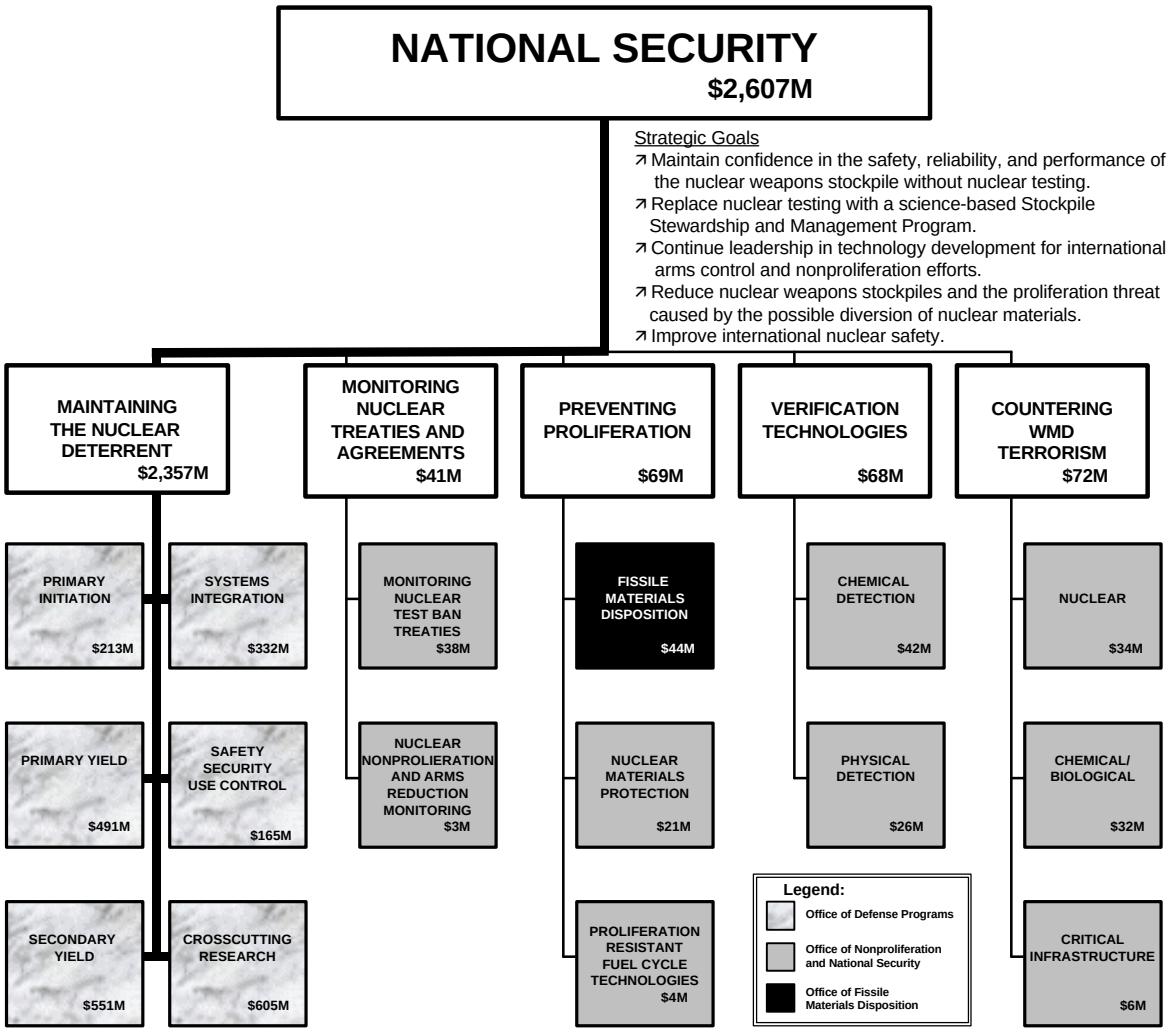
Chapter 3
Maintaining The Nuclear Deterrent



Chapter 3
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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.

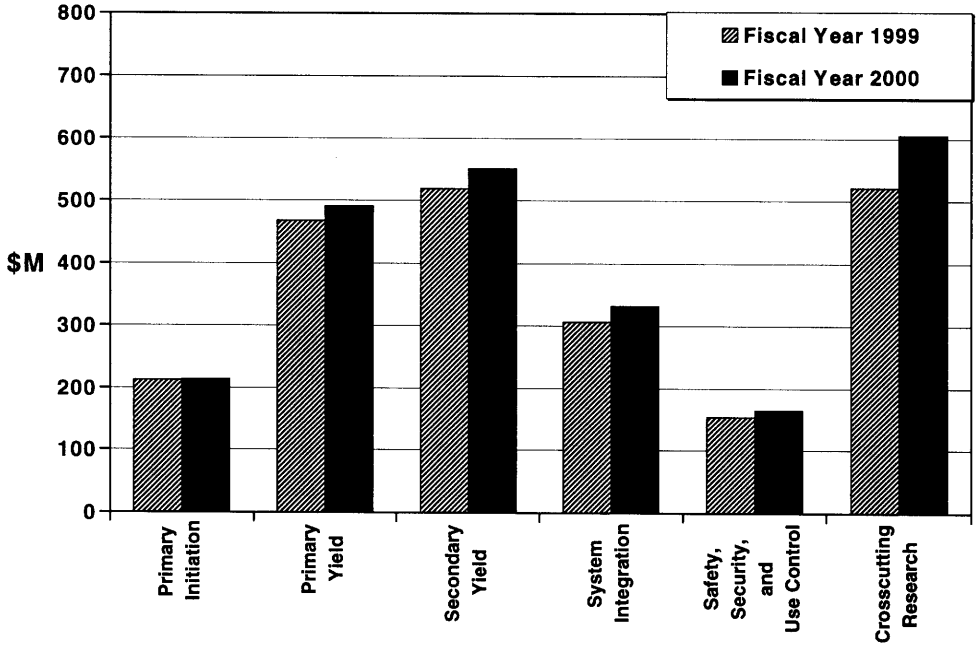
Key Accomplishments

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**