputing baseline performance using current computational capabilities and then developing a scientific understanding of the difference between these computations, original design calculations, and the underground test data. This will be a substantial multi-year effort. It is anticipated that there is much to learn about weapons performance by analyzing anomalous underground test results.

Secondary Yield

Budget: FY98-$438M, FY99-$519M, FY00-$551M

Background

Secondaries are driven by the radiation produced by the nuclear explosion of the primary. Predicting secondary yield requires detailed knowledge of radiation flow, atomic physics, properties of materials, and hydrodynamics. Properties of materials must be understood during processes involving temperatures over 100 million degrees, pressures over 10 million atmospheres, and material velocities of more than one million miles per hour, and these processes are measured in billionths of a second.

A significant portion of a thermonuclear weapon's yield is produced by the secondary, and, therefore, assessing the expected yield of the secondary is essential to assuring that the weapon will perform as specified.

Program Description

Understanding how to extrapolate theory, experiments at much smaller scales on above-ground facilities, and code predictions to the full secondary system will be the focus of much of the research in this area. Secondary design efforts will rely very heavily on ASCI code predictions, with validation effort being accomplished through nearly all of the program's experimental facilities as well as archived nuclear test data.

Baselining and Data Archiving for secondary systems will be conducted in concert with the primary systems baselining and data archiving effort. Establishing performance margins for the weapons in the stockpile is an essential part of this effort.

Examples of specific R&D activities supporting the secondary yield strategic objective are not discussed here. Further details are contained in the classified "Green Book," the *FY2000 Stockpile Stewardship Plan.*

Systems Integration

Budget: FY98-$283M, FY99-$306M, FY00-$332M

Background

System integration is the disciplined approach that assures that each subsystem will perform normally in the presence of each of the other subsystems and that the entire system performs as required when mated to the delivery system and subjected to normal and abnormal environments as specified in the stockpile-to-target sequence. System integration is essential to ensuring that the physics and engineering packages can be assembled together and function with DoD supplied systems and components as a weapons system.

Program Description

Flight Testing provides the most comprehensive manner of testing the integrated weapon system. In high-fidelity flight tests, special nuclear materials are replaced by inert components of the same dimensions and mass distribution. These flight test mockups are called joint test assemblies (JTAs). For example, flight tests of the Peacekeeper missile are launched from Vandenburg Air Force Base to Kwajalein Atoll in the South Pacific. Similar tests are performed on bomb systems at the Tonopah Test Range. Such tests allow as complete an evaluation of the non-nuclear system performance in the stockpile-to-target sequence as is possible. With a reduced stockpile fewer JTAs are possible; thus there is the need to further increase the fidelity of these flight tests. Technology development is underway to miniaturize and embed sensors that reduce inherent differences between JTAs and the war reserve weapon systems. These needs motivate research and technology development in sensor technology based upon MEMS (micro electromechanical systems).

Radiation Hardness. In the past, nuclear systems were qualified for radiation hardness by using underground tests. Aboveground facilities, including electro-magnetic pulse sources, pulsed power x-ray sources, and nuclear reactors have been used to simulate various portions of the threat spectrum. Because of the end of underground testing, computational simulation will play an increasing role in this area. The continuing requirement to certify the performance of individual components and the entire system to hostile radiation (x-ray and neutron) environments in the absence of underground testing motivates research that supports the development of simulation capabilities that can confidently predict electronic upset and thermal-mechanical shock and thermal-structural response.

Work also aims at improving experimental facilities for radiation testing, both in pulsed power and laser systems. Mechanical effects from x-rays study the thermomechanical response to high energy radiation transport and deposition. One project compares old underground test data with computer predictions for reduced-scale mock-ups of reentry-body segments. Other specific projects test response of subsystems used, for example, in the primary initiation described previously. Specific tests in conjunction with improvements to computational simulation of radiation effects will continue to be important for systems integration analysis.

Environmental Testing. Various facilities are used to simulate shock, vibration, acceleration, and thermal environments that a nuclear weapon will endure in normal or abnormal environments. With the increasing emphasis on the use of simulation to underpin the certification of the integrated nuclear weapon system, traditional environmental testing must support a dual role of confirmatory tests in the certification process and validation experiments in the process of model validation. This expanded role places greater demands on diagnostic technology and leads to research in the area of improved diagnostics for exploring high shock, fire environments, large mechanical deformation and failure, and material response to radiation environments.

Other Research Activities. System integration strongly motivates engineering research, particularly the development of validated simulation capabilities.

Thermal/Fluids engineering concentrates on energy and mass transport and the induced physical and chemical changes in systems. With fluid mechanics, the research focuses on mass and energy transport in liquids and gases. Thermal sciences concentrates on energy transport in liquids, gases, solids, and their interfaces. Aerosciences applies thermal sciences, fluid mechanics, and reactive processes and a fuller understanding of vehicles and objects subjected to aerothermal environments. Reactive process research is concerned with the chemical and physical changes that result from energy and mass transfer.

Solid mechanics and structural dynamics research is focused on the behavior of structures in regimes of large deformation and failure or in the case of structural dynamics in large jointed structures such as a reentry body. These disciplines are underpinned by material mechanics research which seeks to develop engineering descriptions of material response primarily in regimes of nonlinear response.

Because electrical systems are critical to use control, weapon arming, radars, contact fuzing, etc., electrical engineering research is concentrated on electrical systems, circuits, and the physics of microelectronics behavior. Electromagnetics concentrates on the physics of high voltage and high currents. Increasingly, the emphasis is the effect of aging at the device and circuit level on system performance.

As the scope and complexity of the engineering simulations that support system integration grows, it becomes necessary to develop more formal methodologies for treating uncertainties in simulation. Defense Programs research in this area is providing national leadership in developing methods for uncertainty quantification. These methods will deliver capability to enable quantitative characterization of the accuracy of calculations of nuclear weapon systems. In related disciplines, optimization methods are being developed that provide the capabilities to optimize engineering designs though computational studies, determine the optimum paths for the manufacturing of systems and components, determine sensitivities to a multivariate parameter set, and generate solutions for other problem sets requiring optimization techniques.

Safety, Security, and Use Control

Budget: FY98-$153M, FY99-$154M, FY00-$165M

Background

Although much of the issue of nuclear weapons safety and security is integral to other nuclear weapons design and assessment activities, the primacy of nuclear weapons safety in meeting national security goals requires that it be highlighted as a separate functional area. There are, however, separate groups responsible for independent safety assessment, and even if relatively small in terms of overall effort, these efforts are essential to our confidence in the safety of a nuclear weapons system. This document can say little about use control activities.

Maintaining safety and security of any nuclear weapon and preventing its unauthorized use has from the earliest days of the nuclear weapons program been paramount because of the potential consequences. National policy permits no relaxation of the highest possible standards in this area.

Program Description

Nuclear weapons safety research is focused on ensuring nuclear, conventional, and radiological safety of the weapons. This is a combination of nuclear science, chemistry, materials science, and systems analysis. For nuclear safety, the issue lies not in accurate prediction of the yield of a regular and well-characterized implosion, where the emphasis is on exotic material properties and conditions, but rather on setting an upper bound on criticality levels in irregular geometries that result from fire and mechanical insults. Safety codes will emphasize accurate modeling of materials strength properties. Issues are not only to prevent criticality, but also to maintain pit integrity in fires or crushing accidents. Safety studies also assess the likelihood that accident scenarios or unauthorized actions might result in the generation of detonation signals at the primary.

Necessary refurbishment in the stockpile expected over the next decade provides the opportunities for upgrading safety critical components within the nuclear weapon system. Two critical technologies that have the potential of inherently safer and higher performance are micro electrical mechanical structures (MEMS) and direct optical initiation. A range of research activities support the migration of these technologies into practical design options for the future. These and other miniaturization technologies make it possible to embed safety and security features more deeply within the weapon system than possible with existing macroscopic surety systems.

The research effort in MEMS structures is focusing on improved fabrication technologies, and developing functional device and component prototypes. The attractiveness of MEMS technology stems from inherent characteristics of the candidate material polycrystalline silicon. Its mechanical properties are excellent: it is stronger than steel (polysilicon has a strength of 2-3 GPa, depending on surface flaws; while steel has a strength of 200MPa - 1GPa, depending on the process parameters), is extremely flexible (the maximum strain before fracture is ~0.5%); and does not readily fatigue. Most importantly, polysilicon is directly compatible with modern

integrated circuit fabrication processes. Batch fabrication in integrated circuit foundries makes it possible to produce MEMS in large volumes at extremely low cost.

Research is focused on increasing the complexity of the devices that may be created using polysilicon surface micromachining. The complexity is governed by the number of mechanical layers available in the given fabrication process. For example, with a ground plane and one mechanical level, an actuating comb drive may be created. With two mechanical levels, one can create mechanisms such as a gear constrained to rotate on a hub, and various types of mirrors. By adding a third mechanical level, this not only enables the creation of linkages to connect actuators to mechanisms, but opens up an entirely new range of design possibilities.

The challenges associated with adding extra layers of polysilicon to a surface micromachining fabrication process are primarily related to residual film stress and device topography. Recent research advances are developing technologies focused on reducing polysilicon stress.

Other research is aimed at improving the flexibility and applicability of the devices that can be developed with MEMS technology. The creation of microsystems (e.g., that sense, think, act, or communicate) often requires electronic circuitry coupled with mechanical elements. The monolithic integration of electronic circuitry (such as CMOS) on the same chip as electro-mechanical devices has many advantages over approaches that involve complex multi-chip packaging schemes. Batch fabrication of "systems on a chip" enables very low cost production. By reducing the number of components in the system, significantly improved system reliability may be achieved. For example, reducing the chip count, eliminating the bond wires connecting electrical to mechanical circuits, and reducing the complexity of the packaging/assembly process all benefit reliability. Finally, monolithic integration enables overall system performance, particularly for micro-sensing systems, to be increased by many orders of magnitude by reducing electrical interconnect parasitics, such as capacitance.

The obvious and overwhelming benefits of a monolithic integrated CMOS/MEMS technology have motivated numerous fabrication approaches to be pursued by MEMS researchers. The DOE program is focusing on “Integrated Trench Technology” to realize the potential of integrated systems. Integrated Trench Technology forms the mechanical devices in a trench prior to the fabrication of the associated CMOS circuitry. A 12 micron deep trench is first etched into the silicon substrate. Using special photolithography methods, surface micromachined polysilicon devices are formed in the trench. The trench is then filled with silicon dioxide, and then planarized to a level even with the surface of the wafer using a process called Chemical-Mechanical Polishing. At this point, a perfectly planar wafer is ready to start CMOS processing, with the mechanical devices having already been created and annealed. At the end of the CMOS processing, electrical interconnections are made to the mechanical devices. Finally, the silicon dioxide encapsulating the mechanical devices in the trench is etched away, resulting in mechanical devices electrically interconnected to adjacent circuitry on the same chip.

Research supporting direct optical initiation technology focuses on the development of physics-based models in lasers, optical parametric oscillators, and nonlinear optics and processes.

In addition optical components, such as microoptics and photosensitive materials, are under development. For all these technologies there is a concomitant requirement to understand radiation effects so companion research in this area is being conducted. Specific activities include developing an ultra-compact optical source for direct optical initiation. Development of an optically-triggered sprytron which combines plasma and laser expertise to reliably trigger the sprytron using a laser signal, then using those requirements to develop a miniature laser and optical delivery system.

Crosscutting Research

Budget: FY98-$413M, FY99-$521M, FY00-$605M

Background

A number of programmatic efforts and research facilities support multiple strategic objectives and therefore are best discussed separately as crosscutting research. These efforts in inertial confinement fusion, computational science, materials science and chemistry, surveillance, manufacturing, and neutron science support weapon analysis and certification through both specific experiments and testing and validation of codes. Much of this research is quite basic in nature but all of it is pursued with the purpose of improving the capability to maintain the nuclear deterrent.

Program Description

Inertial Confinement Fusion (ICF). The mission of the ICF program is: (1) to address high energy density physics issues for the science-based stockpile stewardship program and (2) to develop a laboratory microfusion capability for defense and energy applications. DOE has, for the past two decades, viewed ICF as a principal means by which to preserve nuclear weapons design competencies under a test moratorium or test ban treaty. Although ICF experiments do not directly replicate nuclear weapons configurations, these experiments share similar design methodologies and underlying physics. Furthermore, laser and pulsed power facilities operated primarily by the ICF program are the only way, in the absence of underground testing, to reach physical conditions similar to those that pertain to some portions of a nuclear weapon. ICF is a crosscutting area of research, however, because the facilities are relevant to studying issues related to primaries and secondaries with a particular role in testing and validating computer codes. ICF facilities will also continue to be used as sources to study the effect of hostile environments on nuclear weapons systems.

Experiments on ICF facilities provide integrated tests of computer simulations in conditions relevant to weapons performance. Simulation tools developed for ICF use include many of the same physical models (e.g., hydrodynamics, radiation transport, atomic physics, material behavior, etc.) required to simulate and predict weapon performance. In this context, ICF experiments provide an opportunity for model validation which, in turn, increases the confidence

in predicting weapon performance. General capabilities and technologies developed by the ICF Program have applications to a broad range of stewardship activities.

The ICF Program has a long history of publication in the scientific literature, with hundreds of refereed journal articles being written each year. ICF Program scientists have received numerous awards for both physics research and advanced technology development. Technological spin-offs from the ICF Program have had impacts well outside of stewardship; examples include the development of novel biological imaging techniques and micro-impulse radar.

The research and development activities associated with ICF are discussed below under high energy density physics, fusion ignition, and facilities.

High Energy Density Physics. The study of material brought to extreme conditions in temperature and density is referred to as high energy density physics. Development of an understanding of materials under these conditions requires information about the intrinsic state of the material itself (atomic physics, opacity, material properties, and equation of state) as well as an understanding of the evolution of the material under external forces (hydrodynamics and radiation transport). In general, high energy density physics problems are particularly complex because system evolution is often to a turbulent, non-linear state in which all memory of initial conditions and driving forces is lost. Activities in specific areas of high energy density physics are discussed below.

Hydrodynamics. The physics of hydrodynamic flows and instabilities is important to understanding the operation of inertial fusion targets and nuclear weapons. Hydrodynamic instabilities are coupled and it is necessary to calculate them well into the non-linear regime. Indeed, nonlinear hydrodynamics is a “grand challenge” scientific problem important in a number of other fields including astrophysics, fluid flow, and aircraft design. Subtleties peculiar to defense interests, such as strongly-coupled plasma conditions, high-Z materials, and thermo-nuclear burn make the problem more difficult. Fundamental nonlinear hydrodynamic phenomena of interest include Rayleigh-Taylor and Richtmyer-Meshkov instabilities, high-mach-number flows, high vorticity flows, and compressible turbulent flows in solid, gaseous, and plasma states. A fundamental understanding of these topics and the ability to test that understanding in relevant regimes are important in carrying out the stewardship program.

The experimental capabilities developed by DOE/Defense Programs over the past two decades make it possible to conduct experiments that address these hydrodynamics issues in above ground experiments in scaled experiments at temperatures and pressures of interest. The suite of facilities used in this work include facilities in the Inertial Confinement Fusion Program (NIF,

Nova, Omega, Z, Nike, Trident) as well as gas guns, shock tubes, and microsecond pulsed power facilities (Pegasus, Atlas).

Hydrodynamic experiments are being designed and analyzed with large-scale hydrodynamics codes that provide the integration of physical processes to model many of the compound phenomena in the experiments in much the same manner that compound phenomena are modeled in weapons. The three-dimensional codes developed under the ASCI Program are crucial to this

effort; indeed, benchmarking of the hydrodynamics packages via experiment is essential to development of a predictive capability for weapons.

There is already a strong history of success within Defense Programs of laboratory measurements of hydrodynamic behavior. Rayleigh-Taylor and Richtmyer-Meshkov instability growth rates have been measured successfully in a variety of configurations using high power laser facilities (primarily Nova). This work has been recognized in the larger scientific community via numerous awards and publications. In addition, studies of complex features have been carried out on microsecond pulsed-power facilities. In doing these experiments Defense Programs has built up diagnostic capabilities which are used broadly throughout the program and will be immediately applied as new facilities are brought on line.

An interesting spin-off of the laser-based work is the use of large lasers for "laboratory astrophysics." In particular, a group of national laboratory and university researchers have actively collaborated during the past few years on studies of fundamental nonlinear hydrodynamics common to both supernovae and nuclear weapons. This high visibility work has invigorated the stewardship program scientifically and has also resulted in productive scientific interaction between the defense laboratories and scientists external to Defense Programs.

The restricted energy and pulse duration capabilities of current facilities have limited the capability to study hydrodynamics in the weapons-relevant regime. New facilities under construction as part of the stewardship program such as the National Ignition Facility (NIF) and Atlas will enhance the program's ability to study hydrodynamics in several major ways:

- Larger samples may be used in experiments. For a given diagnostic resolution this will allow more detail to be observed and thus allow more accurate comparison of data and simulation. This is especially important in the non-linear regime where precise comparison between subtle features of data and calculation is necessary to ensure proper code validation. As an example, the capability of NIF to irradiate larger samples will allow the capability to study three-dimensional flow effects.

- Samples may be accelerated for longer times, which will allow studies to proceed farther into the regime of non-linear, turbulent behavior. This is critical for validating ASCI codes. Present day above ground experiments cannot begin to adequately explore the turbulent hydrodynamics regime characteristic of weapons.

- Stronger shocks may be generated over larger samples. This will provide access to a greater regime of parameter space relevant to weapons than can be done with current facilities. As an example, it will be possible with NIF to study systems driven with multiple shocks.

Equation-of-State and Material Properties. The equation-of-state of a material is a description of the relationship between its density, temperature, and pressure. Knowledge of equations of state is critical in determining how materials react to a wide range of physical environments. The accurate hydrodynamic description of an event or system—such a description addresses heating, phase changes, ionization, compression, and expansion—depends on accurate equation-of-state data for the materials involved. Thus, improved equation-of-state information is essential to producing a reliable predictive capability for inertial fusion ignition and weapon performance.

An equation-of-state describes a three-dimensional variable space, relating pressure, density, and temperature or energy and will involve additional properties such as ionization and thermodynamic derivatives (e.g., sound speed and compressibility). The extent of this space for application to weapons physics is vast, covering up to five or more orders of magnitude in the variables. Such a space, when used in weapons simulations, must be represented by computational models. These models must be constrained by existing data, which are very scarce. A small number of materials appear to be well calibrated up to 20- to 40-million atmospheres (Mbar) of pressure. Data at higher pressures is needed because inertial fusion ignition can produce pressures up to one billion atmospheres. However, these are all comparative data calibrations of one material against another; absolute data in the multi-Mbar regime are needed and almost nonexistent. The regime above 1 Mbar must be investigated dynamically by strong shocks which are difficult to characterize, control, and measure. A large parameter of the space is cross-cutting to weapon interests.

For equation-of-state measurements there is a distinction between data “on the Hugoniot,” which results when material at standard temperature and pressure is shocked once, and data “off the Hugoniot,” which refers to shocked material whose initial state results from a previous shock or preheating - a common occurrence. Both “on the Hugoniot” and multiple shock experiments must be modeled and understood.

Defense Programs has long carried out a program of equation-of-state measurements using a suite of facilities, including gas guns, diamond anvil cells, lasers, and pulsed power devices. This work has been visible in the external scientific community. A recent example was the measurement of the equation-of-state of deuterium near 1 Mbar using the Nova laser. This work received a major award from the American Physical Society (The Excellence in Plasma Physics Award) in 1998. This work and the diagnostic techniques developed through it has implications for both primary and secondary weapons research as well as astrophysics.

The next generation of stewardship facilities relevant to this problem (NIF, Atlas, and advanced gas guns) will enhance capabilities significantly and in particular allow improved access to higher pressure and off-Hugoniot regimes. For example, with its higher energy, NIF should be able to perform equation-of-state measurements at pressures up to 10 Gbar. At lower pressures NIF will be able to carry out experiments with larger samples than previously available. The use of larger samples will help reduce experimental error and thus lead to improved equation-of-state measurements. With its increased energy and corresponding larger samples, the Atlas facility should provide an improved capability for on and off-Hugoniot equation-of-state measurements.

Radiation Transport and Radiation Hydrodynamics. The transfer of heat and radiation is critical to understanding inertial fusion target performance. Radiation transport occurs through streaming, scattering, absorption, and reemission of photons and is dependent on materials on physical geometries. Advanced simulation codes must be able to handle radiation transport under conditions in which the radiation travels either a long or short distance between interactions with the surrounding medium. These two extremes, streaming and diffusion, require different software treatments. This is a difficult computational challenge.

Radiation transport experiments are carried out primarily on Inertial Confinement Fusion Program facilities such as Nova, Omega, Z, and NIF. Facilities with high energy and/or high radiation temperature capability are required for such experiments. A parallel program to develop new radiation transport computational capabilities is underway in the ASCI Program as part of their effort to develop the next generation tools for simulation of inertial fusion targets.

Radiation transport experiments can be one-, two-, and three-dimensional. In one-dimensional experiments radiation interacts with planar foil or other similar target. These experiments address basic physics of the interaction of radiation with a given inertial fusion target material, including issues such as how the material absorbs radiation (known as opacity and discussed in the next section) and ablation. Two and three dimensional experiments focus on issues specific to producing a symmetric radiation drive on an inertial fusion capsule. Such three-dimensional radiation flow experiments often serve as excellent “integrated” testbeds for simulation codes.

Experiments in all three areas described above have already been carried out, especially using Z and Nova. Looking ahead, the higher temperatures and longer pulse duration available on NIF will be valuable in expanding our capabilities to study radiation transport. Some of these types of experiments have been reported in the scientific literature.

Opacity and Nonequilibrium Physics. As described above, the atomic physics describing the interactions of radiation and matter is fundamental to radiation transport. This is referred to as opacity. The opacity of a given material depends sensitively on the degree of ionization of the material, which is a function of the plasma temperature and density as well as the surrounding radiation field. A thorough understanding of the electronic structure of the material (energy levels, spectral lineshapes, etc.) is also required. The plasma environment may also affect the electronic properties of a given material. The development of an opacity model involves atomic physics, spectroscopy, the physics of dense plasmas, and related areas such as molecular dynamics simulation. Opacity is most easily calculated under a condition known as “local thermodynamic equilibrium.” For many applications it is necessary to consider both the “equilibrium” and “non-equilibrium” case.

Because of the enormous amount of atomic data required and the intractable nature of many-body problems, current opacity models rely on simplified assumptions and use approximations. The plasma opacity models used in weapons design remain, in crucial respects, incomplete and untested. Their accuracy is often addressed by comparing code results with other code results. Increased confidence in calculated opacities is essential to the full simulation of weapons.

Plasma opacities are also crucial to accurately predicting the energy balance of ignition targets, in which they determine energy propagation and losses in high-Z hohlraum walls. Until recently, large ad hoc opacity correction factors were included in hohlraum simulations to make them consistent with measured x-ray conversion efficiencies. New measurements and computational techniques have removed many of these uncertainties, but large uncertainties in opacities for weapons-relevant materials remain.

Calculations of radiation transport and energy balance in macroscopic environments require the use of opacity data over several orders of magnitude of material temperature and density. If the problem involves transport of spectral lines or other features, or if interactions involve matter that is not in local thermodynamic equilibrium, the opacity information at each temperature and density must also carry a detailed spectrum. That is, the opacity is a function of wavelength where the range of wavelengths can be large. Thus, many radiation flow calculations must access an enormous amount of opacity information.

Over the last ten years a sophisticated capability to execute opacity experiments has been developed using lasers (Nova, Omega) and nanosecond pulsed power facilities (Z). These experiments are among the most sophisticated in the world in the area of plasma opacity. The ability to diagnose plasma temperature and density independently has been important in this effort and many broadly applicable innovative diagnostic techniques such as x-ray laser interferometry have been developed in the course of this research. Much of this work has been published in the scientific literature and it has had a significant impact in the astrophysical community as well as the nuclear weapons program. Opacity has long been of interest in the astrophysical community, as it is a major factor in understanding energy transport in stars. As an example, a recent series of experiments carried out first on Nova and later Z elucidated the opacity of iron under astrophysical conditions, and thereby helped resolve some long-standing anomalies.

The opacity experimental data base will be significantly expanded in future Omega, Z, and NIF experiments. The greatest utility of NIF in this area will be its enhanced energy over Nova and Omega, which will allow access to higher temperatures.

A particular area where improvements will be pursued is in the area of non-equilibrium opacities. In the equilibrium case the spectral shape of the opacity is a function simply of plasma conditions. In the non-equilibrium case collision and radiative processes affecting each of the potentially millions of excited states present must be tracked in order to calculate excited state populations and produce a correct frequency dependent opacity. Detailed calculations of millions of excited states within hydrodynamics simulation codes is not practical. A major goal is to derive simplified opacity models appropriate for use in the nonequilibrium regime.

Fusion Ignition Experiments. Demonstration of ignition in the laboratory has long been identified as a grand challenge science problem and is a major goal of the National Ignition Facility (NIF). A National Ignition Plan has been formulated which lays out the program of work for indirect and direct drive ignition on NIF:

- Indirect drive—Hohlraum energetics and laser plasma interactions.
- Indirect drive—Hohlraum drive symmetry.
- Indirect drive—Capsule physics and ignition capsule optimization.
- Indirect drive—Ignition implosions.
- Direct drive—Symmetry, drive uniformity, capsule physics.

The plan specifies that actual ignition experiments will begin on NIF in FY2006.

The demonstration of ignition is an important milestone for the stewardship program for several reasons. First, ignition provides a means to study the physics of burning plasmas. Ignition capsules will be used in experiments aimed at understanding burn in primaries and secondaries. Certain experiments in the areas of hydrodynamic mix, radiochemistry, and weapons effects will also require ignition. Secondly, ignition is a stringent integrated test of computational modeling capability and thus provides an important test of next generation weapon simulation codes. In the larger view, the demonstration of ignition is a major evolution in Defense Programs capability which will most likely open up entirely new areas of research.

Facilities. Laser and pulsed power devices are the two types of facilities within the ICF program. These provide complementary capabilities to perform experiments appropriate to both primary and secondary physics at energy densities that are not accessible through other kinds of laboratory experiments. The laser and pulsed power facilities within the ICF Program constitute the most advanced set of high energy density physics research facilities in the world.

Laser facilities within the ICF Program are:

- National Ignition Facility—The NIF project is underway to construct a 192 beam laser facility that will deliver 1.8 megajoules of blue laser energy to a target. At this time the baseline cost and schedule for the NIF are being revised. The qualitative expectation of first experimental results from the NIF in the 2004 time frame remains part of the program plan. Once completed NIF will be the principal facility for high energy density weapons physics research.

- NOVA Laser at Lawrence Livermore National Laboratory—This 10 beam, 30 kilojoules laser facility is scheduled for shutdown in FY1999 in order to support NIF construction.

- Omega Laser Facility at the University of Rochester—This 60 beam 30 kilojoules laser facility will be the principal focus of ICF experiments until start-up of experiments on NIF and will continue to develop techniques for application at NIF.

- Nike Laser at the Naval Research Laboratory—This facility provides up to 4 kilojoules of laser energy with exceptionally smooth beam uniformity. Nike is used to test the physics

concepts underlying direct drive ignition and to carry out other high energy density physics experiments requiring high beam uniformity.

Pulsed power programs are listed below:

- Atlas/Pegasus—Atlas, under construction at Los Alamos National Laboratory, will extend experiments performed using the existing Pegasus device at Los Alamos National Laboratory to regimes of higher energy density and partial material ionization. Although listed here for the sake of organization, Atlas is funded out of the broader Stockpile Stewardship budget and not out of the ICF program line.

- Z—A large Z-pinch device located at Sandia National Laboratories which has recently demonstrated record x-ray output powers (>200 Terawatts) and energy (almost 2 Megajoules). Z is used for weapons physics experiments and to assess the feasibility of z-pinch driven indirect drive for producing high yield.

Diagnostics. Diagnostic techniques for ICF experiments use x-ray or neutron measurement techniques that are often derived from underground test diagnostics, and therefore ICF experiments will maintain diagnostic capabilities that are essential to test readiness. A set of diagnostics has already been developed for weapons physics and ICF experiments on current laser and pulsed power facilities. Goals for diagnostic development include: x-ray framing cameras with enhanced time resolution; better reflective optics and multilayer coatings for x-ray imaging; and more sensitive x-ray detectors with better spatial resolution. The high levels of x-ray fluence anticipated from future targets will force sophisticated shielding techniques. New diagnostics for ignition experiments on NIF will have to be developed and prototypes will be tested on existing facilities (Nova, Z, Trident). Neutron fluxes will be orders of magnitude higher for ignition experiments than for sub ignition experiments. Development will be undertaken to extend the dynamic range of current techniques and to develop new techniques to accommodate the higher fluxes. Some of these new techniques may be adaptations of nuclear test diagnostics to the smaller size, lower fluxes, and shorter time scales of NIF. An appropriate suite of calibration facilities required to support these diagnostics will be identified and developed as needed.

Target Fabrication. The ICF program has a significant development program in place to manufacture cryogenic fuel capsules with the required smoothness on a schedule consistent with NIF. Numerous non-cryogenic targets will also be developed in support of the experimental program. Research into target development techniques involves work in a broad variety of fields related to chemistry and materials and is an essential component of the high energy density physics experimental program.

A more complete discussion of the integrated experimental and theoretical/computational program in crosscutting physics is available in the classified version of the “Green Book”, The FY-2000 Stockpile Stewardship Plan.

Computational Physics / Advanced Strategic Computing Initiative (ASCI). In the absence of underground testing, quantifying the effects of aging and changes introduced to nuclear weapons through remanufacture (the assessment and certification process) will require integrated high-fidelity simulation based on algorithms and models that accurately reflect the underlying physical processes in relevant physical regimes. The increased complexity involved in "full-physics" three dimensional simulations is evidenced by comparing the greater than 100 Teraflop speed of the top-end ASCI machines to the 100 Megaflops of recent vintage high performance computers. The development of the codes and platforms for these high-fidelity simulations will be the principal product of the ASCI program. ASCI's goal is to deliver the required hardware and software in FY2004, the time beyond which designer test experience will fall rapidly.

There are three principal thrusts in this development:

- **Platforms**—the development of massively parallel processing computers to reach the 100's of Teraflops needed for high fidelity three-dimensional simulation of nuclear weapons systems.

- **Applications Codes**—the development of physical models, algorithms, and integrated code packages that will run on massively parallel machines to enable the simulation of a three-dimensional simulation of a full weapons system.

- **Programming Support Environment**—the development of program tools and libraries to enable the development of advanced application codes and enable their use by designers. An important component of this is the development of visualization and analysis tools to enable designers to see and understand the very large data sets that will be generated by ASCI codes.

Simulation tools for nuclear weapons stockpile assessment must integrate scientific knowledge that is derived through ongoing experimental and theoretical programs to make predictions about complex configurations that cannot be directly assessed through analytic models. In the absence of further nuclear tests, some of these predictions are not susceptible to full scale experimental validation. Therefore, a program of research to maintain knowledge in core science and engineering disciplines is required. Confidence in the predictions of these codes will be established by comparison to archived test data and to their ability to predict the results of above ground experiments in relevant physical regimes and geometries in an ongoing iterative scientific process.

The ASCI Alliances program is a collaboration between laboratories and universities centers to bring university expertise to bear on the solution of ASCI problems. These centers will work on unclassified ASCI-scale simulation problems, the solutions to which will require the development of models, algorithms, numerical methods, and data visualization and analysis techniques applicable to problems central to the Stockpile Stewardship mission. Currently five such centers are funded at California Institute of Technology, Stanford, University of Utah, University of

Illinois and University of Chicago. In addition, a number of smaller, discipline-focused activities at other universities are funded with more narrowly defined and nearer term deliverables.

It has become increasingly apparent that handling, analyzing, and visualizing the terabyte data sets that will be produced by ASCI codes poses a formidable challenge and has led to the development of Data and Visualization Corridors as part of the "See and Understand" effort. Because this is now a niche requirement it is not expected that commercial vendors will focus on solutions of the problems of end-to-end storage, management, access, and visualization of these large data sets and therefore an industry-laboratory-university partnership is needed under Defense Programs Sponsorship to make progress in this key area. Technology roadmaps have been developed for networking, data manipulation, graphics, and display technologies.

Enhanced Surveillance. Enhanced surveillance represents a portfolio of smaller R&D projects to understand the aging of specific materials used in nuclear weapons including any special nuclear materials, insensitive high explosives, ceramics, and polymers. The affect of aging on integrated circuit reliability is also being investigated. This portfolio also includes the development of diagnostic instrumentation such as optical techniques for chemical measurements, static radiographic techniques using neutrons or X-rays, the development of superconducting quantum interference devices (SQUIDs) for non-invasive mechanical measurements, and gas analyzers.

Advanced Design and Production Technologies (ADAPT). This is an effort to apply modern manufacturing technologies to the nuclear weapons production complex. Various components of this effort support every aspect of nuclear weapons production, from efforts to develop near-net casting models, useful for pit casting, to virtual prototyping – the ability to develop a mechanical model of the entire weapons system to make it easier to explore how to optimize component design and location. Automation is known to improve quality and productivity in civil industry and so is desirable for adaptation to DOE's production complex. R&D is needed to adapt it to DOE's small lot production. The needs of Defense Programs is one of the major drivers noted in the Department's crosscutting Roadmap and Program Plan for Robotics and Intelligent Machines.

Los Alamos Neutron Science Center (LANSCE). LANSCE is a proton linear accelerator with a storage ring and neutron spallation source that provide the capability for proton and neutron radiography and for a wide variety of experiments in nuclear physics and materials science. Defense Programs shares funding of the LANSCE facility operations with the DOE Office of Science. Proton and neutron scattering experiments relevant to weapons physics provide fundamental measurements of materials properties of actinides and measurements of nuclear cross-sections. In particular, more accurate nuclear cross-sections are needed to better understand radiochemical data from past nuclear tests.

Proton radiography has illuminated the behavior of high explosives and may have application to primary hydro-testing. The use of high energy protons (>10 GeV) for radiography is a new application based on using magnets to refocus protons scattered deep inside a sample material, just as a camera focuses light scattered off of an opaque surface. Protons have the distinct advantage of very high penetrating power and low induced image background, advantages that

may more than compensate for the lower inherent material contrast. The primary proton beam from the linear accelerator has been used to produce multiple time-sequenced radiographic images in detonated samples of high explosives. These experiments were used to calibrate reactive burn models of high explosives and were critical for the certification of the B61 Mod 11 primary at cold temperatures.

Neutron radiography can be used to examine weapon components statically and is a potential resource for information on dynamic materials behavior in weapon components. Neutron resonance spectroscopy provide dynamic temperature measurements of burning high explosives. Low energy neutrons have wavelengths comparable to atomic dimensions. Therefore, neutron scattering experiments provides information about the structure of materials at atomic scales. Neutron scattering also has a direct application to plutonium equation-of-state studies.

Other applications of low energy neutron scattering techniques being pursued at LANSCE include:

- Plutonium crystallography to study the response of the phase composition of stockpile plutonium to thermal cycling.

- Measurements of the distribution of crystal grain orientations in a material to guide more accurate modeling of strength.

- Plutonium phonon spectroscopy to put detailed electronic structure calculations of the interatomic potential on a sound footing for the development of equation-of-state models based on fundamental properties. These experiments will require further development of the Pharos spectrometer at LANSCE over the next two years and the growth of large crystals of plutonium.

- Three-dimensional mapping of internal strain fields in weapon components will benchmarks finite element structural models of welds and joints. This is important for remanufacturing process design and for prediction of distortion, cracking and lifetime of pits and gas reservoirs.

- High explosive microstructure characterization will determine total internal porosity inside the high explosive crystals, in the binder, and at the crystal binder interface. These characteristics, which affect sensitivity, safety, and performance, will be studied as a function of age and shock damage history.

- Studies of dynamic shockwave behavior are possible because large, instantaneous neutron fluxes are available at LANSCE. Dynamic experiments will take advantage of neutron resonance radiography to measure temperatures on time scales of several to tens of microseconds with epithermal (1 to 100 eV) neutrons.

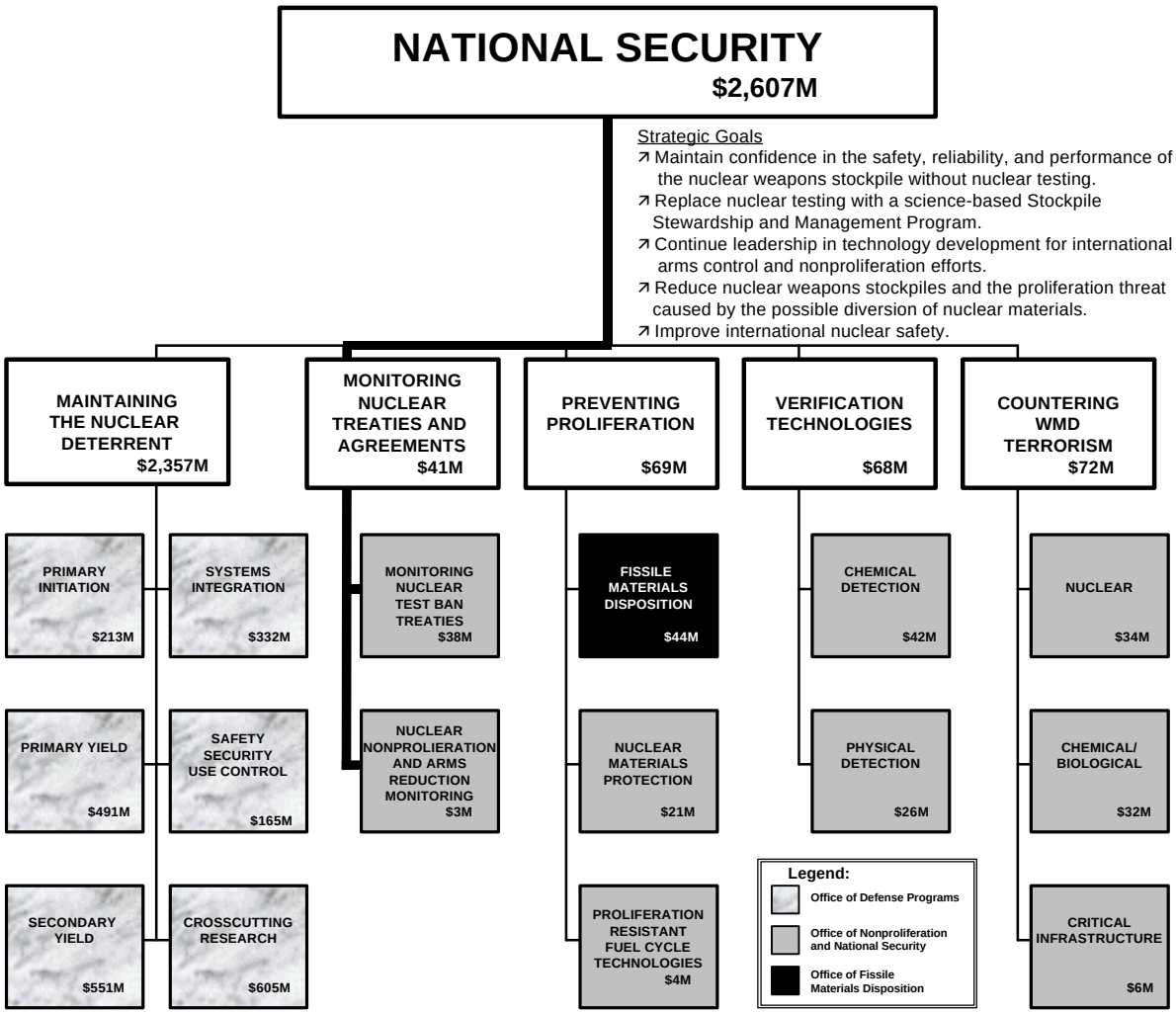
- Radiochemical measurements of Pu^{238} produced in nuclear tests are an important primary yield diagnostic. The cross-section values used to interpret these measurements have large uncertainties, however, and the new gamma-ray detector array at LANSCE will be used to measure the production rate of Pu^{238} when Pu^{239} is bombarded with neutrons in the range of 6 to 30 MeV. Better cross-section determinations will allow more accurate assessments of archived underground test data.

Several projects are underway or proposed to enhance the capabilities of LANSCE. The first project will increase the power level to 160 kW through the development of a brighter source and through improved radio frequency bunching. This project will be completed in FY 2000. The second project will double the number of neutron scattering instruments from 7 to 14. The instrument project will be completed in FY 2001. The LANSCE Dynamic Experiments Laboratory would establish a dedicated firing site for dynamic experiments taking full advantage of the LANSCE accelerator's peak, single pulse capability. Key applications will be to study weapons hydrodynamics phenomena and high explosive performance, and to develop dynamic proton radiography techniques as part of technology R&D for an Advanced Hydrographic Facility. A long pulse spallation neutron source is proposed to provide advanced capabilities for neutron scattering using cold neutrons, a field of research that underpins many of today's advanced technologies in areas such as polymers and ceramics.

Summary Budget Table (000$)

Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Primary Initiation	**218,000**	**212,000**	**213,000**
Primary Yield	**399,000**	**468,000**	**491,000**
Secondary Yield	**438,000**	**519,000**	**551,000**
Systems Integration	**283,000**	**306,000**	**332,000**
Safety / Security / Use Control	**153,000**	**154,000**	**165,000**
Crosscutting Research	**413,000**	**521,000**	**605,000**
Total	**1,904,000**	**2,180,000**	**2,357,000**

Chapter 4
Monitoring Nuclear Treaties and Agreements



Chapter 4

Monitoring Nuclear Treaties and Agreements

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Overview

Definition of Focus Area

The goal of this focus area is to develop technologies and systems, and the attendant scientific basis thereof, to (1) enable remote detection, location, identification, characterization, and attribution of nuclear-test-ban treaty violations with sufficient timeliness and confidence to permit effective national and international treaty verification; and (2) support close-range monitoring activities related to strategic arms reductions. The current focus is largely on development of a robust capability to monitor the Comprehensive Nuclear-Test-Ban Treaty (CTBT), when it enters into force. However, the CTBT is only the latest tool to address the underlying world conditions which make it imperative to monitor for nuclear proliferation and testing. U.S. monitoring requirements will remain in effect, whether or not official entry into force of CTBT ever occurs.

National Context and Drivers

For over 35 years, the Department of Energy (DOE) jointly with the Department of Defense (DoD) has provided sensor systems and technology to detect atmospheric and space nuclear detonations (NUDETs) from satellites. Beginning with the first Vela satellite launched in October 1963, these systems have comprised the national capability to monitor nuclear treaties including the Limited Test Ban Treaty and the Nuclear Nonproliferation Treaty. Twelve Vela satellites were launched between 1963 and 1970; the last of these was turned off in 1984 -- after 14 years of successful operation, despite being designed as an R&D system expected to function for only 18 months. Vela optical and electromagnetic pulse sensors detected many atmospheric NUDETs during their operational lifetimes.

In 1965 the Air Force, in planning for the Defense Support Program (DSP) missile early warning satellite system, decided that space and atmospheric NUDET detection (to support the warfighter as well as treaty monitoring) should be added as a secondary mission on these DoD satellites. An Air Force / Atomic Energy Commission Memorandum of Understanding was signed to document the agreement, naming the payload “RAdiation DEtection Capability” (RADEC). With the exception of one Air-Force-funded optical sensor, the DSP RADEC payloads are provided by DOE to the satellite contractor as government furnished equipment (GFE). The U.S. NUDET Detection System (USNDS) sensors flown on DSP have accumulated an enviable record of success. Since the early 1970s, the Air Force has launched eighteen DSP satellites, most of them carrying RADEC payloads; all of the RADEC payloads have exceeded their five-year on-orbit design life. Five more systems are ready for launch; it is expected that an operational DSP constellation will be maintained until about 2010. In addition to addressing the warfighting and treaty monitoring operational missions, DSP RADEC data from the on-board environmental sensors is routinely provided to the Air Force 55th Space Weather Squadron for use in modeling space weather, and, on request, to other military and commercial satellite operators for anomaly resolution and assessment of environmental threats to their operations.

Since the DSP system consists of a small number of satellites deployed in geosynchronous equatorial orbits, it cannot provide coverage of Earth's polar regions nor does it "see" a given location with more than one satellite for some locations of interest. The resulting lack of complete coverage and limited event location-determining capability led the DOE and the Air Force in 1975 to place additional USNDS sensors on the Global Positioning System (GPS). GPS provides multiple satellite coverage world-wide, permitting accurate location determination for all nuclear events from the surface of the Earth into space. Similar to DSP, GPS-based sensors address both warfighting and treaty monitoring missions, and are supplied as GFE by DOE to the Air Force satellite system contractors with one exception, the Air Force-funded electromagnetic pulse sensor.

To date, USNDS sensors have flown on 33 GPS satellites. The last of the 28 Block IIA satellites was launched in November 1997 to maintain a fully operational 24 satellite constellation. One Block IIR replenishment satellite has been on orbit since July 1997. The last of 21 Block IIR USNDS systems will be delivered in 1999. Then deliveries of the next generation, GPS Block IIF USNDS sensors, will commence. Even though the GPS orbit's harsh radiation environment makes the payloads more susceptible to radiation damage, all of the payloads launched to date have operated well past their design life and have been turned off only when the satellites themselves were no longer operational.

In the arms reduction area, current program emphasis is on preparing for START III negotiations. The U.S. negotiators will need options regarding technology choices and levels of intrusiveness. Additional, overlapping program drivers are the Mayak Transparency Mandate from the Biden Amendment and the Trilateral Initiative.

Linkage to Requirements

Goals for U.S. nuclear detonation monitoring capabilities are specified in Presidential Decision Directives. U.S. national monitoring requirements are more stringent than those of the international CTBT community. Specific requirements for the satellite systems are detailed in an Air Force Operational Requirements Document, which specifies performance parameters for warfighting as well as treaty monitoring missions.

As further support for the nuclear test monitoring goals and objectives, the President, in his August 11, 1995 statement on the CTBT, recognized that our present monitoring systems will not detect with high confidence very low yield tests. Therefore, he put forward the conditions that would safeguard a successful treaty that included "Continuation of a comprehensive research and development program to improve our treaty monitoring capabilities and operations."

The research and development performed for monitoring nuclear treaties and agreements is being performed in response to the National Security Strategic Goal, Objective 5, Strategy 3, of the U.S. Department of Energy Strategic Plan. Objective 5 is to continue leadership in policy support and technology development for international arms control and nonproliferation efforts.

Strategy 3 specifically requires developing improved sensor systems for treaty monitoring and verification.

Uncertainties

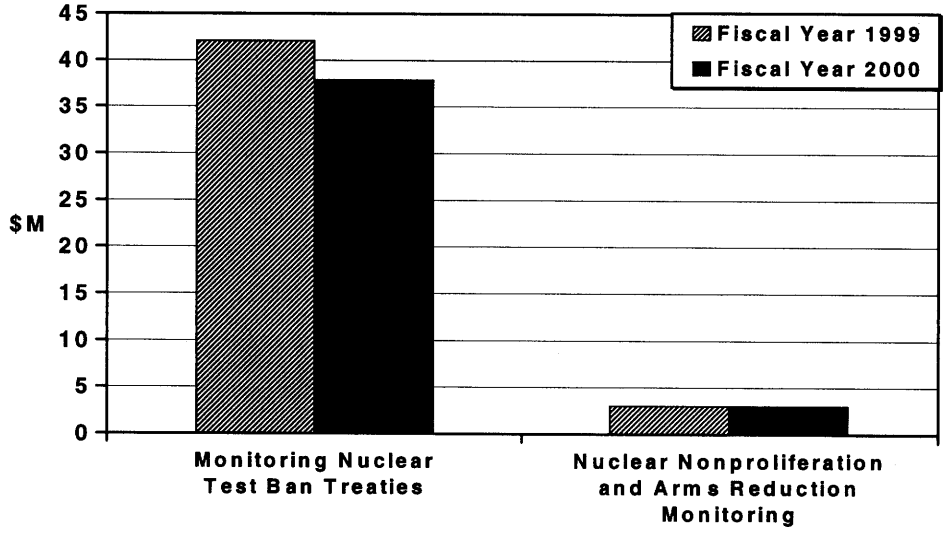
It is uncertain when, or even if, the CTBT will enter into force, banning nuclear tests in all environments, underground as well as underwater, in the atmosphere, and in space. Even without a formal treaty, however, nuclear testing will likely be constrained by declared moratoria. In any case, U.S. monitoring requirements will remain in effect, whether or not official entry into force ever occurs.

Likewise, it remains uncertain whether the Russians will ratify the START II agreement, a prerequisite to START III negotiations. However, short of further formal arms reductions, the United States remains engaged in a range of agreements and transparency measures to improve control and monitoring of nuclear weapons and materials in Russia.

Investment Trends and Rationale

Investment in research and development for nuclear test ban treaty monitoring is declining and is expected to continue to decline for the next several years. For the satellite-based systems the decline is due to the transition from research and development to production of the upgraded operational sensors for the new block of GPS satellites. For the ground-based systems the decline is based on maintaining progress toward meeting monitoring goals, while striking a balance with the needs of competing Departmental programs in light of slipping interagency schedules for CTBT monitoring system implementation.

Monitoring Nuclear Treaties and Agreements



Investment in research and development for arms reduction monitoring is expected to remain flat at a relatively low level. The chart shown below shows investments by activity areas that will be discussed in the remainder of this chapter.

Federal Role

National security is a constitutional role of the Federal government. DOE's roles in support of the national security goals for nuclear treaty monitoring and arms reduction are, through the expertise and facilities of the DOE national laboratories, to provide policy support and perform research and development for both remote and close-range ground-based systems, for example, for on-site inspections. For the satellite-based systems, after completing the relevant research, development, and demonstrations/validations, DOE actually fabricates monitoring sensors for operational deployment on DoD satellites.

Key Accomplishment

The key accomplishment of the DOE's longstanding nuclear treaty monitoring technology program is that it has resulted in the present U.S. continuous world-wide capability to detect nuclear explosions in all environments. What remains to be done is to improve the technologies so they can, in all environments and under all conditions, meet the challenging sensitivity requirements of the CTBT era, as well as to continue to provide technical support for strategic arms reduction monitoring activities.

Monitoring Nuclear Test Ban Treaties

Budget: FY98-$45.9M, FY99-$42.1M, FY00-$37.9M

Background

The signing of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) in September 1996 was a turning point in history, creating for the first time an international norm against all nuclear testing. It marked the end of the negotiations phase, which had been heavily supported by the DOE CTBT R&D program, and began the preparatory phase to the long-sought Treaty's entry into force. The preparatory phase is organized around two main activities:

- Building the international verification regime (the key element of which is the CTBT worldwide network of sensor stations, the International Monitoring System (IMS) comprised of seismic, hydroacoustic, infrasound, and radionuclide stations) that will monitor global environments to ensure that the Treaty is not violated; and

- Gaining ratification of the Treaty by States Signatories.

An international organization, the Preparatory Commission (commonly known as PrepCom), has been established for this phase. The PrepCom is the precursor to the Comprehensive Nuclear-Test-Ban Treaty Organization that will come into existence at Treaty entry into force.

Program Description

Simply stated, the performance needs for nuclear test ban monitoring sensors and their associated data systems are to detect, locate, identify, characterize, and help to attribute detonations occurring anywhere underground, underwater, in the atmosphere, or in space and to report the results to military and arms control operational users in a timely manner. The research and development program for monitoring nuclear test treaties has two key components:

- U.S. Satellite-based Systems.
- U.S. and International Ground-based Systems.

Satellite-Based Systems

Budget: FY98-$17.0M, FY99-$14.7M, FY00-$13.4M

Description and Objectives. With each new generation of satellites come changes to satellite subsystem interfaces, command structures, structural form factor, and telemetry data formats. GPS has already transitioned through five such changes, design for the sixth (Block IIF vehicles 1 through 6) is underway, and the seventh (Block IIF vehicles 7 and beyond) is rapidly approaching. This means that the data processing system -- which provides the primary data interface to the spacecraft and also collects data from, and controls, each sensor subsystem -- must be re-designed at each transition. DoD pressure to reduce size, weight, and power demands continuing development of increasingly more sophisticated microprocessor-based on-board systems, and, as sensors become more complex in order to meet CTBT requirements, there will be orders of magnitude more data to sample, filter, and store in memory.

Over the next 10 years the entire existing satellite-based nuclear test monitoring system will be replaced with an upgraded system satisfying the presidentially directed CTBT monitoring requirements. Recent program developments include an extended-energy-range x-ray sensor, that will improve detection of the evasive testing in space of primitive nuclear weapons, and an enhanced satellite-to-ground communications link. Next generation sensors currently under development include the following:

- **Enhanced Optical Sensor—**To ensure that the satellite-borne non-imaging optical sensors will be able to see even very weak light signals from small nuclear explosions, a next generation optical sensor is under development to improve detection sensitivity. This sensor is planned to be operationally deployed on GPS Block IIF satellites to provide complete worldwide, real-time high-sensitivity coverage and will replace the old bhangmeters.

- **Enhanced Electromagnetic Pulse (EMP) Sensor**—The nuclear detonation monitoring community within the U.S. has long maintained that monitoring multiple nuclear-explosion-induced signals from different physical phenomena is essential to reliable detection, identification, and attribution of evasively conducted nuclear tests. Both optical and EMP signals can provide timely evidence of an atmospheric nuclear detonation with sufficient information to locate the event to the accuracies required for treaty monitoring. But, in addition, EMP data will meet the accuracy requirements for warfighting, and will provide supplementary event characterization information to further aid in attribution.

  For CTBT the U.S. has more stringent detection requirements than for previous treaties. This magnifies the need for prompt, dual-phenomenology monitoring to address evasive testing scenarios. The Department of Energy is sponsoring the development of a new EMP sensor, to be called the V-sensor, that will be sufficiently sensitive to detect evasive nuclear detonations and will also be capable of on-board discrimination against EMP-like background signals. Thus, unlike currently deployed EMP sensors, it will be able to operate autonomously. This sensor will be operationally deployed on GPS Block IIF satellites.

- **Compact Gamma-Ray and Neutron Sensor**—The Space and Atmospheric Burst Reporting System (SABRS) is a DOE-sponsored project to develop a lightweight, low-power, small, inexpensive, and easily accommodated satellite payload for detection and characterization of nuclear detonations in the upper atmosphere and in space. SABRS is intended to replace most of the functionality of the exoatmospheric RADEC sensors currently hosted on the DSP satellites. The programmatic goal is to sustain the required capability to detect gamma-rays and neutrons, after the DSP constellation is retired. This goal supports the treaty monitoring mission as well as DoD warfighting missions.

R&D Challenges. The challenge in achieving the performance improvement targeted for the enhanced non-imaging optical sensor is extreme, involving the development of focal plane array "active pixel" technology. In effect, many individual optical sensors will be implemented in a space not appreciably larger than that required for today's single optical sensor (bhangmeter).

Implementing independent, autonomous EMP sensors is a challenge because of high false trigger rates, but recent work has led to powerful discrimination techniques to mitigate this problem.

The technology challenges for the compact gamma-ray and neutron sensor are to provide sufficient sensor sensitivity and an acceptably low rate of false alarms, using a small, low-cost payload. The immediate technical objective is to develop a SABRS demonstration /validation experiment to be flown in space to prove the new design concepts.

R&D Activities. Preparations are underway for a proof-of-principle flight experiment for the enhanced non-imaging optical sensor to demonstrate and validate this new approach to nuclear test monitoring.

Wide-band radiofrequency signal detection is the key to successful implementation of an enhanced EMP sensor. In this effort wide-band radiofrequency sensor technology is being married to multi-channel trigger technology. Data from the Fast On-orbit Recording of Transient Events (FORTÉ) satellite, a DOE small-satellite, proof-of-principle experiment launched August 29, 1997, is being analyzed to refine the design of the operational EMP sensor.

The planned replacement for DSP is the geosynchronous Space Based Infrared System (SBIRS) constellation. SABRS payloads on SBIRS satellites could provide a means to continue meeting requirements in the post-DSP era. Other possible platforms, such as the Advanced Extremely High Frequency communications satellite constellation, are also being considered. In anticipation of finding a suitable operational host vehicle, preliminary design work is proceeding.

Accomplishments. The prototype detector array for the enhanced non-imaging optical sensor has been successfully fabricated and the signal processing integrated circuit design is complete.

Data from FORTÉ has confirmed that the V-Sensor design is both adequately sensitive and capable of discriminating against EMP-like background signals. The V-Sensor will incorporate much of the FORTÉ radiofrequency sensor technology and add an event timing capability and an onboard signal processor for noise rejection.

In early 1998, the Air Force and DoD Space Experiments Review Boards approved and ranked the SABRS demonstration / validation experiment as a valid “space test experiment,” and as such the Air Force Space Test Program has identified a host platform for the experiment: DSP Flight 22, to be launched in 2002. The DSP satellite host is ideal, as it also carries the current operational gamma ray and neutron sensors, against which the demonstration data can be compared and validated.

Ground-Based Systems

Budget: FY98-$28.9M, FY99-$27.4M, FY00-$24.5M

Description and Objectives. At DOE our CTBT monitoring-related mission is to carry out research and development and deliver the research products to the U.S. agencies responsible for monitoring compliance with the CTBT and for operating the U.S. National Data Center for CTBT monitoring. DOE provides technologies, algorithms, hardware, and software for systems to detect, locate, identify, and characterize nuclear explosions in a cost-effective manner at the thresholds and confidence levels that support U.S. goals. In addition, the CTBT R&D Program supports the PrepCom in numerous ways.

The requirements for monitoring capabilities specified in the Presidential Decision Directives vary depending upon geographic location. They define specific regions of interest, not all of which are addressed by the DOE program. Internationally, however, monitoring needs are driven by requirements specified in the CTBT itself, and they are global. U.S. security policy prevented considering the use of U.S. space assets as part of an International Monitoring System (IMS). International duplication of U.S. satellite-based detection systems was considered too costly. So it was decided that the IMS would be ground-based. To ensure that effects from a nuclear test anywhere in any of the Earth's environments will be detected, the treaty language specifies networks of atmospheric, underground, and oceanic monitors: two types of radionuclide sensors, infrasound arrays, seismic sensors and arrays, and hydroacoustic sensors. These sensor systems were selected for CTBT monitoring in part because their capabilities complement each other. In addition, the U.S. will maintain and enhance its own ground-based National Technical Means, combining monitoring data supplied by the IMS with data from additional ground-based monitoring assets at the U.S. National Data Center.

Monitoring compliance with the CTBT presents difficult challenges. In all environments the task is complicated by the similarities between effects from nuclear explosions and effects produced by non-nuclear sources -- for example, each day there are several hundred earthquakes which produce signals large enough to be detected by the proposed seismic monitoring network. Furthermore, seismic evidence of an underground nuclear event depends not only on the geological environment near the detonation, but also on the physical characteristics of the path between the event and the sensor. For this reason it is vital to calibrate each deployed seismic array with respect to the monitored region. For the verification regime to meet these challenges, work remains to be done in sensor development, in data collection to calibrate the sensor networks, and in data management and analysis techniques that will ensure timely assessment of events. The CTBT R&D program (see http://www.ctbt.rnd.doe.gov) to date has been driven by requirements to meet national goals; achieving those goals will be enhanced if the International Monitoring System is a success.

To achieve global monitoring, improved sensors, sensor arrays, array analysis methods, and networks are needed to increase the U.S. ability to detect nuclear explosions and distinguish them from innocuous events. DOE's monitoring system R&D efforts are focused on engineering the radionuclide and infrasound systems, miniaturizing the seismic sensors, and determining the best ways to deploy all the sensors, including the hydroacoustic.

To achieve accurate location and identification capability, the sensor networks must be calibrated. To do this, detailed information is required about the paths over which signals could travel to a sensor station. In general, as a signal propagates from its source, it is delayed, attenuated, and altered in many ways, possibly time-variant, by the path that it takes (for example by geologic structures, winds, or oceanic conditions). Accurate location and identification are possible only after these effects have been taken into account.

Data collected by the IMS sensors will flow continuously to the International Data Center and, when requested, to the national data centers, where automated and interactive analysis techniques will be used to detect, locate, characterize, and identify the sources of the events. DOE is working on a number of data visualization and interactive analysis and system assessment projects to minimize the manpower required for data management and analysis tasks. We are also developing hardware and software to ensure data authenticity and integrity and system security for data being distributed from national and international data centers.

R&D Challenges. The principal challenges in CTBT monitoring are to detect the signals from very-low-yield nuclear explosions as well as from nuclear explosions conducted under conditions that mask the signals produced, and to distinguish these signals from the ambient background of natural and human-induced sources. The monitoring task is complicated by the fact that many natural and human-induced, non-nuclear events can produce signals that, to a single sensor technology, may appear similar to those from a nuclear explosion -- perhaps causing false alarms. Further, background noise or other interferences can mask or reduce the quality of evidence from events of interest for any of the technologies -- perhaps causing a true event to be missed.

Seismic. Historically, seismic sensors have greatly contributed to monitoring underground nuclear tests. However, the small signals and high backgrounds associated with evasively tested underground nuclear detonations force us to go to regional seismic monitoring system as opposed to the more traditional teleseismic systems. This means that data is recorded at distances less than 2,000 km from events of interest, rather than at much greater distances. Regional systems retain the challenge of characterizing the geology around the source and also face the more difficult challenge of characterizing more variable (albeit shorter) transmission paths through the Earth's mantle. Although the seismic monitoring problem is daunting, it is an important technology when it comes to monitoring underground testing, and advanced processing and calibration techniques show promise for improving its effectiveness.

Infrasound. The strength of the infrasound monitoring method is that infrasound is hard to hide. Acoustic evidence will propagate from all impulsive releases of energy into the atmosphere. Infrasound challenges include reducing false alarms by improving discrimination of nuclear from other impulsive releases and maintaining adequate signal-to-noise in the face of wind conditions at the sensor locations. The new generation of infrasound monitoring systems benefit from improved data computational techniques and selective siting of sensor arrays based upon comprehensive calibration studies.

Radionuclide Sampling. This is the unequivocal smoking gun for nuclear reactions within the atmosphere. However, radionuclide sampling does not provide timely evidence and it does not provide location information. Its strength stems from the development of reliable autonomous sensing stations that can process immense volumes of air so that extremely small evidence constituencies can be assayed continuously.

Hydroacoustic. These underwater systems provide undeniable evidence of explosive events, but nuclear detonations cannot be discriminated from other impulsive sources transmitted through the water. Nonetheless, since other technologies cannot operate in water and two-thirds of the Earth is ocean, hydroacoustic sensors play an important role.

Network Calibration. The CTBT requires monitoring smaller explosions (relative to the Threshold Test Ban Treaty, which allowed underground tests up to 150 kilotons) and under evasive testing conditions, which can further reduce the signal output. These small signals require much denser networks to meet our monitoring goals. But reduced signal amplitudes also fundamentally change the nature of the monitoring problem. In the case of seismic monitoring, calibrating the networks for regions of interest to the U.S. will require a detailed understanding of the Earth's interior structure, its oceans, and its atmosphere, as well as development of techniques to make this vast reservoir of knowledge accessible to automated and interactive processing systems.

Calibration Events. In order to calibrate the regions of interest, it is essential to have data on extremely well-located and well-characterized calibration events (e.g., explosions or earthquakes). Currently, only a very small number of events that meet the stringent criteria have been identified within the regions of highest interest. For example, only a few events have been identified in India or Pakistan, countries that have of late commanded greater interest due to their recent weapons tests. It is clear that, in order to properly calibrate the world's regions of interest, a concerted effort to identify and acquire data from calibration events, along with additional region-specific geophysical and geological information, is needed. Agreements between U.S. and foreign government agencies could greatly facilitate cooperative experiments that could provide the critically-needed data.

Data Management. Although the data flow process is straightforward in concept, there are many challenges that must be successfully overcome. Consolidating gigabytes of data from different technologies in a single data-analysis system with little time delay presents technological challenges for communications, data surety, automated and interactive signal processing, and complex data integration. The challenge in assuring data integrity and system security arises from the fact that the data comes from host-country-owned data sources and must be shared with a wide variety of users. Data surety and integrity are essential -- users must be confident that the data are authentic and have not been tampered with. Sensors need to be physically protected from damage or interference, either inadvertent or intentional, and the commands and data they receive and transmit need to be protected from corruption or falsification.

R&D Activities. Monitoring systems research and development activities include:

- Developing prototype radionuclide particulate and radioxenon sensors based on well known scientific principles but requiring innovative and complex engineering to meet global monitoring specifications including high reliability and automation, low maintenance, and high sensitivity.

- Developing a turn-key infrasound prototype ready for commercialization and deployment.
- Field testing of the radionuclide and infrasound prototypes with independent evaluation by the national user organization, the U.S. National Data Center operated by the Air Force Technical Applications Center.
- Engineering and software support to the commercial vendor selected by the Air Force to commercialize and deploy the radionuclide prototypes.
- Logistical and equipment support to international testing of the radionuclide prototypes, during independent evaluation by other countries.
- Demonstration of the radionuclide monitoring systems fully integrated into the global communications infrastructure including data authentication and data analysis capabilities.

Network calibration research and development activities include:

- Minimizing false events by calibrating the IMS networks for accurate locations and event identifications.
- Collection and integration into the Knowledge Base of seismic data and ground truth information (e.g., accurate location and time of occurrence) on calibration quality events.
- Developing algorithms for using the ground truth data for location and identification.
- Participating in field activities as required to obtain high quality ground truth information.
- Collaborating with other countries on seismic data collection opportunities, particularly dual use events.
- Developing Knowledge Base reference event databases to allow events to be interpreted in their proper regional context.

Data management and analysis research and development activities include:

- Develop the Knowledge Base architecture to manage the large amounts of data that human analysts must bring to bear in analyzing events.
- Develop and test the parameters needed to implement detection, location, and identification algorithms.

- Develop advanced computation techniques that will enable the processing system to use the discrete data to analyze events at any location.

- Test identification algorithms on small-magnitude reference events from the regions of monitoring interest.

- Validate advanced waveform-modeling techniques for interpreting signals generated by new events.

- Develop interpretation methods that take advantage of the synergy between the monitoring systems (i.e., events that occur at interfaces between monitoring environments which will be recorded on two or more of the monitoring systems).

- Develop and demonstrate the data authenticity and key management architecture to be used in the International Monitoring System and International Data Center.

Accomplishments. DOE has developed prototypes of two very sensitive, automated, self-contained instruments that meet the Treaty radionuclide monitoring requirements: one detects airborne radioactive particles and the other airborne radioactive isotopes of xenon gas. Both instruments autonomously collect air samples, analyze the samples, and transmit data to the data centers. The key contribution of the radionuclide sensors is their ability to distinguish nuclear explosions from non-nuclear events. The Treaty specifies a worldwide network of 80 radionuclide stations, but when the CTBT negotiations began, economical radionuclide measurement systems that could meet the monitoring goals were not available. Although the relevant science has long been well known, significant engineering was needed to make the systems automated and reliable, and to provide near real-time data reporting.

DOE has also developed a prototype infrasound system to meet CTBT requirements. This system could be used in the new global atmospheric infrasound monitoring network, which will complement the other monitoring technologies. A nuclear weapon test in the atmosphere would release large amounts of acoustic energy (sound). The sub-audible part of the signal (frequencies below 20 hertz) is called infrasound. The Treaty specifies a world-wide network of 60 infrasound stations. Although infrasound sensor technology is relatively well understood (it was widely deployed in the early 1960's), during Treaty negotiations there were no commercially available systems that met the Treaty requirements.

In some of the regions of primary interest to U.S. monitoring needs, DOE has developed region- and station-specific seismic travel-time corrections that will permit location algorithms to produce accurate results, once an event has been detected. The automated processes for determining the location of an event makes use of models which estimate the time required for signals to propagate from a given source location to a given sensor station. Previously existing global travel time models were insufficient to ensure that events will be located within the one thousand square kilometers over which the Treaty allows an on-site inspection to be conducted.

DOE continued development of computer tools for manipulating time series data called SAC2000 and MatSeis. Both programs allow direct access to the database format used at the U.S. and International Data Centers, provide CTBT-specific signal-processing functionality, and have an easy to use graphical interface. Both programs are available through the DOE's CTBT R&D web site (http://www.ctbt.rnd.doe.gov).

DOE delivered Release 2 of the CTBT "Knowledge Base" to the U. S. National Data Center in 1998. This provided a pre-operational structure for managing large data bases pertaining to multiple technologies, regional geophysical and geologic information, and parameters specific to particular monitoring stations. In future releases, such data will be accessed by automated processing systems and human analysts to provide monitoring and verification information.

Nuclear Nonproliferation and Arms Reduction Monitoring

Budget: FY98-$2.0M FY99-$3.0M FY00-$3.0M

Background

The Department's nuclear weapons threat reduction responsibilities are part of the Administration's interagency-wide effort to reduce the number of nuclear weapons and amount of weapons grade material both in the U.S. and in the Former Soviet Union (FSU). A joint effort being coordinated between DOE and DoD is to delineate respective responsibilities and define a comprehensive technology development program in support of U.S. nonproliferation agreements. The goals of the coordination are to set priorities, avoid duplication of effort, and take advantage of synergies. Execution will be by the Department of Energy and the DoD Defense Threat Reduction Agency (DTRA).

Initial declarations of warhead, component, and material inventories and periodic updates are a critical part of a lasting regime at reduced levels of nuclear arms. Verification of the declarations is especially important, as the U.S. and Russia proceed to lower warhead levels and fissile materials stockpiles, to ensure that false declarations cannot serve as the basis for rapid reconstitution of nuclear forces. For example, Congress has required that it must be proven that the nuclear material stored under Mayak Transparency came from actual nuclear weapons. This requires that the collected signatures must be unique to nuclear weapons and the measurement information must be passed through an information barrier, which then provides a binary (yes/no) decision that it satisfies or does not satisfy the criteria for nuclear weapons. After a weapon is dismantled, it then will be necessary to track the weapon components to their long-term storage site and continuously monitor the vault to make sure that the material does not return to the weapons stockpile.

Program Description

The two central goals of the strategic arms reduction monitoring program are to develop technologies able to:

- Confirm that an object being examined is a nuclear weapon or is a weapon component;
- Prevent the release of any nuclear weapon design information.

The requirements for warhead transparency agreements and START may vary, but have a common goal of providing confidence that the agreement or treaty is being satisfied. There are numerous signatures, most of them radiation signatures, that can indicate that an object is a nuclear weapon, but as the level of confidence is increased, there is also an increasing level of intrusiveness and possible compromise of sensitive weapon design information.

R&D Challenges. The Russians have sensitivities to the radiation signature measurements on nuclear weapons and components that differ from U.S. concerns. Because we do not know what radiation signatures will define Russian weapons, we must search for solutions that provide an acceptable level of confidence that we are monitoring the dismantlement of actual weapons. We must be able to provide assurance that we are not making measurements on arrangements of excess, weapons grade nuclear material, or spoofs using non-weapons capable radioactive material. Another difficulty is that several types of weapon designs can make it almost impossible, using radiation measurements, to confirm that a declared item is a weapon.

Because of the uncertainties in any treaty negotiations, a layered approach is being taken in order to provide the negotiators with technology options. Measurement and signal processing techniques are being developed that can, when they are conducted in sequence, provide increasing levels of confidence that a declared item is a nuclear weapon. The increasing levels of confidence also require increasing the levels of intrusiveness and the raw data will likely contain sensitive design information. In order to protect this information it will be necessary to develop information barriers, to test them, and by conducting vulnerability assessments (red teaming) to make certain no sensitive information is being revealed. Also, tracking and long-term monitoring of stored weapons components requires a balanced approach that will provide confidence that the storage containers remain intact and the components do not leave the storage area to be reused in nuclear weapons. A combination of micro-technologies, integrated radiation sensor systems using neural networks, and non-nuclear techniques are being developed as alternatives. Also important, is the need to be sure normal site security is not compromised by the treaty monitoring system.

Accomplishments

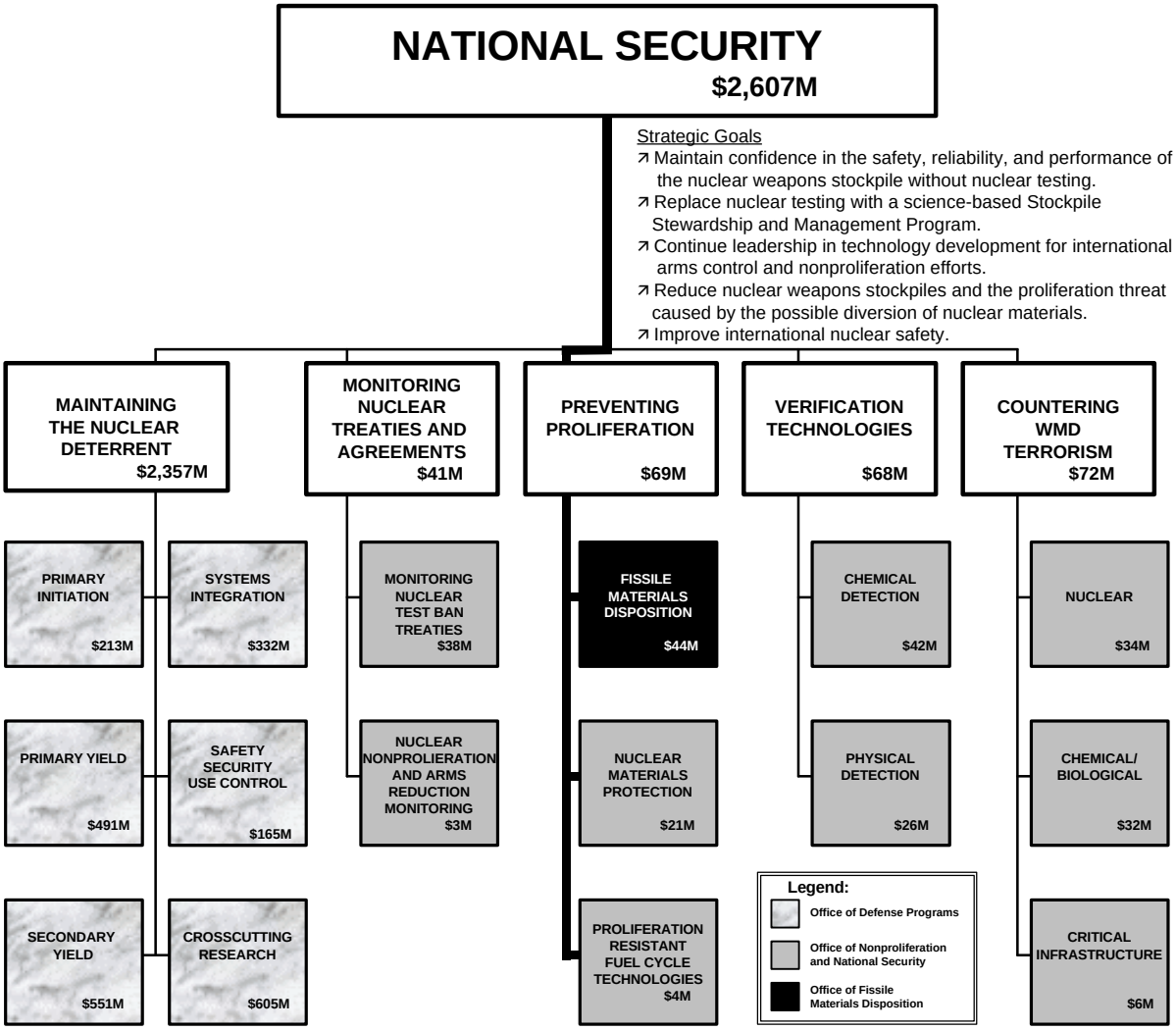
- Developed an approach to measure unclassified nuclear weapons attributes such as threshold mass and $^{240}Pu/^{239}Pu$ isotopic ratio for verification of warhead dismantlement and reductions.

- Developed options for possible START III negotiations, using radiation and alternate signatures, that will provide increasing levels of confidence a nuclear weapon has been dismantled.

Summary Budget Table (000$)

Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Monitoring Nuclear Test Ban Treaties	**45,900**	**42,100**	**37,900**
U.S. Satellite-based Systems	17,000	14,700	13,400
U.S. and International Ground-based Systems	28,900	27,400	24,500
Nuclear Nonproliferation and Arms Reduction	**2,000**	**3,000**	**3,000**
Total	**47,900**	**45,100**	**40,900**

Chapter 5
Preventing Proliferation



Chapter 5
Preventing Proliferation

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Overview

Definition of Focus Area

The current environment of warhead dismantlement and decreased requirements for any new weapons leaves the Department of Energy with more nuclear materials on hand than at any time in history. The Department of Energy has an associated responsibility to protect these materials from theft and diversion and to eliminate, where possible, stockpiles of weapons-usable fissile materials through disposition. The DOE research and development portfolio in the area of preventing proliferation addresses: development and adaptation of technologies that convert U.S. weapons-usable materials to a form that will prevent the plutonium from ever being used for nuclear weapons and assisting Russia in the demonstration of plutonium conversion technologies; development of technologies to control and account for nuclear materials and physically protect these materials; and development of proliferation resistant fuel for commercial reactors to reduce and eventually eliminate the international traffic in highly-enriched uranium (HEU) for commercial purposes.

To enable fissile material disposition, necessary process development and tests must be completed to provide the design and operational bases for surplus plutonium disposition facilities. DOE plans to disassemble "pits" and dispose of the surplus plutonium by (1) immobilizing it in a ceramic form surrounded by vitrified high level waste, the "can-in-canister" approach, and (2) by burning it as mixed oxide (MOX) fuel in existing domestic reactors.

Technologies to control and protect nuclear materials must remain state-of-the-art to ensure these materials do not fall into the hands of increasingly sophisticated terrorists. Detection technologies must accurately gauge and quantify mixed-matrix and shielded nuclear materials, while reducing worker exposures. Intrusion detection, barrier and vault systems, as well as countermeasures, must remain effective against continuously emerging threats.

Highly enriched uranium is used peacefully for civil energy production, research, and medical isotope production, but is also used in nuclear weapons. To reduce the danger of proliferation, the United States has pursued the elimination of HEU commerce by striving to develop low enriched fuel suitable for these necessary functions. The fissionable uranium may be able to be 'diluted' with non-fissionable uranium to lower the enrichment while maintaining the benefits. Fuel and target fabrication techniques must be developed, and fuel and target qualification tests must be performed to ensure successful performance within reactors.

National Context and Drivers

The Department foresees a future national security environment with continued uncertainties and risks of international terrorism from weapons of mass destruction. In the aftermath of the Cold War, significant quantities of weapons-usable fissile materials have become surplus to national defense needs both in the United States and Russia. The threat that nuclear weapons or materials could fall into the wrong hands through theft or diversion is a clear and present danger. The

danger exists not only in the potential for proliferation of nuclear weapons, but also in the potential for environmental, safety and health consequences if surplus fissile materials are not properly managed.

United States policy is to protect and control nuclear materials; to seek to eliminate, where possible, accumulation of stockpiles of highly enriched uranium and plutonium; and to reduce and eventually eliminate the civilian use of HEU in research and test reactors and in targets for medical isotope production. The U.S. will also ensure that, where these materials already exist, they are subject to the highest standards of safety, security, and international accountability. DOE is committed to safely dispose of the nuclear materials made surplus by the downsizing of the nuclear arsenal in conformance with arms control and nonproliferation treaty requirements. The Department has developed several strategies that will contribute to a reduction in the global nuclear danger associated with inventories and supplies of nuclear materials that could be used for the proliferation of nuclear weapons.

Linkage to Goals and Objectives

The R& D efforts for preventing proliferation support the Department's national security strategic goal, Objective 4, to reduce nuclear weapons stockpiles and the proliferation threat caused by the possible diversion of nuclear materials. Strategy 2 of Objective 4 would reduce inventories of surplus weapons-usable fissile materials worldwide in a safe, secure, transparent, and irreversible manner. Reducing/eliminating the civilian use of HEU and taking back the spent research reactor fuel from the U.S. and abroad will remove the threat of theft or diversion from these civilian reactors.

- Research and development activities for preventing proliferation are also linked to various external requirements as described in:
- Presidential Decision Directives related to preventing proliferation of weapons of mass destruction,
- Highly Enriched Uranium Purchase and Blending Agreement.
- Department of Defense Cooperative Threat Reduction Program (Senate Language).
- Mayak Transparency Mandate from the Biden Amendment.
- Trilateral Initiative and
- Presidential Summit Agreement Moscow 1996 and Helsinki 1997 (that is, excess fissile materials storage and disposition transparency).

Uncertainties

The research and development portfolio in this focus area is directed at establishing a technology base to support the design leading to the construction and subsequent deployment of facilities to disposition surplus plutonium. The technical risks corresponding to successfully meeting the goals and objectives of the investment in the portfolio are considered to be manageable. However, the start of construction of the facilities in the United States is dependent on progress on bilateral agreements with Russia for plutonium disposition. Negotiations with Russia are ongoing and agreements may be reached sometime in 1999. Were negotiations to be suspended the pace of research and development would probably be affected.

Success in converting research and test reactors from highly enriched uranium to low enriched uranium faces technical and political uncertainties. Technical uncertainties relate to the ability to develop and fabricate low enriched uranium fuels and targets with increased density to match the performance levels of higher enriched uranium fuels and targets. The technical risk is considered manageable because of the success of the advanced fuel development work already accomplished. The political uncertainties involve the willingness of foreign research reactor operators to agree to convert to low enriched uranium fuel and targets, as well as the desire of foreign governments to seek to reduce the civil use of highly enriched uranium. The United States attempts to reduce these political uncertainties with incentives and export restrictions.

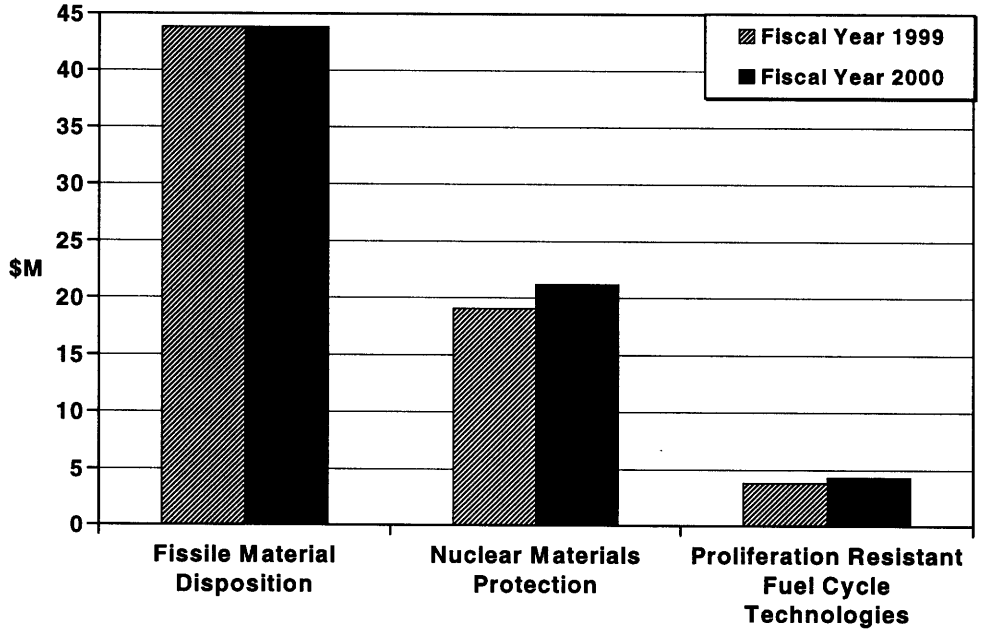
Investment Trends and Rationale

The investments in development efforts are directed at establishing the information that is needed to design and operate facilities to disposition surplus plutonium in the United States. In addition investments are being made in Russia for small-scale tests and demonstrations in plutonium disposition technologies to facilitate Russian decisions regarding plutonium disposition. The Department's current plans are to start design and complete design of U.S. plutonium disposition facilities in the FY1999 through FY2002 time frame. Consequently, the investment is front-loaded to support the design efforts. Some development activities would continue at a lower funding level after the completion of design in order to validate specific process operations. In Russia, the investment is also front-loaded, with most of the investment completed by FY2000. Continuation and expansion of U.S. and U.S.-Russian small-scale testing and demonstration of plutonium disposition technologies is needed to build trust and cooperation and help prepare for reciprocal implementation of future plutonium disposition actions and agreements. This would help fill the gaps in technical knowledge, remove uncertainty regarding the viability of certain technologies, and lead to the successful disposition of surplus plutonium.

DOE executes R&D activities associated with the disposition of surplus plutonium through the expertise and facilities provided at the national laboratories. A lead laboratory is assigned the responsibility for the technical work in a program area. In turn, the lead laboratory contracts with other national laboratories and institutions, such as universities and industry. DOE establishes goals, provides guidance and direction in each program area, and in consultation with the lead laboratory, prioritizes the work and activities in each program area.

The chart shown below shows investments by activity areas that will be discussed in the remainder of this chapter.

Preventing Proliferation



Federal Role

Congress in Public Law 103-337 directed that DOE establish an Office of Fissile Materials Disposition and that the head of the Office shall be responsible for all activities of the Department relating to the management, storage, and disposition of fissile materials from weapons and weapons systems that are excess to the national security needs of the United States.

Key Accomplishments

In the area of preventing proliferation, the accomplishments further the technological bases for the design and operation of the disposition facilities. In pit disassembly and conversion, a full-scale demonstration of core functions was designed, constructed, and started at Los Alamos National Laboratory. Eight of 30 different pit designs have been disassembled and converted. In Russia, the development of a Russian plutonium conversion and nondestructive assay prototype was initiated. In immobilization, the baseline ceramic form was established and detailed flowsheets and equipment concepts were prepared. Demonstrations of feasibility of several key processes were completed. In Russia, small-scale tests of plutonium vitrification were performed. In the reactor option, the preliminary process parameters for MOX fuel fabrication, using powder derived from a pyrochemical process of weapons plutonium metal conversion, were established. Sample MOX fuel from this process was fabricated, irradiated, and examined. Also, analytical methods for detecting gallium and basic research and development on gallium/fuel cladding interactions were completed.

Accomplishments in materials control and accountability research and development lead to safer inventories of special nuclear materials by furthering the technology base of SNM detection and physical protection. Special nuclear material may now be found in unopened waste drums via non-destructive assay and in vehicles or on persons via enhanced security portals. Remote inventory monitors continue to improve the ability to detect tampering and diversion of SNM while removing the worker from possibly harmful exposures.

Proliferation resistant fuel cycle research and development has demonstrated that all but six western-European high-powered research reactors are able to be converted from using HEU to LEU fuel and, of those that are able to convert, all but ten have plans to do so. The Department has supported reactor conversion in over 20 countries and has supported the acceptance specification policy in over 40 countries.

Fissile Materials Disposition

Budget: FY98-$44.7M, FY99-$43.8M, FY00-$43.8M

Background

The Department, in a Record of Decision on the Fissile Materials Storage and Disposition Programmatic Environmental Impact Statement issued January 1997, announced a strategy for the disposition of surplus weapons-usable plutonium in a manner such that these materials can never again be used for nuclear weapons. The Department plans to disassemble “pits” and dispose of surplus plutonium (1) by immobilizing it in ceramic form surrounded by vitrified high level waste, the “can-in-canister” approach, and (2) by burning it as mixed oxide (MOX) fuel in existing, domestic reactors. Pursuing both of these approaches provides important insurance against any unforeseen problems in implementing either approach by itself and provides the United States with flexibility and leverage needed for working with Russia and our allies on the critical task of reducing excess Russian weapons plutonium. Accordingly, the Department’s plans include completing the necessary process development and small-scale technology tests, including “can-in-canister” immobilization tests and tests of MOX fuel fabricated from weapons plutonium and subsequent irradiation.

Program Description

For the immobilization approach, the Department needs to resolve the technological issues associated with formulating plutonium in ceramic materials, the production processes, and the impact of impurities on the surplus plutonium forms, in order to have confidence that this approach can provide success in a timely and cost-effective manner.

For the reactor approach, the Department needs to resolve issues associated with potential impacts to fuel performance from other materials alloyed in plutonium in order to have confidence that this approach can also provide success in a timely and cost-effective manner.

In order to deploy either of these disposition approaches, the Department needs to complete operational testing of the processes that would be used to dissemble pits and convert the plutonium from pits and other forms into a plutonium oxide form which would serve as feed material for both disposition technologies as well as be made available for international inspection.

Pit Disassembly and Conversion

Budget: FY98-$19.4M, FY99-$17.9M, FY00-$18.3M

Description and Objectives. The U.S. activities are to develop, demonstrate and document core functional capabilities required to disassemble surplus weapons pits and convert them to plutonium oxide in a manner as safe, environmentally sound, and cost effective as practical. Development and demonstration of this process will minimize the cost, schedule, and technical risks associated with the upcoming design, construction and operation of the production facility.

For the Russian effort, the work consists of analyses, and testing as appropriate, of different conversion technologies. The objective is for the Russians to select a pit conversion technology leading to a prototype demonstration of the technology. The Bochvar Institute will do the work, with support from U.S. Department of Energy laboratories.

R&D Challenges. The major overall challenge for the U.S. program is developing a technology that accommodates about 30 unique surplus pit designs, and keeping the process robust and cost-effective, while minimizing operator radiation exposure. The challenge in Russia, is the selection of a conversion technology that the Russians can readily deploy.

R&D Activities. The major R&D activities involve the testing of a prototype demonstration at Los Alamos National Laboratory that will provide the process parameters for and operating experience in several core modules. Activities include: development of an optimum joint pit disassembly /plutonium extraction and conversion approach; development of a plutonium oxide packaging and non-destructive assay (NDA) system; development of a non-plutonium pit part disposition approach; and development of robotics for the above functions. For work in Russia, the goal is for the Russians to select a pit conversion technology leading to a prototype demonstration of the technology. Each of these areas is described below:

- **Development of an Optimum Plutonium Extraction and Conversion Approach**—A pit bisector module coupled with a pyrochemical plutonium metal to plutonium oxide conversion module will be operated to obtain operating process parameters.
- **Development of a Plutonium Oxide Packaging and Non-Destructive Assay System**—The basic functions of plutonium oxide canning will be manually demonstrated on about 50 pits. Then the canning system will be automated and the automated canning and NDA system will be demonstrated on about 200 pits, covering all surplus pit types.

- **Development of a Non-Plutonium Pit Part Disposition Approach**—Pit disassembly results in numerous unique pit parts which require development of particular process steps for disposition. Development involves establishing processes, equipment, and procedures for disposition of particular pit parts, such as for the decontamination of uranium and beryllium hemishells.

- **Development of Robotics**—Several of the process steps will be automated to reduce the radiation exposure to operators. Requirements for robotics will be developed and robots selected and tested in a glove-box environment.

- **Russian conversion**—The options for the conversion of Russian surplus weapons plutonium will be analyzed, and the technology selected will be developed and tested in Russia.

Accomplishments

- Designed, constructed, and started a full scale demonstration system of core functions at Los Alamos National Laboratory.

- Designed, constructed, and started operation of full-scale glove box modules for pit bisection and plutonium oxidation at Lawrence Livermore National Laboratory.

- Disassembled and converted plutonium from eight of 30 different types of surplus pits.

- Demonstrated a fully automated NDA system.

- Initiated development of a Russian plutonium conversion and nondestructive assay prototype system.

Immobilization

Budget: FY98-$14.7M, FY99-$16.5M, FY00-$18.0M

Description and Objectives. The U.S. activities are directed at resolving technological issues associated with immobilizing plutonium in a ceramic. Research and development is being conducted to establish the process, and associated parameters, and develop and define the equipment that will support the deployment of the can-in-canister immobilization technology.

For the Russian effort, the work consists of experiments involving the immobilization of plutonium in glass and ceramic matrices. The objective is to demonstrate to the Russians that immobilization can be used for plutonium disposition, even if only for waste streams from the disposition facilities. This work is conducted at the Bochvar Institute and Radium Institute in Russia, with support from the DOE national laboratories.

R&D Challenges. Challenges include developing a product and technology that accommodates the full range of impurities and constituents in the non-pit surplus plutonium while keeping process and equipment simple, flexible, cost effective, and low radiation exposure to operators. The challenge in the Russian program is to convince Russia that recovery of plutonium from very low concentrations of plutonium containing materials is not economical.

R&D Activities

- **Immobilized form Development**—Development work in this area focuses on providing: compositions of the ceramic immobilization forms that accommodate the range of plutonium feed materials expected; the related processing parameters for fabricating the plutonium forms; important physical and chemical properties of the final form needed for process/equipment development; and a preliminary product control model that establishes acceptable ranges for feed compositions and processing parameters. These development activities involve laboratory experiments with plutonium, uranium, desired neutron absorber elements, and the other materials contained in the expected feed; non-radioactive experiments with surrogate materials; and analysis of data related to the feed material and the physical chemistry of the ceramic form.

- **Immobilization Process/Equipment Development**—Development work in this area involves: converting a wide range of feed materials into a homogeneous oxide feed to the immobilization process using mechanical and chemical process; blending this feed with uranium oxide and other ingredients; pressing the feed blend into disks; firing/sintering them into the immobilized plutonium ceramic form disks; and packaging cans of plutonium ceramic disks into arrays inside large canisters, which are then filled with molten high-level radioactive waste glass. Key process steps and equipment that need to be developed and tested for the specific ceramic formulation with actual plutonium feed materials include design of the canister package and internals, glass pour testing of prototype canisters, canister loading, and use of surrogate test materials.

- **Russian Process Development**—Work involves tests on the immobilization of plutonium in glass and ceramics and tests on the recovery of plutonium from glasses and ceramics.

Accomplishments

- Established baseline ceramic form that accommodates the expected range of impurities.

- Defined detailed flowsheets and equipment concepts. Completed feasibility demonstrations for several key processes. Key prototype equipment is being procured and assembled. A ceramification test system has been designed and is being

assembled. Concepts for disk handling and can loading have been successful in feasibility tests. A simplified system for loading cans into canisters was successfully demonstrated.

- Conceptual design of the can-in-canister configuration was completed.

- Performed small-scale tests of plutonium vitrification in Russia.

Reactor Option

Budget: FY98-$10.6M, FY99-$9.4M, FY00-$7.5M

Description and Objectives. The MOX technology is used in Europe and does not require extensive research and development for implementation in the U.S. The effort is directed at fabricating samples of MOX fuel and conducting limited experiments and tests of the sample MOX fuel to assess the effect of gallium contained in weapons-grade plutonium on fuel performance. The objective of this effort is to assure the plutonium and uranium material forms used for fabricating MOX fuel will produce acceptable fuel, and examine key issues related to the successful performance of MOX fuel in commercial nuclear reactors.

R&D Challenges. The challenge is understanding and reconciling the differences between MOX fuel produced from weapons-derived plutonium and that which is commercially produced in Europe. Differences include variation in plutonium oxides, isotopics, and the presence of impurities introduced in the manufacturing of nuclear weapons, i.e., pits. In addition, the MOX fuel containing small amounts of gallium may need to be shown to be acceptable for commercial power plant use.

R&D Activities

- **Evaluate Effects of Variations in Fuel Oxides**—Activities involve producing plutonium and uranium oxide powder that is different from that produced in the European process and fabricating MOX fuel to demonstrate the suitability of these different feed materials.

- **MOX Fuel Qualification**—Activities involve irradiating sample fuel made from weapons origin plutonium and completing post-irradiation examination to determine fuel performance.

Accomplishments

- Established preliminary process parameters for MOX fuel fabrication using powder derived from a pyrochemical process of weapons plutonium metal conversion.

- Developed bench-scale analytical method for detecting gallium in Pu oxide powder/fuel and completed basic R&D on gallium/fuel cladding interactions.

- Developed draft plutonium oxide feed specification.
- Fabricated, irradiated, and began examination of demonstration MOX fuel that was produced using a pyrochemical process.

Nuclear Materials Protection

Budget: FY98-$17.7M, FY99-$19.1M, FY00-$21.2M

Background

In recent years, the worldwide proliferation of weapons of mass destruction has emerged as one of the most serious dangers confronting the United States. This is a continuing and evolving problem with far-reaching consequences for international and domestic security and stability. In response to this emerging threat to our security, the President directed the prioritization of a number of initiatives and programs throughout the United States government and the Department of Energy. One of these priorities is the effective protection, control, and accountability of nuclear materials, technology, and expertise in the United States.

The Department of Energy has more nuclear materials on hand than at any time in history, and has an associated responsibility to protect these materials. Should a terrorist gain access to special nuclear materials (SNM) there is considerable potential for radiological sabotage which could endanger not only Department of Energy employees but also the general public. This scenario must be protected against. Other assets of national security significance requiring protection include nuclear weapons, weapons design information, and the national energy infrastructure.

Maintaining a technological “edge” over potential adversaries is an essential part of the DOE protection strategy, and since terrorists are becoming increasingly sophisticated and well funded, continued investments in protection technologies are required. Not only must the Department protect against the use of traditional terrorist tools such as bombs, explosives, and armed teams, but also insiders, lethal agents, directed energy weapons, and the terrorist use of computers.

For over 30 years the Department has invested in the development of safeguards and security measures and technologies at almost every national laboratory to help counter these threats and ensure the preservation of national security and public safety. It does not appear that investments in this area can be relaxed without accepting considerable risk to Departmental assets requiring protection, or the general public.

Program Description

The nuclear materials protection activity is focused on the following two areas:

- Nuclear Material Control and Accounting.
- Physical Protection.

Technologies emerging from both of these areas are used by DOE facilities to offset specific threats. In order to make sure that projects funded under this program reflect capabilities that are truly needed, the program is formulated based on user needs that have been submitted by field sites. These needs are then expanded into requirement documents that can be used by laboratories and quality panels to provide input and oversight of projects that receive funding. Technologies often make their way to field users initially as part of a beta test program so that laboratory developers can receive direct feedback on the adequacy of their designs. Continuous dialogue with field users throughout the development cycle has lead to the successful fielding of numerous technologies and an improved security posture for the Department.

Materials Control and Accountability

Budget: FY98-$10.3M, FY99-$9.8M, FY00-$10.1M

Description and Objectives. Nuclear Materials Control and Accountability (NMC&A or MC&A) is that part of safeguards that detects or deters theft or diversion of nuclear materials and provides assurance that all nuclear materials are accounted for appropriately.

Materials accounting establishes and tracks nuclear material inventories and detects loss or diversion of nuclear materials. A materials accounting program employs physical inventories, measurements, accounting records, and reports to ensure that inventory records are correct and complete. It provides credible assurance that diversion has not occurred and that other functions of the safeguards system have been effective in protecting these materials.

Materials control limits access to nuclear materials to authorized personnel in authorized locations, ensures the integrity of accounting systems, and deters theft or diversion of materials.

Our objective is to develop technologies, technical expertise, and information that supports DOE field sites in their efforts to design, implement, and manage nuclear material control and accounting systems that meet the policy requirements of the Department.

R&D Challenges. Maintaining control and accountability of nuclear materials within the defense nuclear complex requires:

- Measurement technologies that can accurately quantify nuclear materials embodied in “mixed matrix” form.
- Advanced methods for detecting shielded nuclear materials and for identifying specific materials (versus simple recognition of radiological material presence).
- Automated and unattended verification of vaulted inventories (in storage) to enhance worker safety, while simultaneously protecting those materials by reducing physical access.

- Self calibrating measurement equipment and non-nuclear standards to reduce exposure of employees to nuclear materials.

R&D Activities. DOE's approach involves:

- Application of advanced technologies to address the shortcomings between user needs and available solutions including:
  - Advanced calorimetry technologies for small samples and in-process glove boxes
  - Detection technologies for shielded and mixed matrix materials
  - Non-destructive assay systems for difficult-to-measure materials
  - Interfaces linking measurement systems to accounting databases
  - Calibration and standards technologies
  - Spectrum analysis software for nuclear materials measurements

- Maintenance of core competencies in nuclear materials detection, measurement, control and accountability, and

- Provision of DOE site support for nuclear materials measurement and control issues.

Accomplishments. Recent accomplishments include:

- Development and fielding of non-destructive assay systems for characterization of SNM in packages and waste drums,

- Advancements in vehicle and personnel portal SNM detectors,

- New calorimeter operating systems capable of integrating multiple calorimeters simultaneously, and

- Fielding of autonomous vault inventory monitoring systems to detect unauthorized tampering with or removal of SNM.

Physical Protection

Budget: FY98-$7.4M, FY99-$9.3M, FY00-$11.1M

Description and Objectives. DOE develops technologies, technical expertise, and information that supports DOE field sites in their efforts to design, implement, and manage protection systems that meet the policy requirements of the Department and mitigate the official DOE design basis threat.

Protecting the people and physical assets present throughout the national defense nuclear facilities requires continuous measurement of the vulnerabilities and performance characteristics of deployed and emerging protection systems. Specific threats that must be countered by protection, detection, and mitigation technologies include the activities of malicious "insiders", and the

presence of explosive, chemical, or biological agents. Additionally, protective forces within nuclear facilities face a number of unique operational constraints (for example, nuclear reactors must not be struck by a ricocheting bullet).

R&D Challenges. Achieving physical protection objectives requires overcoming a number of challenges:

- To enable design and management of effective security systems, good system modeling and analysis techniques must be available. Good modeling systems rely on accurate security system performance information originating from solid testing programs. Current resources do not permit adequate performance information to be generated.

- Recent tests have shown that barriers and vault systems used by the Department are not as robust as once thought. An activated barrier that supplements existing barriers is therefore required. Although many approaches have been investigated, a promising technological alternative has not yet been identified.

- Development of intrusion detection equipment that can be used to replace existing equipment before it is discontinued by commercial manufacturers.

- Balancing the above requirements against planned developmental improvements in critical existing systems (like ARGUS and ASSESS) such that they do not become obsolete.

R&D Activities. The Physical Protection program invests in the following seven areas:

- Quantification of the performance of security equipment against current and emerging threats:
  - Interior and exterior sensors
  - Explosives detection equipment
  - Access delay equipment
  - Video equipment
  - Entry control and biometrics
  - Vehicle and personnel screening.

- Elimination of specific protection system vulnerabilities and deficiencies.

- Explosive protection.

- Protective system modeling and analysis.

- Alarm annunciation and access control improvement (ARGUS).

- Protective force performance improvement.

Accomplishments. Technological means have been applied to develop, modify, test, or implement numerous physical protection, detection, assessment, delay and response capabilities throughout the DOE complex:

- Redesign of an activated barrier currently in use to extend operational shelf life and confidence.
- Fielding of frangible non-lead ammunition.
- Fielding of an automated closed-circuit television (CCTV) camera tester.
- Fielding of a relocatable security system.
- Fielding of a high security wireless alarm communications link.
- Fielding of a technology capable of screening vehicles for hidden people.

Proliferation Resistant Fuel Cycle Technologies

Budget: FY98-$3.5M, FY99-$3.8M, FY00-$4.3M

Background

Reducing the threat of the proliferation of nuclear weapons continues to be one of the foremost goals of United States foreign policy. A key element of this policy is the reduction, and eventual elimination, of highly enriched uranium (HEU) in civil commerce. HEU is used as fuel for nuclear research and test reactors and as targets for medical isotope production, but can also be used in nuclear weapons.

Since the 1950s the United States has provided peaceful nuclear technology to foreign nations in exchange for their promises not to develop nuclear weapons. A major part of this program has been to provide research reactor technology to allow recipient nations to pursue medical, agricultural, and industrial applications of nuclear energy.

To reduce the danger of nuclear weapons proliferation, the United States in 1978 began the Reduced Enrichment for Research and Test Reactors (RERTR) program. One of RERTR's most important and successful activities has been the development of low enriched uranium (LEU) fuels to permit conversion of research reactors from HEU.

Program Description

The fundamental objective of the RERTR program is to provide the technical means needed to minimize, and eventually eliminate, international traffic in highly enriched uranium (HEU) for civilian purposes, and thereby to reduce the nuclear weapons proliferation potential of such material. To achieve this goal, the RERTR program develops the technical means needed to fabricate and qualify low enriched (less than 20% fissionable U^{235}, remainder non-fissile U^{238}) fuel and other research reactor devices such as targets for producing molybdenum-99, and to develop and test new targets and modified chemical processes to produce molybdenum-99. Currently, these fuels and targets are fabricated and qualified using highly enriched uranium (90 to 93% fissionable U^{235} and less than 10% U^{238}).

R&D Challenges. The major obstacle to converting the most sophisticated high-power research reactors is the lack of fuel with adequate density. In the past, HEU was used in order to provide enough fissile uranium within the density achievable for these fuels and other devices. In order to convert the reactor to LEU fuel, while still providing enough fissile uranium, more non-fissile uranium must be incorporated into the fuel matrix, resulting in a denser fuel. The current effort, which began in March 1996, is focused on developing fuels with a uranium density in the range of 8 to 9 grams of uranium per cubic centimeter of fuel. While progress has been made, the best density achieved thus far has been around 4 to 5 grams of uranium per cubic centimeter.

R&D Activities. RERTR Program research and development activities are focused on two activities:

- Fuel Development to:
  - Develop fabrication techniques for research and test reactor fuels of very-high-density, but low-enrichment, uranium for use in the more powerful and sophisticated research reactors unable to use current technology LEU fuels
  - Perform the tests needed to qualify the new LEU fuels
  - Demonstrate the same performance with the new LEU fuels as achieved with current HEU fuels.

- Target Development to provide alternative targets and chemical processes which will allow the use of LEU to produce fission-product molybdenum-99 for use in medical applications including:
  - Development of target fabrication technology
  - Development of chemical process technology for recovery and purification of the molybdenum-99
  - Adaptation or development of technology for disposing of radioactive waste
  - Obtaining FDA approval to market the drug product produced using LEU instead of HEU.

Accomplishments

- Approximately two-thirds of the work required to eliminate use of HEU in U.S.-supplied research reactors has been accomplished. The program's development of a low enriched fuel makes it possible for all but six western reactors (with power greater than one megawatt) to convert. Of the U.S.-supplied reactors with power greater than one megawatt that are able to convert, most have planned to do so.

- The RERTR program has supported reactor conversion efforts in two dozen countries and supports the Foreign Research Reactor Spent Fuel Acceptance Policy, involving over forty countries.

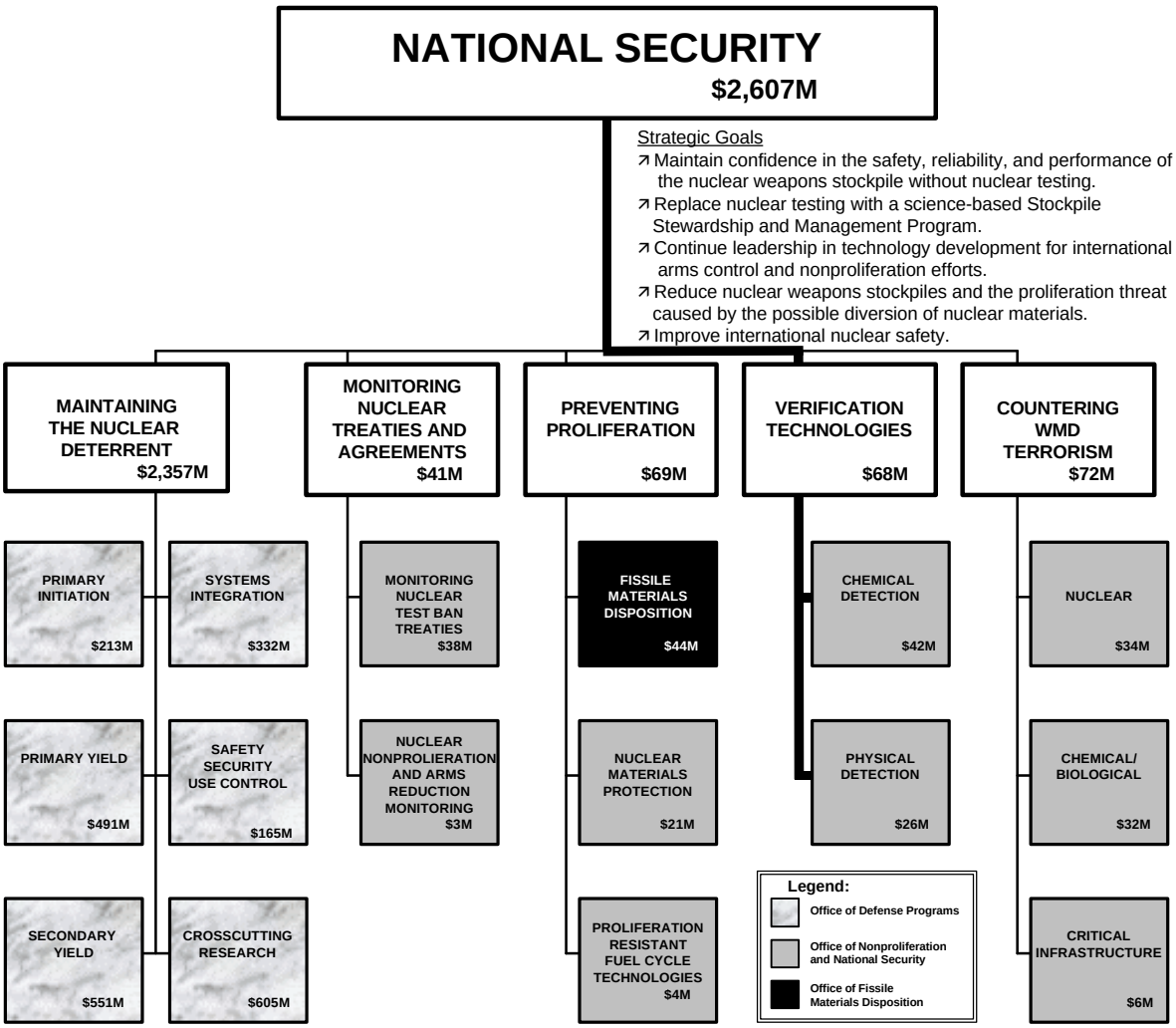
- Recent irraditation tests of a low enriched uranium-molybdenum alloy fuel sample have shown excellent results, exceeding the potential of uranium-silicide alloy fuel.

- A prototype LEU target for medical isotope production has been developed and is being tested in Indonesia. The RERTR program is conducting joint development work on LEU targets for medical isotope production with Indonesia, Argentina, Canada, and South Korea and is beginning joint work with Australia.

Summary Budget Table (000$)

Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Fissile Material Disposition	**44,700**	**43,800**	**43,800**
Pit Disassembly and Conversion	19,400	17,900	18,300
Immobilization	14,700	16,500	18,000
Reactor Option	10,600	9,400	7,500
Nuclear Materials Protection	**17,700**	**19,100**	**21,200**
Materials Control and Accountability	10,300	9,800	10,100
Physical Protection	7,400	9,300	11,100
Proliferation Resistant Fuel Cycle Technologies	**3,500**	**3,800**	**4,300**
Total	**65,900**	**66,700**	**69,300**

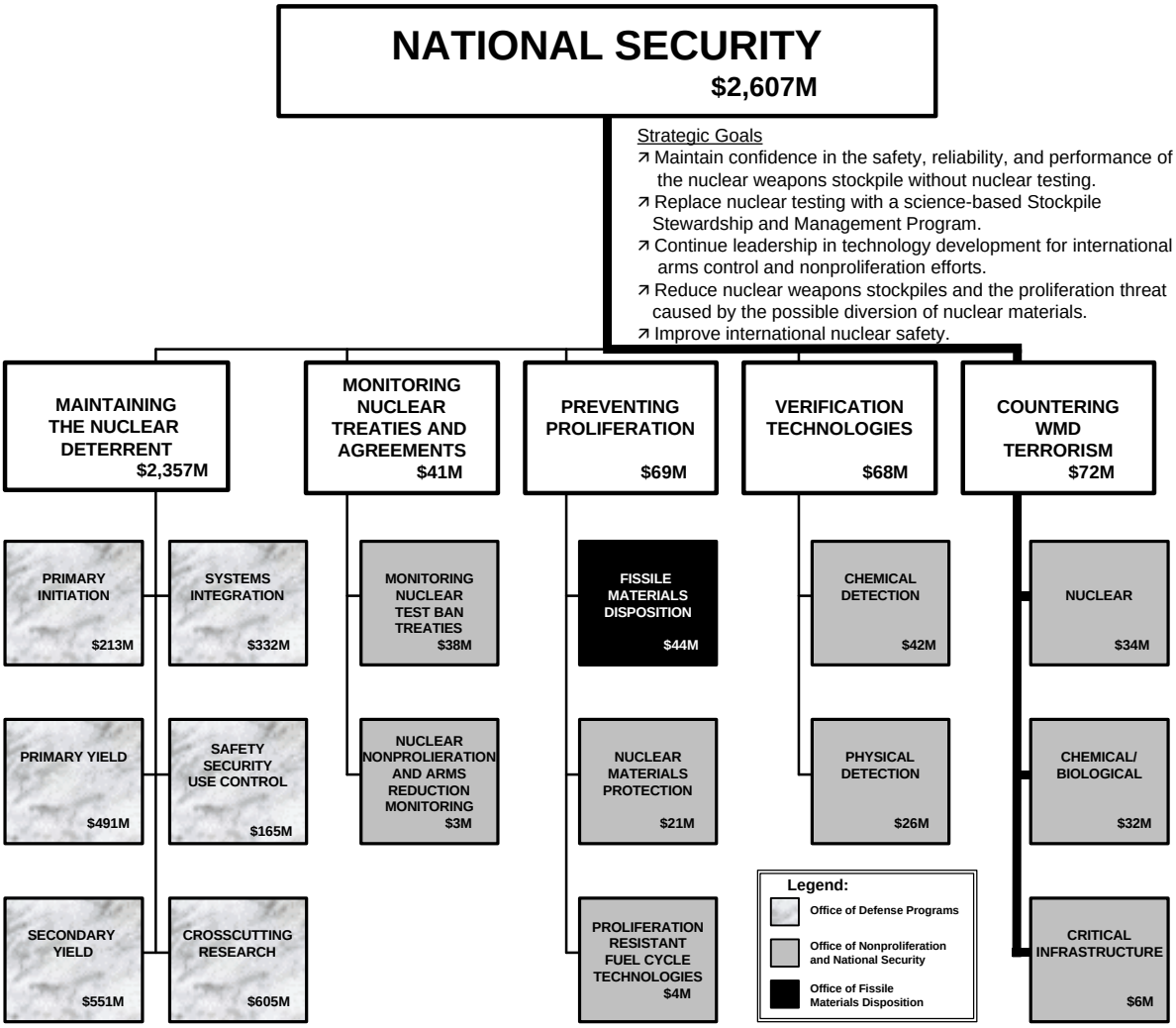
Chapter 6
Verification Technologies



Chapter 6.

This chapter will be issued as a separate supplement.

Chapter 7
Countering Weapons of Mass Destruction Terrorism



Chapter 7

Countering Weapons of Mass Destruction Terrorism

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Overview

Definition of Focus Area

The research and development focus area on countering weapons of mass destruction terrorism is concerned with all forms of weapons of mass destruction. The scientific basis for the research spans a very broad spectrum including nuclear science, physics, engineering, chemistry, and biology.

The Department of Energy has a comprehensive program to provide the means to provide protection to the national nuclear complex, special nuclear material, classified information, and other critical assets of the Department of Energy. The three primary research and development activities include: nuclear materials control; responding to chemical/biological proliferation; and critical infrastructure protection.

The Nuclear Challenge

The Department of Energy is the lead government agency for nuclear materials issues. Insuring the security of nuclear weapons and materials in Russia and the other states of the Former Soviet Union is crucial; and, thus, aggressive continuation of the Nunn-Lugar nuclear safeguard initiatives begun several years ago is a top priority. The U.S. must develop the capability to dispose of surplus weapons plutonium as soon as possible in order to enter into a bilateral agreement with Russia to enable the disposition of surplus Russian plutonium (as described in the chapter on Preventing Proliferation).

A 1997 task force of the Defense Science Board found that with a continued, comprehensive long-term program capabilities could be developed to deal effectively with nuclear terrorism over a wide range of possible scenarios. Throughout the process of building and transporting a nuclear device, there are signatures which can be exploited by improved intelligence, improved law enforcement operations, and enhanced detection capabilities. An improved posture to defend against the nuclear transnational threat includes many elements: information and intelligence, security, detection, disablement, mitigation, and attribution. A comprehensive program, developed within the overall architecture for responding to transnational threats, should integrate each of these elements

The Chemical and Biological Challenge

Chemical and biological agents share characteristics that make them especially grave threats. They are relatively easy to obtain, can be developed and produced with modest facilities and equipment, can be lethal even in small quantities, and can be delivered by a variety of means. But there are also substantial differences, which must be taken into account when devising strategies and postures to deal with the threats. For example, the effects of many chemical agents occur rapidly and present unique challenges for emergency response personnel. The effects of biological agents, conversely, may not be seen for many hours or even days; the first indication of an attack

may be victims arriving at hospitals. These differences between the numerous agents that might be used require that the response architectures be carefully developed, and recognize these distinctions.

There is no "silver bullet" in the fight against chemical and biological terrorism; the complexity of this problem requires the development of an architecture that broadly addresses the threat -from deterrence, to detection and response, to recovery and attribution. In each of these areas a robust capability is required that integrates operations and training with key technological components. The technological challenges in this area are legion - in many cases our ability to prepare and respond to the potential use of chemical or biological agents is constrained by the present state of technology.

The Infrastructure Protection Challenge

The facet of national security that involves protecting information and information systems that exist within the defense nuclear complex continues to expand in scope and complexity. Weapons design data must be carefully protected (confidentiality); the integrity of various forms of research data must be assured (integrity); and many systems that affect worker and public safety must not be disrupted (availability). Detection of unauthorized cyber activity, that may be distributed over time or geographical location, remains a true challenge for the technical and operational communities. The capability to respond to cyber attacks and to reconstitute affected systems requires tools and methods that provide understanding of how systems act and react under widely varying conditions.

National Context and Drivers

With the end of the Cold War, we are facing increased threats to the United States and its interests by organizations and individuals with motives and methods quite different from those posed to the nation during the era of confrontation with the former Soviet Union (FSU). Among these threats is international terrorism, often by groups without a traceable national identity.

There is a new and ominous trend to these threats: a proclivity towards much greater levels of violence. Transnational groups have the means, through access to weapons of mass destruction and other instruments of terror and disruption, as well as the motives to cause great harm to our society. For example, the perpetrators of the World Trade Center bombing and the Tokyo Subway nerve gas attack were aiming for tens of thousands of fatalities. These examples also indicate the intent of groups to radically alter a nation's political strategy and resolve.

A component of what makes these threats different is that they are difficult to deter, detect, and control. The difficulty of attribution that arises with transnational threats allows attacks against the United States and its allies that nation states would not risk directly for fear of retaliation. As such, national boundaries are not effective barriers and are used to the adversary's advantage. This situation results in the denial of an entire arsenal of traditional and well-developed political, diplomatic, and military strategies for addressing threats to our nation.

While deterring terrorism is not new to the Department of Energy, which has sustained a modest Nuclear Emergency Search Team (NEST) program within its Stockpile Stewardship and Management Program, the breadth of the weapons of mass destruction (WMD) terrorism problem and its overlap with nonproliferation programs is much greater than before the dissolution of the Soviet Union.

An effective response to these threats requires the interaction of the federal, state, and local law enforcement and emergency response agencies, the broader national security community, and the international community – agencies and parts of society that have had little history of integrated planning, strategy, or action. The collective efforts of these organizations will play an important role in increasing the nation's security against transnational threats. There are many customers for our technology.

Linkage to Goals and Objectives

The research and development performed for countering weapons of mass destruction terrorism is being performed in response to the National Security Strategic Goal, Objective 5, Strategies 2 and 3, of the U.S. Department of Energy Strategic Plan. Objective 5 is to continue leadership in policy support and technology development for international arms control and nonproliferation efforts. Strategy 2 addresses inspection systems capable of identifying radiation signatures of potential nuclear smuggling packages. Strategy 3 specifically addresses developing improved sensor systems for early detection, identification, and response to weapons of mass destruction proliferation and illicit materials trafficking.

The DOE has formulated a program of research and development that support U.S. Government requirements to respond to weapons of mass destruction terrorism and proliferation threats. The activity is responsive to the relevant Presidential Decision Directives that outline what the U.S. response must be.

Uncertainties

In the post Cold War era, there is a great deal of uncertainty due to the fact that significant amounts of surplus special nuclear material is under foreign control. In particular, the control of nuclear material in the former Soviet Union is problematical, considering their very poor economic conditions. One particular problem for reducing uncertainty is insuring the disposal of surplus weapons grade material under foreign control without direct access that would expose sensitive weapons design information. Sensors are needed which will ensure that the material is in fact surplus weapons material. Another source of uncertainty is that foreign commercial nuclear industries over which we have no control also generate nuclear material that can have weapons applications. Such material can be used not only by the nations operating the facilities, but could potentially find its way to transnational organizations. Packaging and a small amount of shielding can make detection of such materials difficult even in the controlled environment of border entry points. Nuclear material detection in larger areas, such as within a city, is even more difficult. Trained law enforcement officials, foreign and domestic, must be made willing and able to use the

sensor systems. Sensor systems with sufficient detection capability, simplicity of design, and reasonable cost must be developed. Even if illicit nuclear material is intercepted, we may not know who was responsible. This intercepted material must be analyzed for any clues to the source of the material so that countermeasures can be taken.

Developing technologies to respond to the proliferation and potential use of chemical and biological weapons presents many challenges and uncertainties. The range of chemical and biological agents available for the purpose of domestic terrorism is much broader than those previously studied in detail. Also, technologies and systems must be developed for users with minimal training, and with potentially unrealistic and shifting perceptions of the threat and our ability to respond.

With respect to organization and coordination, preparing a response to the domestic use of WMD presents unique challenges in that the organizations with operational responsibility, and those with scientific and technical capacity, reside in different sets of organizations. This will continue to require sustained coordination.

Investment Trends and Rationale

Approaches to reducing the threat from nuclear smuggling include both effective control of nuclear material at its source and detection of nuclear material in transit.

Foreign proliferation signatures can be similar to commercial activities or masked by large-scale commercial chemical production. Power production reactors can produce plutonium (Pu) and the Pu can be separated from the spent fuel. This makes it possible for third world countries with nuclear power reactors to produce weapons useable material.

The procedures used to obtain samples influences the outcome for any forensic analysis. Depending on the physical form of the signature, i.e., solid, liquid or gas, and the operational situation, different sampling protocols must be applied. Typically, forensic applications require the most rigorous protocols. In the case of most effluent species, careful consideration must also be given to approaches that will enhance sensitivity. The problem is further constrained by operational considerations that demand that sampling be quick, easy, simple, and efficient. Finding the optimum combination of sampling methods and conditions is a challenging problem to solve.

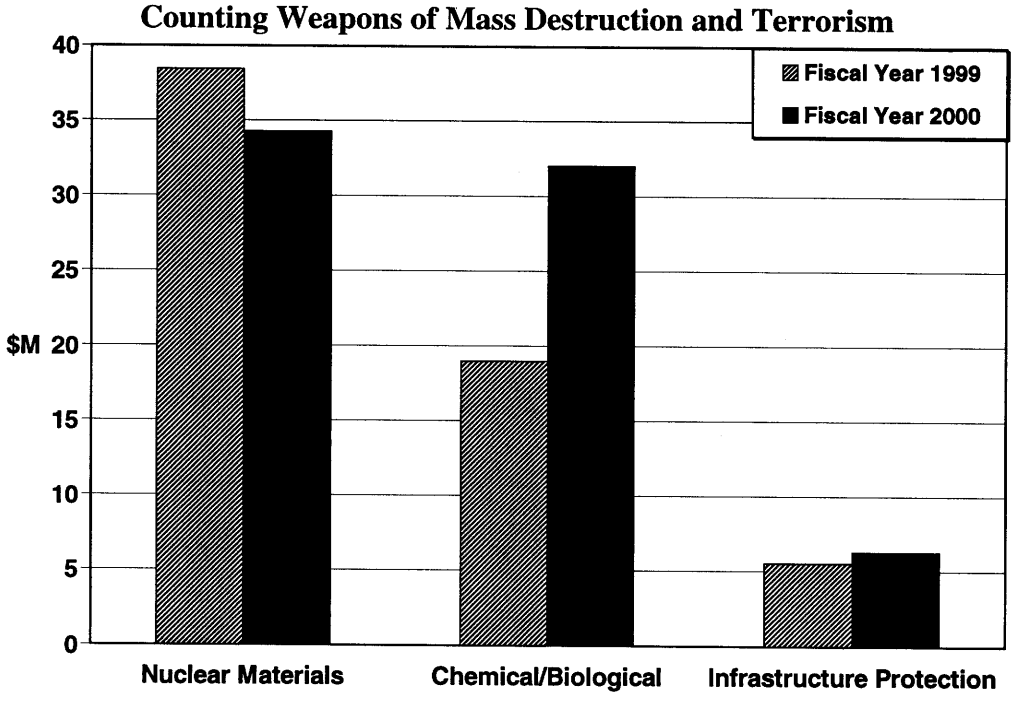
To protect large areas modular search systems, adaptable for either vehicle or fixed applications and incorporating next generation data processing and networking, as well as advanced detectors, must be developed. Present technology could, at best, provide a low probability of intercept. There is a need to develop a movable, rapidly deployable array of several hundred (perhaps even a thousand) networked sensor modules for nuclear search and screening over large areas and determining whether a network of multiple detectors is substantially better than the sum of its parts. Particularly of interest to technology development is an understanding of the scenarios against which detection equipment might be arrayed and their respective priorities.

A multi-faceted approach is being used because there are numerous aspects to reducing the nuclear threat. Our activity ranges from basic research to develop new high-resolution, room-temperature radiation detection materials to the development of small, smart systems that can be integrated to monitor a storage facility or provide a broad area intercept capability.

Existing radiation detectors use low-resolution materials or use materials that require cooling to liquid nitrogen temperatures. Some detectors provide the user the capability to detect radioactive material, but it is difficult to resolve the isotopic lines in order to identify the material, while others require excessive power or storage of liquid nitrogen to cool the detector. Any of these options make it difficult for the user in the field. For this reason, research goals include development of processes to routinely grow inexpensive, uniform material for use in next generation radiation detectors.

Investments in the areas of chemical and biological defense/nonproliferation/counterterrorism are increasing across the Government due to increasing concern over biological terrorism in particular. This is also true within the DOE where our budget request is significantly higher for Fiscal Year 2000. It is important to note that our investment in this technology area is heavily leveraged against existing biological/chemical expertise resident at the DOE national laboratories.

The chart shown below shows investments by activity areas that will be discussed in the remainder of this chapter.



Federal Role

National Security is a constitutional role of the Federal Government. DOE executes research and development activities associated with the detection of proliferation activities through the expertise and facilities provided at the national laboratories. A single laboratory may manage a program activity area. Alternatively, multiple laboratories may be involved in a program activity area. Inter-laboratory programs are managed from DOE headquarters. In turn, individual laboratories contract with other institutions, such as universities and industry. DOE establishes goals, provides guidance and direction in each program area, and in consultation with the laboratories, prioritizes the work and activities in each program area.

In the chemical and biological areas, at least at the present time, the Federal Government will play the primary role in developing terrorism response technologies. This is particularly true in the development of new technologies and systems for use in domestic preparation and response. As President Clinton recently stated: “there is no market” in the chemical and biological weapons area. This will likely evolve if the threat continues to increase, and after more equipment is available.

Key Accomplishments

The countering weapons of mass destruction terrorism research and development activity has made significant progress toward meeting its goal and objectives. Broad accomplishments include:

- A pager-sized radiation sensor system was developed and is being deployed extensively by Customs.
- Both personnel and vehicle special nuclear material (SNM) portal monitors were developed and commercialized.
- A DOE-developed handheld gamma ray and neutron material identification system was recently used by the United Nations Special Commission (UNSCOM) for Palace inspections in Iraq.
- A notebook-size time-of-flight mass spectrometer for detecting chemical compounds such as explosive residues was developed.
- Key miniaturized components were developed that will enable a hand-held chemical and biological toxin detector.
- The DNA sequencing of the virulence plasmids of the threat pathogens *B. anthracis* (anthrax) and *Y. pestis* (plague) were completed. These data provide new insight into the genes that are responsible for the action of these pathogens and are key components to identifying engineered organisms.

Nuclear Materials

Budget: FY98-$40.0M, FY99-$38.4M, FY00-$34.2M

Background

The long-range research and development strategy presented here addresses domestic and international safeguards and enabling technologies as well as nuclear smuggling and terrorism. The technologies are used close to the source (as opposed to remotely) and concentrate on nuclear material. Support includes technology for WMD detection, e.g., material analysis, environmental monitoring under new International Atomic Energy Agency (IAEA) protocols, or computer systems which might automate and link a network of detectors.

Program Description

The vision of the nuclear materials research activity is the development of enabling technology to inhibit nuclear materials diversion in nonproliferation and counterterrorism applications. The long-term R&D program is within the context of the overall DOE program for stewardship of nuclear weapons and materials. It is part of a comprehensive, end-to-end architecture for reducing the nuclear threat. It integrates capabilities to:

- Warn of nuclear materials transit,
- Analyze materials, including support to law enforcement agencies, and
- Detect and attribute the presence of nuclear materials.

The technology in the areas above is closely linked with the Department's activities to:

- Diagnose, access, disarm and render safe threat devices, and
- Respond to the consequences of a nuclear terrorist incident.

Warning of Nuclear Materials Transit

Budget: FY98-$22.5M, FY99-$20.9M, FY00-$18.4M

Description and Objectives. This activity is part of an integrated strategy for provision of technology to the intelligence community and international partners such as law enforcement. The aim is to detect illicit nuclear materials at points along an integrated pathway from the source, including source protection, to their application by an adversary. In this section we highlight our efforts for two applications:

- Transparent warhead and materials reductions.

- Detection of illicit nuclear materials traffic.

R&D Challenges. Research and development challenges for transparent warhead and materials reductions include:

- **Remote Means to "Measure" Bulk Amounts of Pu and HEU**—The technical challenges are to acquire data in choke points or perhaps even from outside facility boundaries using unattended sensors.

- **No "Net Production"**—The technical challenges are to gain confidence in Russian declarations of process flow, to distinguish between warheads and components in their dismantlement program and those associated with stockpile refurbishment, and to assure that operations within the stockpile refurbishment program do not mask a reconstitution effort.

As the U.S. and Russia proceed to lower warhead levels, we must be sure that previously dismantled nuclear weapons and weapons components, nonstrategic weapons, and fissile materials stockpiles cannot serve as the basis for rapid reconstitution of strategic nuclear forces. Russia has not reciprocated to previous DOE declarations of material inventories and locations. This is urgent given the substantial asymmetry in knowledge of each side's stockpile and because it will take time for reciprocal verification arrangements to build confidence in these declarations.

The technical challenges of verification and collection to support arms control agreements apply not only to Russia but to other nuclear states as well. Of course, the opportunities to access such information will vary from case to case. The accessibility and openness of travel within the U.S. makes locating transiting special nuclear materials particularly difficult because of the large number of locations that must be under surveillance, the large numbers of people and product crossing our borders, and the short detection range of existing nuclear detectors.

R&D Activities. The 1997 Defense Science Board Summer Study made several recommendations for improving the capability of U.S. and allied intelligence and law enforcement to detect transnational threat operations of all kinds, including nuclear. These include:

- Accelerated development of knowledge engineering tools, including a worldwide internet-like information system with contributions from and (managed) access for law enforcement and intelligence, world-wide.

- Particular focus on detecting nuclear threats because signatures of nuclear threat operations are likely to be larger and/or more exploitable than for other types of threats.

Accomplishments

- A pager-sized radiation sensor system was developed and is being deployed extensively by Customs and other law enforcement agencies in the U.S. and worldwide.

- Both personnel and vehicle special nuclear material (SNM) portal monitors were developed and commercialized. We continue to work with manufacturers and foreign governments to evaluate and deploy systems at border crossings and ports of entry.

- A DOE-developed handheld gamma ray and neutron material identification system was recently used by the United Nations Special Commission (UNSCOM) for Palace inspections in Iraq.

Materials Analysis

Budget: FY98-$10.4M, FY99-$10.7M, FY00-$9.7M

Description and Objectives. International sanctions and law enforcement require solid evidence. The materials analysis activity element seeks to advance the state-of-the-art in the detection and analysis of activities that threaten the National Security and the public safety by identification and quantitative measurement of chemical and physical signatures. Historically, the focus has been on nuclear proliferation by nation states. Although this remains a valid concern and the mainstay of the activity, the scope of our activity has recently been broadened to include the potential for deployment of WMD by sub-national (terrorist) groups and assistance to law enforcement agencies under the Statement of Principles signed by the Secretaries of Energy and Treasury and the Attorney General. By definition, analyses that provide information suitable for a policy decision or a court of law are “forensic” in nature. Many of the technologies developed under the materials analysis activity are targeted toward forensic applications or ultimately will be applied in that manner.

The research and development approach to deterring proliferant or terrorist activities has two principal components: the identification of potential signatures and the application of useful analysis techniques. These requirements are addressed through improved understanding of WMD production processes, by the development of enabling analytical technologies, and by coupling state-of-the-art techniques in sample collection, analysis, and data reduction.

Over the last 50 years, signature analysis has evolved from simply using available analysis capabilities and relatively random samples to the development of application specific technologies and well-coordinated sampling efforts. The nuclear materials analysis activity exploits not only the world class intellectual and physical assets of the DOE Laboratories, but also their unique understanding of nuclear and chemical materials, as well as their broad experience with proliferation and terrorism issues. R&D needs in four areas are addressed:

- Selection of useful signatures.

- Development of improved sampling methods.

- Development of new analytical instruments and improved procedures.

- Evaluation of analysis technologies.

R&D Challenges. Research and development challenges related to development of alternative signatures are due to a number of changing operational and analytical considerations. There is a continuing need to evaluate the efficacy of new or different signatures. The drive for alternate signatures and for improved sampling are being driven by:

- Countermeasures by proliferants or terrorists to suppress the signatures generally known through international (e.g., IAEA, UNSCOM) fora.
- The need to acquire samples from more remote locations.

Research and development challenges related to improved sampling methods are constrained by operational considerations that demand sampling be quick, easy, simple, and efficient. Aside from quantitative analysis, sampling must often address collateral informational needs such as the dating of materials and processes or establishing the chronology of certain proliferation activities. Such concerns can have a significant influence on what is collected along with the species of interest, as well as how it is collected (e.g., instantaneous versus long term). Actually finding the optimum combination of sampling methods and conditions is not trivial nor is it often intuitively obvious.

Research and development challenges for advanced analytical technologies stem from the principle requirements for new technology: miniaturization and field application. Examples of specific needs are:

- Developing forensic methodology for nuclear contaminated materials.
- Identifying trace metals and the origin of seized nuclear materials.
- Developing an architecture for a grid of samplers within a geographic region to obtain environmental samples.
- Achieving high sensor sensitivity in cluttered backgrounds with low false alarm rates.
- Developing portable, high sensitivity devices that will allow inspectors to screen environmental samples and select only the most promising ones for return to the laboratory -- resulting in more rapid and less expensive laboratory analyses.
- Deriving secondary information (e.g., age, sex, tobacco or drug use) from fingerprints.

Research and development challenges for performance evaluation is related to what is perhaps the most important facet of technology developments, testing the product of these R&D efforts against realistic sources or samples. This serves three purposes. First, it provides valuable feedback to the development cycle that can be used to refine the technology. Second, it gives potential users an opportunity to assess the technology. Third, it generates “real” data that can be used to improve interpretation of results and to enhance attribution techniques.

R&D Activities. The "life-cycle" of a nuclear or chemical weapon starts with the procurement of the raw materials, proceeds to the production of special nuclear material (SNM) or chemical agents to weaponization and implementation of a device. There are many possible chemical signatures of both nuclear and chemical weapons, but the tendency has been to concentrate analysis efforts on a small subset. Even analytic applications tend to avoid trying to measure every possible chemical species; opting instead to strike a balance between the analysis effort required and the amount of information obtained.

With any chemical analysis, the way in which samples are obtained directly influences the outcome. Depending on the physical form of the signature (i.e., solid, liquid, or gas) and the operational situation, different sampling protocols must be applied. Typically, analytic applications require the most rigorous protocols. In the case of most effluent species, careful consideration must also be given to approaches that will enhance sensitivity. Fortunately, selectivity and sensitivity tend to be compatible goals when developing sampling methods.

A variety of modern analytical instruments, including mass spectrometers as well as a host of other devices and systems, provide the means to meet many (but not all) requirements for sensitivity and selectivity, from small, hand-held devices to large, laboratory instruments. Today, the many unique applications found within the nuclear materials analysis activity continue to drive the need for R&D in this area with particular emphasis on miniaturization and a subsequent shift toward handheld or portable systems. This is particularly true of some forensic applications that are starting to move from their traditional laboratory environments to the field in order to provide more real-time information. There is also a need for improved methods for detecting stable elements and compounds.

The IAEA's Strengthened Safeguards System is generating a new set of requirements for "environmental" monitoring to detect the clandestine production of weapons grade material either by reprocessing or enrichment. Field trials have begun within declared nuclear facilities with nearly 1,500 samples obtained as "swipes" and a wide network of trusted laboratories to analyze the samples in order to obtain baselines. The cost per sample was said to be $5K to $10K. Ultimately it will be the application to wide area sampling which provides assurance against clandestine activities.

Accomplishments

- A new thermal model for characterizing nuclear reprocessing facilities has been developed and successfully tested.
- Stable rare gasses have been used to model nuclear fuel types, burnup, and other attributes.
- Specialty absorbent materials have been designed and produced for specific chemical compounds indicative of proliferation.

- A unique magnetic separation method has been developed for removing micron-size particles of SNM from large samples prior to analysis.
- A notebook-size time-of-flight mass spectrometer has been developed for detecting chemical compounds such as explosive residues.
- The first and only flow-through radioactivity detector for the capillary electrophoretic analysis of low level liquid samples has been developed.
- A prototype hand-held gas chromatograph that can analyze gas samples at field locations such as crime scenes has been produced.
- A prototype portable Raman Lidar system was fielded in a recent terrorist exercise in New York City, demonstrating the ability to identify an unknown chemical at a distance of 15 meters in a driving rainstorm.
- A cooperative environmental sampling effort overseas has led to the validation of a “new” proliferation signature.
- Samples of opportunity associated with ongoing criminal investigations (e.g., Unibomber) have been analyzed using unique capabilities developed under the nuclear materials analysis activity.

Detect and Attribute Nuclear Materials

Budget: FY98-$7.1, FY99-$6.8, FY00-$6.1M

Description and Objectives. A system of integrated technologies will be required to prevent the introduction of nuclear materials into the U.S. and to prevent its application against U.S. interests. Our R&D highlights developments in two areas:

- Systems of detectors to cover larger areas.
- Next generation detectors.

R&D Challenges

- Developing modular search systems adaptable for vehicle or fixed application that incorporate next generation data processing and networking capability as well as advanced detectors.
- Developing a movable, rapidly deployable array of several hundred (maybe even a thousand) networked sensor modules for nuclear search and screening over large areas and determining whether a network of multiple detectors is substantially better than the sum of its parts.

- Operational issues of cost and response time/capability. In the long term, a network or modular search systems would be based on advanced detectors and methods developed in the activity described below. Particularly of interest to technology developers is an understanding of the scenarios against which detection equipment might be arrayed and their priority.

- Developing smart detectors to eliminate false and nuisance positives - emphasis on room-temperature operation, reduced size and unit costs, and automated spectral analysis.

- Miniaturizing detectors (e.g., a pager-sized neutron detector), while achieving enough nuclear cross-section in small size.

R&D Activities. Today, assets to detect and localize terrorist nuclear materials or explosives can be effectively deployed only at restricted choke points (e.g., ports of entry) or with warning that closely specifies threat location and time. It would be desirable to have continual coverage of much larger areas (e.g., cities) as might be done with large arrays of detectors or perhaps with fewer mobile detectors that could sweep large areas rapidly. However, high false alarm rates have made large arrays of non-specific detectors impractical. In addition, end-game detection demands close connectivity between operations and technology. Recently, however, progress has been made in ameliorating this problem by using a network logic that correlates “hits” among a large number of detectors, thereby filtering out most false alarms. This, in combination with the potential for improvements in individual detectors of various kinds, for the first time opens the serious possibility of “terminal defense” of larger areas than practical today. Although the Defense Science Board alleged a good chance that such capabilities can be developed, this concept still requires significant R&D and will require substantial investment to demonstrate.

The next generation of detector technologies will enable smaller, smarter, less expensive radiation detectors. These detectors will have the capability to detect and identify nuclear materials either as hand-held or remotely emplaced instruments. This enables not only detection and interdiction of stolen nuclear material (e.g., at U.S. and foreign borders) but also enforcing arms reduction agreements and safeguards applications. A managed mix of both evolutionary and high-risk technologies is appropriate.

Accomplishments

- Radiation detectors have been deployed at several U.S. ports of entry for limited amounts of time in order to determine which radioactive materials are seen in normal commerce. Knowledge of this background is necessary for development of systems with low false alarm rates.
- The GN-4 handheld gamma ray and neutron system has the capability to automatically identify nuclear materials. This system has been commercialized as the Quantrad Ranger.

Responding to Chemical and Biological Proliferation

Budget: FY98-$19.0M, FY99-$19.0M, FY00-$32.0M

Background

An important goal of the DOE research and development program is to reduce the U.S. vulnerability to the use of chemical or biological agents through the development of advanced technologies and capabilities. A key element of the program is the formulation of architectures that bring together operational and technological components to develop systems that address key elements of the chemical and biological threats. This effort builds upon ongoing efforts in other agencies, and addresses key areas in which the DOE has expertise.

Program Description

Preparing and ultimately responding to the use of chemical or biological agents is a complex problem to which there is no "silver bullet." While production of large quantities of the traditional chemical and biological agents would require a substantial effort and investment, production of small quantities, or the procurement of toxic species not generally considered to be "traditional" chemical or biological agents is not difficult. Small quantities of agents, or use of non-traditional agents, are likely to constitute the terrorist threat. This threat presents enormous challenges. The quantities of agents are small and the possible spectrum of agents is broad, presenting formidable detection difficulties. The operational issues for responding to chemical or biological events involving civilians are formidable and are distinct from the issues the military faces where training and equipment are readily available. Finally, recovery and cleanup will present new difficulties in urban areas.

Because of these challenges, chemical and biological terrorism is most effectively addressed in an end-to-end, layered approach. Such a layered approach must involve deterring the use of such weapons, preparing key facilities and cities for the possible use of such agents, having systems in place to rapidly detect the use, and should use be detected, being able to effectively respond. Finally, following an incident we must be able to restore contaminated land, facilities and equipment and to conduct the forensic analyses that would be required for investigation and attribution.

The DOE program has three key components:

- The development of architectures to comprehensively consider how to best prepare and respond. For example, how does one best protect, and ultimately respond, to the use of chemical or biological agents in subway systems? In airports? During sporting events?

- The use of accelerated programs to field the best available systems and technology to meet these needs defined during development of the architecture.

- The development of key technologies that are required for effective preparation and response at various phases of a threat scenario, including pre-incident intelligence, monitoring and warning of agent use, initial response to a release, post-release restoration and attribution.

Understanding the spectrum of preparation and response possibilities in dealing with each phase is critical to developing effective systems. Candidate system concepts in each of these phases are developed in concert with prospective end users of the system (e.g., local "first responders," law enforcement, intelligence agencies).

DOE has developed a five-year plan in which R&D at the DOE laboratories is guided by system concepts that address both operational and technological factors. These system integration efforts, including both existing and emerging technologies, will result in fielded prototype systems targeting the principal phases of a chemical or biological threat scenario. Over the next 3 to 4 years we anticipate fielding systems in four areas:

- Preparation and response for key infrastructure assets.
- Crisis and consequence management for special events.
- Recovery and restoration for domestic facilities.
- Forensics and attribution.

These system integration efforts form a baseline for follow-on systems in which improved technologies would be incorporated, as they become available. Initial efforts are currently underway in the first two areas, which will be described below.

Identification of Needs

In formulating the DOE program we worked closely with other Federal agencies and with representatives of state and local emergency response organizations to clearly define the shortfalls in existing capabilities, with emphasis on areas where technology could make a difference. This process included representation from the Department of Defense, the Intelligence Community, the Public Health Service, the Federal Emergency Management Agency, the Department of Justice and the Federal Bureau of Investigation, the Department of Transportation, and others. Some of the key technology needs identified through this process are shown below:

- **Detection**—Need for detectors that are suitable for a broad spectrum of agents, and subject to minimal false alarms. Need for improved sample collection techniques. Additional requirements include being inexpensive and portable. Need for new technologies to enable detection of agent production or transport.

- **Prediction**—Need for models that can accurately and rapidly predict the dispersion of chemical and biological agents in urban areas.

- **Restoration and Recovery**—Need for environmentally sensitive decontamination techniques with minimal logistics tails. Need for non-aqueous techniques. Need for new techniques to rapidly decontaminate personnel.

- **Protection**—Need for improved personal protection equipment that enable personnel to operate for longer periods of time.

- **Therapeutics**—Need for improved vaccines and therapeutics for many biological agents.

- **Forensics**—Need for more detailed understanding of the DNA/RNA structure of many pathogens to enable strain identification and differentiation. Need for new techniques to rapidly screen samples. Need for collection of samples from throughout the world. Need for improved epidemiological systems to identify anomalous outbreaks.

- **Systems Analysis**—Need for detailed analysis of how to optimally prepare and respond across the threat timeline. Need to understand the role of technology in these operations.

This list of needs has proven valuable in structuring an R&D program around a few integrating themes, described in the next section. Each theme consists of a complementary set of projects that address selected needs from the above list. The overriding goal of the program is to provide high-payoff solutions in 3 to 5 years from the start of an initiative. This perspective differentiates the DOE program from other important Federal activities such as the Chemical and Biological Defense Command Domestic Preparedness Program and the Technical Support Working Group (TSWG) Counterterrorism Program. These programs target incremental contributions that can be made rapidly, typically in the 12 to 18 month time frame.

R&D Challenges to Meeting Needs

The program is structured to capitalize on existing DOE technical strengths in developing capabilities that can have a major impact in the preparation and response to chemical and biological incidents.

Addressing the needs shown above presents many R&D challenges. In focusing the DOE program, primary consideration was given to areas in which the DOE has substantial expertise. The relevant expertise stems from DOE's historical investment in R&D that supports its primary nuclear mission; this amounts to over $1 billion/year in the chemical and biological sciences, sensor technologies, and computation at its national laboratories. These programs range from micro-sensor development, to DNA sequencing for the Human Genome Project, to advanced computing used to predict the transport of toxic gases. Together they constitute the technical foundation for the DOE chemical and biological program. In addition, the program builds upon the work supported by other agencies. These efforts, particularly those supported by the DoD,

have made major strides in recent years. The DOE national laboratories receive over $50 million/year from other agencies, specifically in the chemical and biological defense area.

Many other Federal programs are also addressing this important problem. To avoid duplication of effort, several areas initially identified as candidate areas for the DOE program were not included. For example, the program is not pursuing R&D in protective equipment, personal decontamination, or therapeutics. The program that ultimately resulted from the capabilities/needs assessment is structured around four focus areas—Biological Foundations, Modeling and Prediction, Chemical and Biological Detection, and Decontamination and Restoration.

These four areas, along with their associated R&D challenges and initiatives created by the DOE program to address the challenges, are described below.

Biological Foundations

Budget: FY98-$5.0M, FY99-$5.0M, FY00-$9.0M

Description and Objectives. The goal of this initiative is to develop the ability to identify, at the strain level, biological pathogens of concern; to determine their geographical origin (where possible); and to track the spread of diseases on a molecular level. A secondary goal is to develop the underlying biological science that will support the detection and treatment of biological agents.

R&D Challenges. Significant challenges exist for the analysis of samples containing biological agents. This area is still in the early stages of development, but is moving forward rapidly with the advent of new DNA analysis techniques. These techniques are able to identify specific strains of biological agents that can suggest the source of the sample. Computational tools are also required to enable the tracking of the spread of a communicable disease (i.e., molecular epidemiological tools); such techniques can allow the reconstruction of an epidemic that might be started with a terrorist event. Finally, a significant effort is required in mapping the worldwide distribution of the strain variation of organisms that might be used as biological agents; knowledge of this distribution will be essential in understanding the possible origin of a biological agent.

R&D Activities. This work builds upon DOE capabilities in DNA sequencing and in the advanced light sources used for structure determinations. Ongoing work in this initiative can be divided into three broad-based efforts: Nucleic Acid-based Signatures, Toxin Structural Signatures, and Molecular Epidemiology and Tracking. Within three years the program will develop the capability to geo-locate samples of the top two threat pathogens and to partially locate an additional six pathogens, and will have an initial capability to recognize engineered organisms.

Accomplishments. Over the last 12 months we have completed the DNA sequencing of the virulence plasmids of the threat pathogens *B. anthracis* (anthrax) and *Y. pestis* (plague). These data provide new insight into the genes that are responsible for the action of these pathogens.

Modeling and Prediction

Budget: FY98-$3.0M, FY99-$3.0M, FY00-$4.0M

Description and Objectives. The ability to predict accurately the dispersion, concentration profiles, and ultimate fate of chemical and biological agents released into the environment is fundamental to safeguarding human life and to the effective operation of emergency response teams. A modeling capability must thus be able to accurately predict the transport and fate of chemical or biological agents in a multitude of scenarios that might occur in an urban environment.

R&D Challenges. Methods of predicting atmospheric dispersion are commonly applied on transport scales of hundreds of meters to several kilometers over simple configurations of terrain and surface obstacles. However, the particular needs of predicting, diagnosing, controlling, and responding to clandestine chemical/biological releases in the urban setting, with complex building configurations, present formidable modeling challenges.

Computational fluid dynamics models of the highly distorted wind and turbulence fields created by complexes of tall buildings, subway tunnels and other urban structures are in the very early stages of development and application. Models of airflow inside buildings and subways have been developed to some degree but do not incorporate deposition losses to interior surfaces, a large effect due to the high surface to volume ratios. A comprehensive knowledge base of surface phenomena and agent/analyte deposition and fate, including chemistry and bio-agent viability, must necessarily be incorporated into these capabilities. In addition, there is a need to couple the predictive model results at different scales (e.g., around building transport to interior building transport) and different levels of model complexity (e.g., three-dimensional subway station flow to parameterize subway system transport involving tunnels and other stations). And finally, the acute nature of clandestine events places severe requirements on the timeliness and accuracy of transport and fate model predictions of exposure at all spatial scales.

R&D Activities. This effort builds upon substantial investments by DOE at its national laboratories in high-performance computing. The modeling effort is aimed at developing a robust, operational modeling capability suitable for use in urban areas. Work in this area includes model development for building interiors, subways, outside in urban areas, and the linking of these models. Crosscutting issues, including understanding the deposition of chemical and biological agents and their fate under typical conditions, are also being investigated. Together, advancements in these areas will enable accurate predictions of the extent and impact of a chemical or biological incident. Within two years we expect to be able to use these models to provide guidance for incidents in subways and buildings, and within five years expect to have the outdoor urban models incorporated into an operational, validated system (e.g., National Atmospheric Release Advisory Capability--NARAC).

Accomplishments. We have performed numerous computer simulations of chemical and biological releases in urban areas, both indoors and outdoors. We have provided some of the first data on the exterior effect of *indoor* chemical and biological releases. Authorities responsible for emergency planning for subway systems are currently using these data.

Chemical and Biological Detection

Budget: FY98-$7.5M, FY99-$7.5M, FY00-$12.0M

Description and Objectives. The goal of this initiative is to develop a suite of detection systems that will significantly improve the domestic chemical and biological detection capability. Implicit in this goal is a recognition that there is no "silver bullet" and that detection systems must be suitable for use with the many chemicals and biological species that might be used as agents.

R&D Challenges. The challenges in this area are legion, and are as difficult, or more so, to address as those encountered when developing detectors for use on the battlefield. The counterterrorism mission must deal with a broader set of agents—unlike the battlefield mission, the set of potential agents is not limited by factors such as weaponization, large scale production, stockpiling, or delivery systems. The terrorist is free to choose from well over 100 potential agents. Because one cannot predict in advance which agent(s) might be used, any effective detection system must identify a wide range of agents, and be able to easily add new agent detection capabilities based on intelligence sources. In addition to having high sensitivity, detectors to be used domestically have very demanding false positive requirements. Law enforcement personnel are unwilling to accept false positives that might lead to the evacuation of subway stations or large office buildings, for example. Simple calculations demonstrate that in order to monitor for chemicals continually for a year over 100 million individual measurements will be made. Over this time period, even one or two false alarms may not be acceptable. Finally, in many cases there is minimal supporting infrastructure domestically. This places significant constraints on the cost, ease of use, and maintainability of detection systems.

R&D Activities. This work builds upon DOE advances in laser technology, capabilities in micro-fabrication, and work in the development of DNA-based diagnostics. Key efforts include the development of: an autonomous biological agent detector, a DNA fragment-sizing system, a hand-held chemical agent detector, and an improved mass spectrometer. These efforts are directed at the development of a suite of portable, modular instruments that cover a significant portion of the "threat space" when operated singly but provide greater coverage and lower false alarm rates when operated in combination. Each instrument detects different but somewhat overlapping portions of the chemical-biotoxin-pathogen threat space and detects a different physical property, thereby providing independent confirmation when two or more techniques identify an agent. The different techniques also differ in their level of technical maturity, risks and benefits and comprise a well-balanced detection portfolio.

Accomplishments. Advances have occurred in several areas of our detection initiative. Key components have been fabricated for our "chemical laboratory on a chip" project. New detection limits were demonstrated in a field trial involving a miniature polymerase chain reaction (PCR) amplification-based detector. Advances have been made in our ability to rapidly differentiate strains of biological agents. Finally, calibration of a wind-tunnel facility is complete and detector testing is now possible in a realistic, controlled environment.

Decontamination and Restoration

Budget: FY98-$2.0M, FY99-$2.0M, FY00-$3.0M

Description and Objectives. The objective of environmental decontamination is rapid, effective and safe (non-toxic and non-corrosive) treatment of a range of chemically or biologically contaminated surfaces. This treatment should result in the complete restoration of contaminated areas (e.g., facilities and large urban areas) and equipment to normal operation. In addition, it is desirable to have a single formulation for use on the entire range of chemical and biological hazards. Such a formulation and/or reagent should be deployable in various delivery systems (e.g., liquids, sprays, foams, gels, gases). Ideally, these systems will be readily transportable and operationally simple to use. Additionally, systems will need to be developed and implemented which allow for field and/or laboratory verification of acceptable clean-up criteria. The establishment of realistic clean-up criteria will drive the decontamination technology to be chosen for a specific field application.

R&D Challenges. There are numerous R&D challenges in the safe and effective decontamination of urban facilities. A key issue is to develop a formulation that will destroy (or detoxify) hazardous chemicals or pathogens, but will be harmless to both people and property and/or degrade to harmlessness in a reasonable period of time. Additional constraints are imposed by the desire to have a common formulation that would be suitable for all chemical and biological agents, as well as being effective for a variety of construction materials. There are major logistical and operational issues to which any new technology must be sensitive. For example, different applications (e.g., outdoors, semi-enclosed, indoors, sensitive equipment) will require different dispersal mechanisms and/or methods, including liquid-based, gas-based, gel-based, and foam-based systems. Any proposed reagent must be deployable in a variety of such systems, with easy-to-use delivery systems. Even new technologies, such as plasma-based and/or other energy driven systems, will require simple operating procedures in real applications.

Finally, it will be important to develop appropriate sampling and analysis methods that can be used to show the adequacy of decontamination as it proceeds. These techniques must be able to determine the extent of contamination on a multitude of materials in reproducible ways.

R&D Activities. Existing efforts in the program focus on methods that are minimally corrosive and yet effective for decontamination. The present effort includes the development of improved reagents, the development of improved delivery systems (e.g., gels and foams), the development of new decontamination techniques such as plasmas, and a program to address the environmental issues that will require attention. Over the next three years systems will be fielded that will be suitable for decontaminating sensitive, exposed surfaces.

Accomplishments. We have developed a number of new decontamination technologies, including a revolutionary decontamination plasma jet that is suitable for sensitive materials and is environmentally benign. Additionally, major advances have been made in the incorporation of new reagents into foams and gels.

Systems Analysis and Technology Integration

Budget: FY98-$1.5M, FY99-$1.5M,

Description and Objectives. Much has been written about the vulnerability of the U.S. to a chemical or biological attack and the potential consequences. Currently lacking, however, is a coherent analytical structure for characterizing the threat (over ranges of magnitude, distribution, and agent), developing preparedness and response options, assessing the performance of various capabilities against various threats, and finally deciding on investment priorities. Systems analysis is the program element that takes on these tasks.

R&D Challenges. As mentioned above, a key component of the DOE program is the development of system architectures for specific preparation and response applications. An architecture defines the roles of infrastructure, operations and technology in responding to the threat. It also serves as a structure for determining how multiple technologies should be integrated into an overall system. In making this assessment, system performance objectives are clearly defined and tradeoffs among system elements are explored to arrive at an optimal balance. The systems perspective encompasses the entire *threat-response timeline*, from threat monitoring prior to an incident to cleanup and attribution that could occur much later. The various phases of the timeline and examples of response elements in each phase are shown below:

- Intelligence and Prevention
  –Background monitoring of key threats
  –Denial
  –Deterrence/interdiction

- Crisis Management
  –Incident detection
  –Source localization
  –Impact assessment
  –Device disablement

- Consequence Management
  –Damage/contamination assessment
  –Evacuation and protection
  –Medical treatment
  –Decontamination and restoration

- Forensics and Attribution
  –Identification of agent and its source

The overall success of any preparedness and response system architecture depends on the effectiveness of each of these response elements. This effectiveness, in turn, depends on R&D, training, and acquisition decisions made in each element. Indeed, the system ultimately implemented is determined by the resources allocated to areas such as training, monitoring and

mitigation systems, medical supplies, and equipment for intelligence gathering, emergency response, law enforcement, and clean-up.

R&D Activities. We have identified four application areas for developing initial system concepts:

- Protection and response to incidents in key facilities.
- Protection and response during incidents at "special events".
- Recovery and restoration of urban facilities.
- Forensics and attribution.

Of these, the first two efforts are currently supported to develop initial concepts and tools in conjunction with prospective users of the systems. These efforts are designed to look comprehensively at particular elements of the response system, and to develop the most effective response strategy, while drawing on the best available technology. Each of these systems will provide "application pull" to help guide technology development efforts underway in the four R&D thrust areas. For example, the two current protection and response systems draw on the modeling thrust area for plume dispersal prediction. In addition, concepts are being developed for making best use of information likely to be available from sensors such as those under development in the detection thrust area. DOE's two current system integration efforts are described below.

Protection and Response to Incidents in Key Facilities. The objective of the Program for Response Options and Technology Enhancements for Chem/Bio Terrorism (PROTECTS) project is to field technologies and analysis tools that will support protection of "at risk" facilities; the pilot study focuses on the Washington Metro subway. Our current assessment confirms the nation's subway systems are not prepared to detect or respond to chemical and biological threats. By studying and modeling the problem, we are supporting sensor development and integration and the development of decontamination technologies, so that by the year 2001 there will be an integrated sensor network at five subway stations, with interior modeling and prediction codes linked to those sensors. Lessons learned from the project will be transferred to all subway systems in the United States.

Protection and Response During Incidents at "Special Events." The objective of the Crisis/Consequence Management Information System (CCMIS) project is to provide one system to a major city to protect special events and determine alert conditions. Currently, state and local authorities have no means for detecting biological agents and predicting the subsequent hazard zone. For many situations, Federal assets may not be able to react quickly enough to be able to sufficiently limit casualties. This effort includes systems architecture development, sensor development and integration, modeling, and testing regimes, so that by the year 2002 the following will be available:

- A bio-sensor network with 100 to 150 sensors.
- Urban hazard assessment models that receive and process sensor inputs.
- Integrated planning tools, databases, and communications tools needed to support the network.

Work on the following systems will begin in FY 2000 with the increased funding requested in the Department's FY 2000 budget.

Recovery and Restoration. The objective of this effort is to field a recovery system capable of restoring a medium-sized building and then to transfer the system to local or Federal authorities. Currently, there is no national capability for efficiently restoring an urban facility that has come under chemical or biological attack, nor are the required clean-up standards known. Beginning with design studies, and progressing through testing and evaluation of both sensors and decontamination technologies, this effort will provide a first generation capability by 2003.

Forensics and Attribution. The objective of this effort is to provide law enforcement personnel with the ability to establish within 48 hours the regional origin of the most threatening biological pathogens. Currently, there is a very limited ability to determine the origin of a pathogen, and several weeks of testing and analysis are required before results can be known with confidence. Biological strain variation of the leading pathogens and their regional variations and background levels will be studied, and through work in microbial genomics, low-cost, rapid signature identification technologies will be developed for those agents. By 2003, we anticipate a capability that will allow geo-location of two of the top pathogens, partial geo-location of six additional pathogens, and an initial capability to recognize engineered organisms.

The R&D initiatives are designed to develop the key capabilities required for technology integration efforts that culminate in a fielded capability. In addition, the R&D initiatives will result in single instruments or capabilities that will have utility outside of the particular technology integration efforts pursued under this program.

The technology integration efforts bring together the best available technology in the context of architecture development to address particular capability needs. They will draw upon DOE technology as well as commercially available technology to form the fielded capability. It is expected that there will be follow-on generations of these programs as our technology development efforts mature.

Critical Infrastructure Protection

Budget: FY98-$5.9M, FY99-$5.5M, FY00-$6.3M

Background

Recent attention has been focused on cyber security of the nation's critical infrastructures through the efforts of the President's Commission on Critical Infrastructure Protection. Their report,

entitled “Critical Foundations - Protecting America’s Infrastructures”, documents the increasing risk associated with cyber vulnerabilities in our critical infrastructures.

The United States is in the midst of a tremendous cultural change - a change that affects every aspect of our lives. The cyber dimension promotes accelerating reliance on our infrastructures and offers access to them from all over the world, blurring traditional boundaries and jurisdictions.

Program Description

DOE has an important role to play in defense against cyber threats - collecting information about tools that have the potential to do harm, conducting research into defensive technologies, and sharing defensive techniques and best practices. Access to classified information on computers by foreign nationals is prevented by several methods. Our classified and unclassified computing environments are kept physically separate. Data transfer of classified information is both administratively and technically protected. In the sensitive unclassified environment, both technical and administrative controls are placed on sensitive unclassified information residing on computers.

Network security is undergoing continuous re-evaluation, and necessary enhancements are implemented regularly. For example, in response to changing threats to information resources from Internet users, one can place the entire unclassified computing environment behind a restrictive firewall. This change can be accompanied, for example, by the replacement of static passwords with dynamic one-time passwords from a "smart card" to provide another layer of protection. Other significant security enhancements can be provided with this change as well, including enhanced hacker monitoring, and use of encryption. When a new network server is installed, the institutional default can be that the system be behind this firewall to prevent unauthorized access unless the owner can establish that the system will not handle sensitive information and is required to be truly "open" for programmatic reasons.

Description and Objectives. The facet of national security that involves protecting information and information systems that exist within the defense nuclear complex continues to expand in scope and complexity. Weapons design data must be carefully protected (confidentiality); the integrity of various forms of research data must be assured (integrity); and many systems that affect worker and public safety must not be disrupted (availability). Detection of unauthorized cyber activity, that may be distributed over time or geographical location, remains a true challenge for the technical and operational communities. The capability to respond to cyber attacks and to reconstitute affected systems requires tools and methods that provide understanding of how systems act and react under widely varying conditions.

R&D Challenges. As mentioned in the report by the President’s Commission on Critical Infrastructure Protection:

> "A satchel of dynamite or a truckload of fertilizer and diesel fuel have been frequent terrorist tools. The explosion and the damage are so certain to draw attention that these kinds of attacks continue to be among the probable threats to our infrastructures. Today, the right command sent over a network to a power generating station's control computer could be just as effective as a backpack full of explosives, and the perpetrator would be harder to identify and apprehend.
>
> The rapid growth of a computer-literate population ensures that increasing millions of people possess the skills necessary to consider such an attack. The wide adoption of public protocols for system interconnection and the availability of "hacker tool" libraries make their task easier.
>
> While the resources needed to conduct a physical attack have not changed much recently, the resources necessary to conduct a cyber attack are now commonplace. A personal computer and a simple telephone connection to an Internet Service Provider anywhere in the world are enough to cause a great deal of harm.
>
> Of the many people with the necessary skills and resources, some may have the motivation to cause substantial disruption in services or destruction of the equipment used to provide the service."

The DOE cyber security program faces many dynamic and complex challenges involving critical government functions that impact national security. These challenges include:

- The detection of unauthorized cyber activity that may be distributed over time or geographical location is important.
- The interconnectivity of computer systems makes it increasingly important to prevent and detect unauthorized access to computer systems due to many processes and systems being threatened by one unauthorized user.
- The dynamics of the computer industry cause currently available detection tools to become quickly outdated and thus there is a constant requirement to remain on the cutting edge.
- The proper technologies must also be in place to prevent an insider from adverse activities.
- The capability to respond to cyber attacks and to reconstitute affected systems, through the development of tools and methods that provide an understanding of how systems act and react under widely varying conditions, is essential.

R&D Activities. DOE activities are directed towards:

- Developing an automated information system that will detect anomalous activities on a computer network and automatically respond to mitigate any potential damages.
- Developing advanced tools and technologies to detect/prevent penetrations to computer networks.
- Providing a low-cost experience-based training for network system administrators.
- Providing technical assistance on current threats to DOE information networks.
- Determining mitigation strategies.

Accomplishments. In no other area do technology-based vulnerabilities and solutions "leap-frog" each other as rapidly as in the world of information technology. Examples of DOE accomplishments fall in the following areas:

- Automated security profiling tools to assess general system security parameters.
- Network intrusion detection tools.
- Computer Incident Advisory Capability (CIAC) services.

Several tools and documents have been created as part of funded DOE projects. These tools tend to be finished products, developed for a particular program or, alternatively, for the DOE at large. Programs such as SPI-Net (Security Profile Inspector for Networks), SSDS (Secure Software Distribution System), and NID (Network Intrusion Detector) fit in the later category. Not all of these tools are available to the general public.

The Security Profile Inspector for Networks (SPI-Net) software product provides a suite of security inspections for most Unix systems at the touch of a button. This security inspection suite includes Quick System Profile, Access Control Test, Binary Authentication Tool, Password Security Inspector, Change Detector Tool, and Promiscuous Mode Checker. The Security Profile Inspector is a vulnerability and intrusion detection tool for both Microsoft Windows NT and UNIX systems. Among its features, it inspects for binary file modifications, vulnerable system versions, weak passwords, vulnerabilities from security misconfigurations, and changes on files and directories, thereby protecting from inadvertent user modification as well as intrusions and viruses. The Security Profile Inspector is freely available to all U.S. Government agencies and to contractors directly supporting the U.S. Departments of Energy and Defense.

The Secure Software Distribution System (SSDS) provides automated analysis of network-based computer systems to determine the status of security patches. SSDS determines what patches need to be installed. For the patches that are installed, SSDS checks the permissions and

ownership of the files referenced in the patch and ensures that the system software is authentic. SSDS is composed of two components: a Patch Server and a Vendor Server. Currently, SSDS detects patch deficiencies on Sun systems that run Solaris 2.3 or newer. SSDS is freely available to all U.S. Government agencies, and to contractors directly supporting the U.S. Departments of Energy and Defense.

The Network Intrusion Detector (NID) software product provides a suite of security tools that detects and analyzes network intrusions. NID provides detection and analysis of intrusions from individuals not authorized to use a particular computer, and from individuals allowed to use a particular computer, but who perform either unauthorized activities or activities of a suspicious nature on it. NID is available for use by all authorized Department of Energy offices, national laboratories and facilities, Department of Energy contractors who directly support DOE, and U.S. Government civilian federal agencies.

The workstation daylock is a combination of software and a hardware alarm card for protecting a PC workstation from access by unauthorized personnel.

The DOE Information Security Server (DOE-IS) is an advanced server on the Internet whose goal is to enhance information security data sharing within the United States Department of Energy (DOE) community. The DOE community includes all DOE sites and contractors. The Server contains tools and documents related to information security that have been made available by many sources both within and outside of the DOE.

The Computer Incident Advisory Capability (CIAC) group assists the Department of Energy in its information protection efforts by providing computer security incident response related services. CIAC provides on-call technical assistance and information to Department of Energy (DOE) sites faced with computer security incidents. This central incident handling capability is one component of all-encompassing service provided to the DOE community. The other services CIAC provides are: awareness, training and education; trend, threat, and vulnerability data collection and analysis; and technology watch.

Summary Budget Table (000$)

Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Nuclear Materials	**40,000**	**38,400**	**34,200**
Warning of Nuclear Materials Transit	22,500	20,900	18,400
Materials Analysis	10,400	10,700	9,700
Detect and Attribute Nuclear Materials	7,100	6,800	6,100
Responding to Chemical and Biological Proliferation	**19,000**	**19,000**	**32,000**
Biological Foundations	5,000	5,000	9,000
Modeling and Prediction	3,000	3,000	4,000
Chemical and Biological Detection	7,500	7,500	12,000
Decontamination and Restoration	2,000	2,000	3,000
Systems Analysis and Integration	1,500	1,500	4,000
Critical Infrastructure Protection	**5,900**	**5,500**	**6,300**
Total	**64,900**	**62,900**	**72,500**

Appendix

Budget Profiles (000$)

Research Areas	FY 1998 Appropriated	FY 1999 Appropriated	FY 2000 Request
Maintaining The Nuclear Deterrent	**1,904,000**	**2,180,000**	**2,357,000**
Primary Weapon Initiation	218,000	212,000	213,000
Primary Performance	399,000	468,000	491,000
Secondary Performance	438,000	519,000	551,000
System Integration	283,000	306,000	332,000
Safety / Security / Use Control	153,000	154,000	165,000
Crosscutting Research	413,000	521,000	605,000
Monitoring Nuclear Treaties and Agreements	**47,900**	**45,100**	**40,900**
Monitoring Nuclear Test Ban Treaties	45,900	42,100	37,900
Nuclear Nonproliferation and Arms Reduction Monitoring	2,000	3,000	3,000
Preventing Proliferation	**65,900**	**66,700**	**69,300**
Fissile Material Disposition	44,700	43,800	43,800
Nuclear Materials Protection	17,700	19,100	21,200
Proliferation Resistant Fuel Cycle Technologies	3,500	3,800	4,300
Verification Technologies	**64,800**	**67,400**	**67,500**
Chemical Detection	33,400	41,500	41,700
Physical Detection	31,400	25,900	25,800
Countering WMD Terrorism	**64,900**	**62,900**	**72,500**
Nuclear Materials	40,000	38,400	34,200
Responding to Chemical and Biological Proliferation	19,000	19,000	32,000
Infrastructure Protection	5,900	5,500	6,300
Total	**2,147,500**	**2,422,100**	**2,607,200**